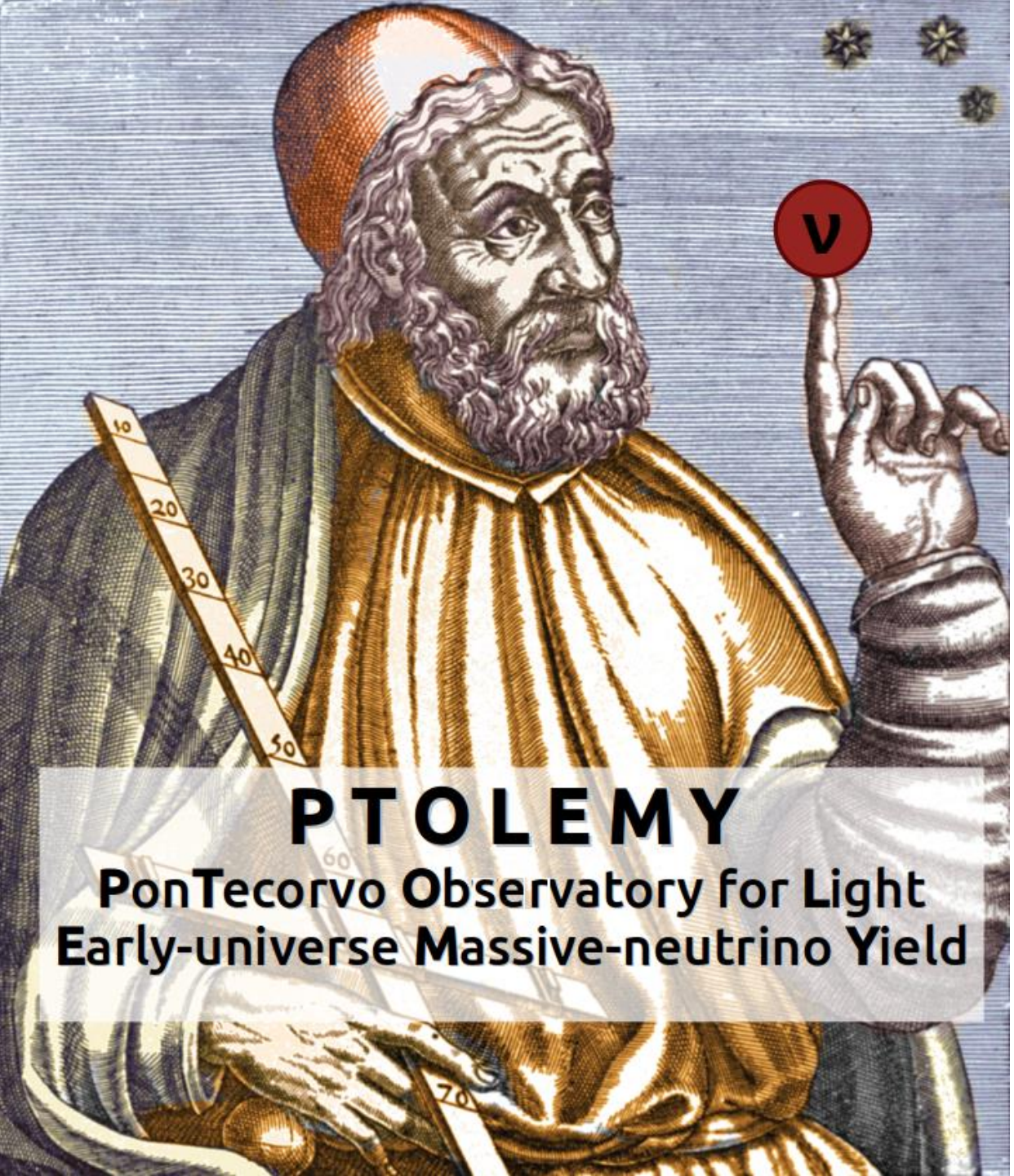


Tackling the experimental challenge to detect relic neutrinos with PTOLEMY

Federico Virzi

Università degli studi dell'Aquila

ICHEP24 19/07/2024

INFN LNGS

RENOVABITUR UT AQUILAE JUVENTUS TUA
JUS LITTERAE SCIENTIAE

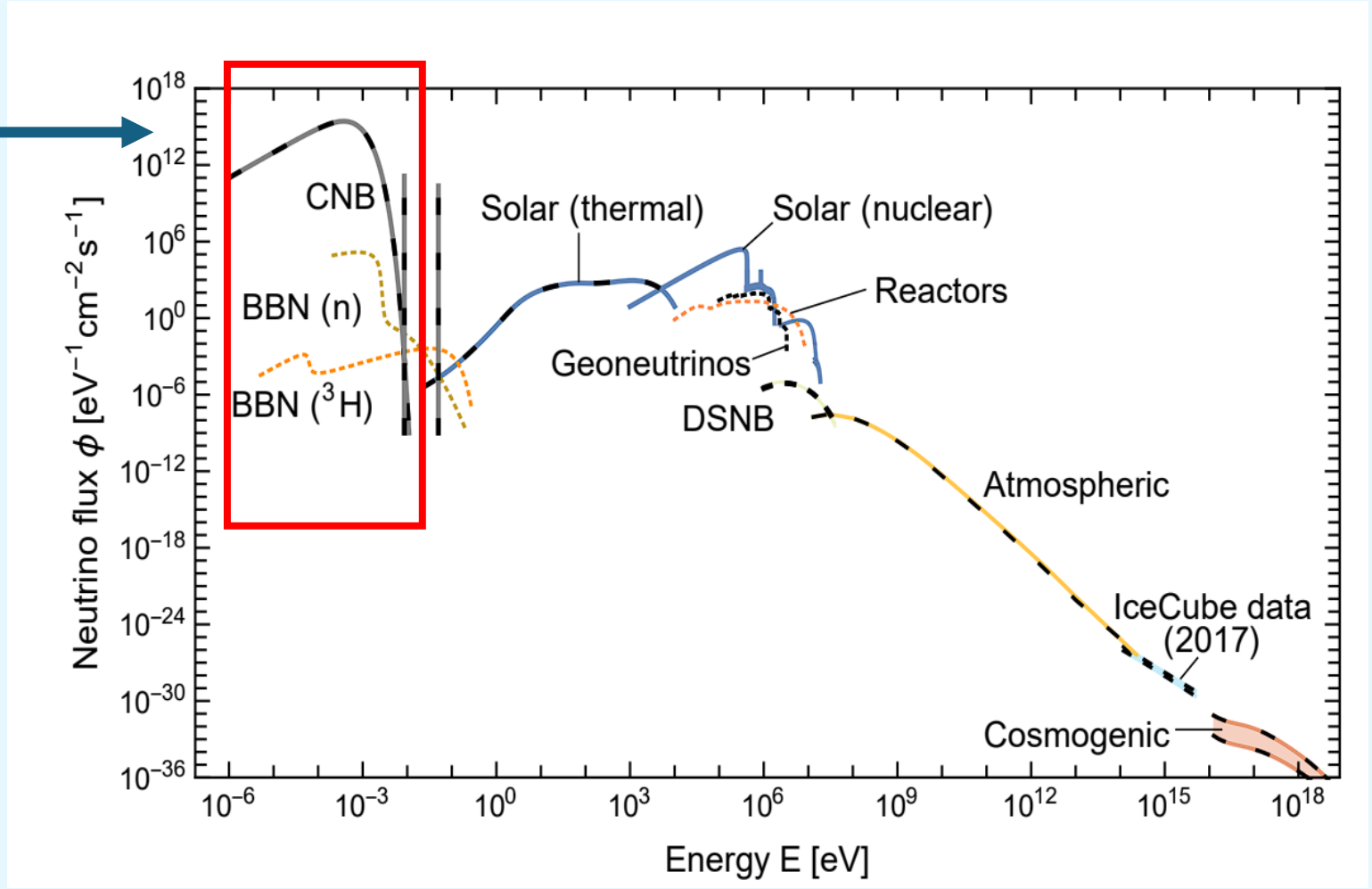
Cosmic Neutrino Background direct detection

- Most abundant neutrino source in the Universe!
- But extremely low Energy

- The only neutrino source at low energy

$K_\nu \approx 10^{-4}$ eV

- Neutrinos do not provide energy for interaction
- Very difficult to detect:



Rev. Mod. Phys. 92, 45006 (2020)

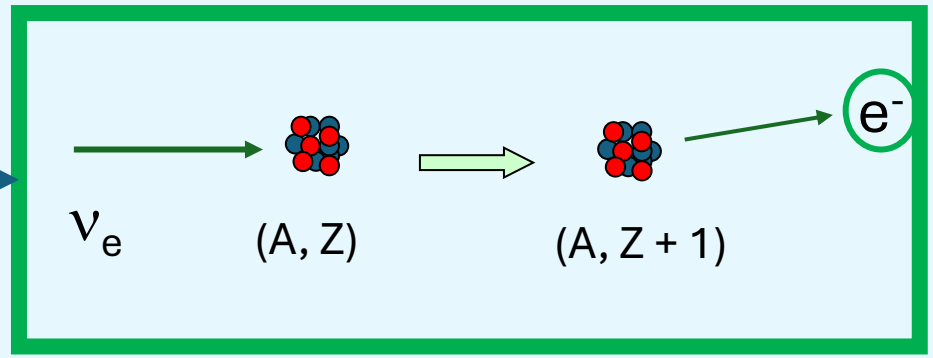
How? → PTOLEMY Project

Cosmic Neutrino Background direct detection: PTOLEMY

- Neutrino capture on beta decaying Nuclei reaction
- Need beta unstable element
- Want maximize interaction with CNB

No energy needed!

Tritium ^3H



1. Neutrino mass
2. Dirac/Majorana
3. CNB
4. Sterile neutrino

PTOLEMY concept: scalable experiment

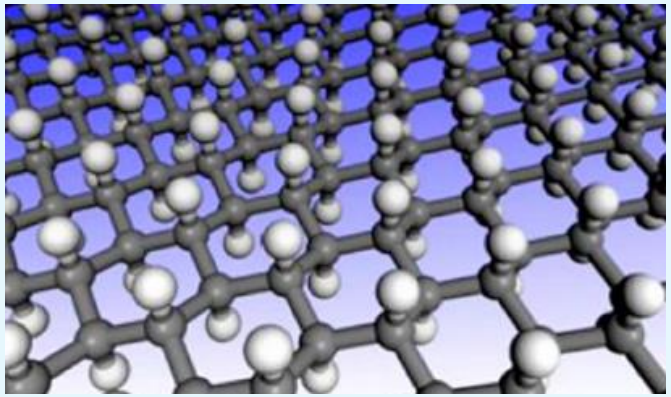
Novel PTOLEMY filter

Solid atomic Tritium

JCAP 0706:015,2007

JCAP 07 (2019) 047

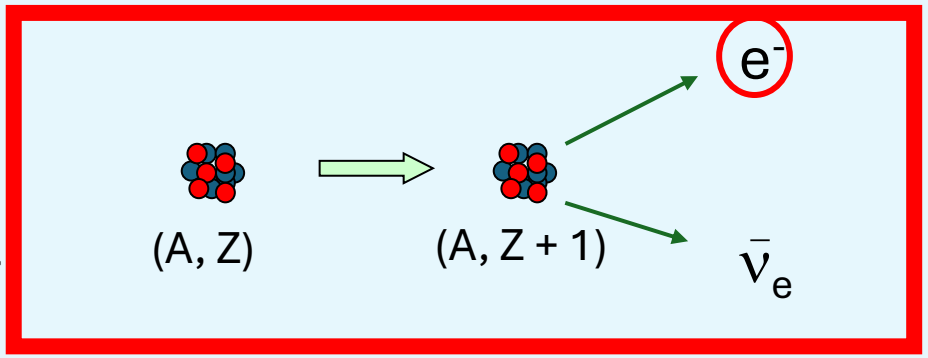
Solid Tritium target



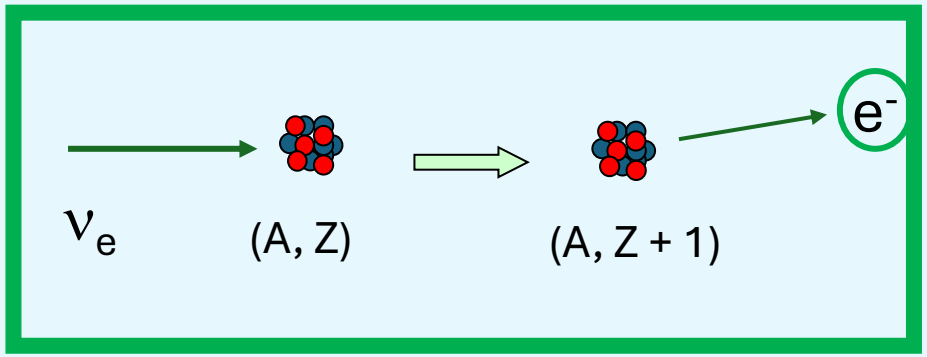
- Atomic Tritium on graphene

- High rate
- Need good energy resolution

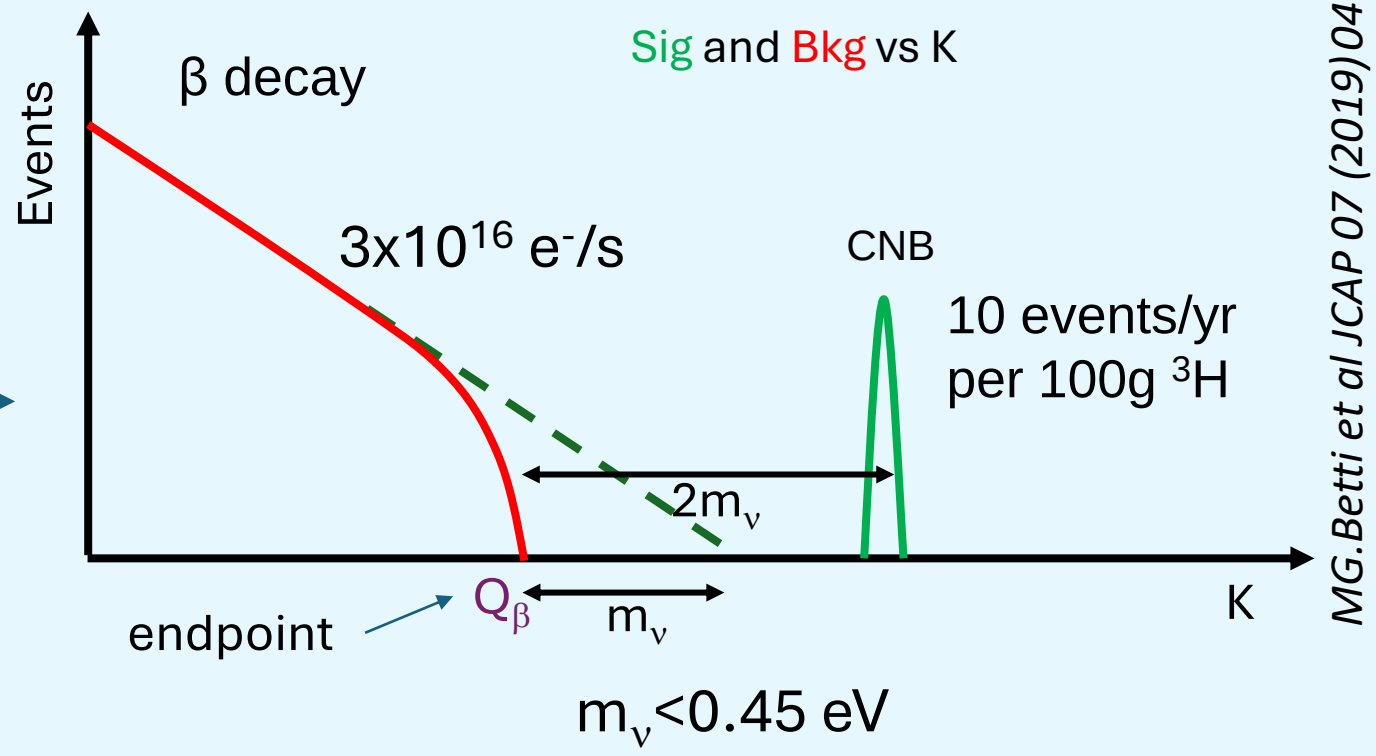
β decay (Background)



CNB interaction



Phys.Rev.D 106 (2022) 5, 053002

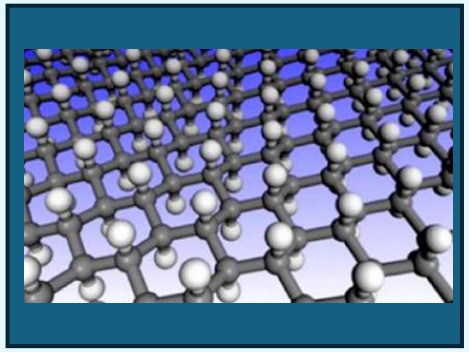


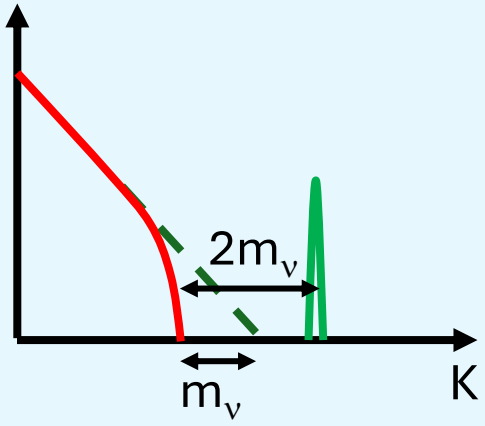
MG.Betti et al JCAP 07 (2019)047

KATRIN *arXiv:2406.13516v1 [nucl-ex] 19 Jun 2024*

PTOLEMY concept I

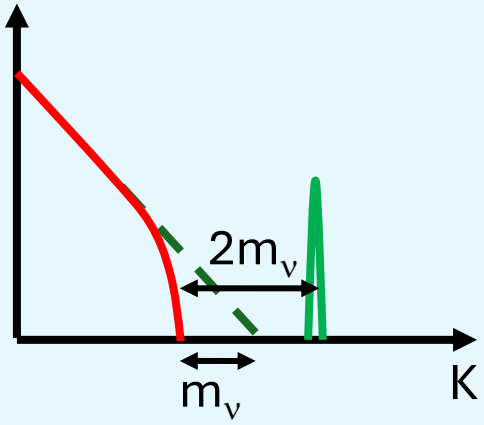
Tritium target





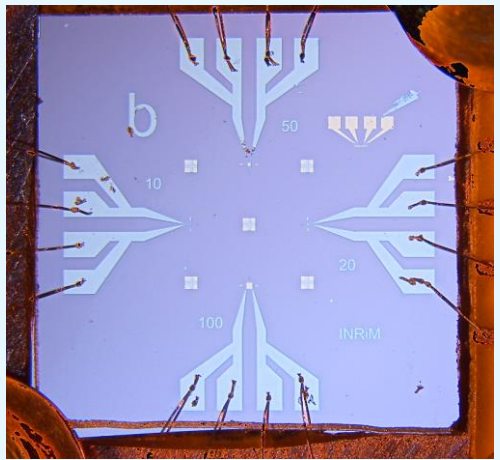
How to measure this?

Obtaining desired energy resolution: TES



Need σ_K=50 meV

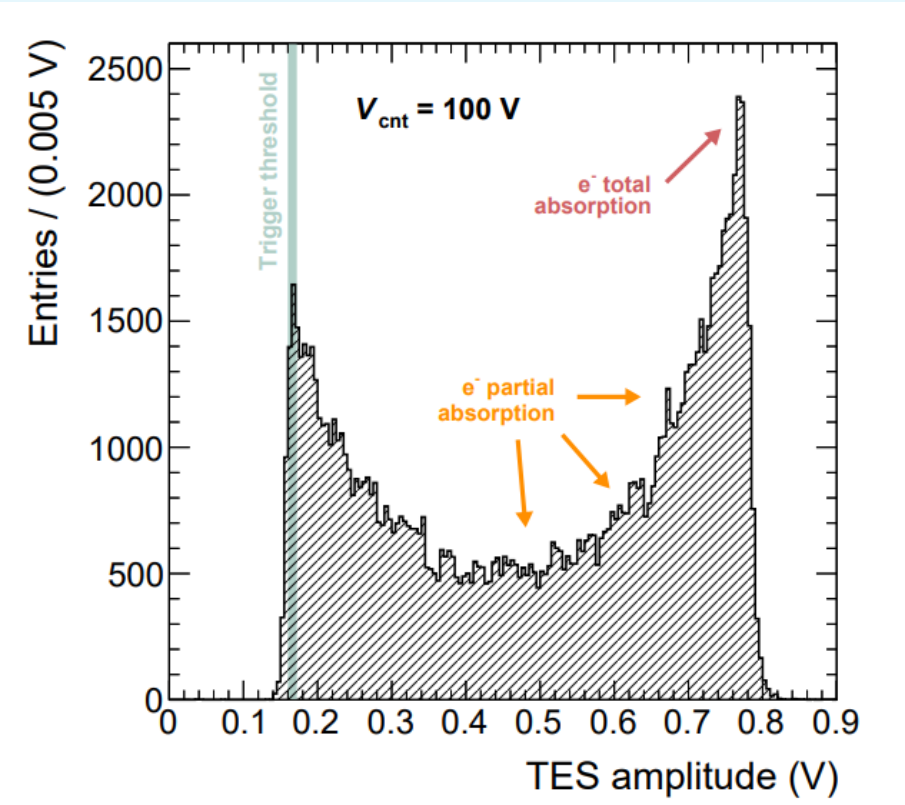
Transition Edge Sensor as microcaloremeter



Typically used for photons

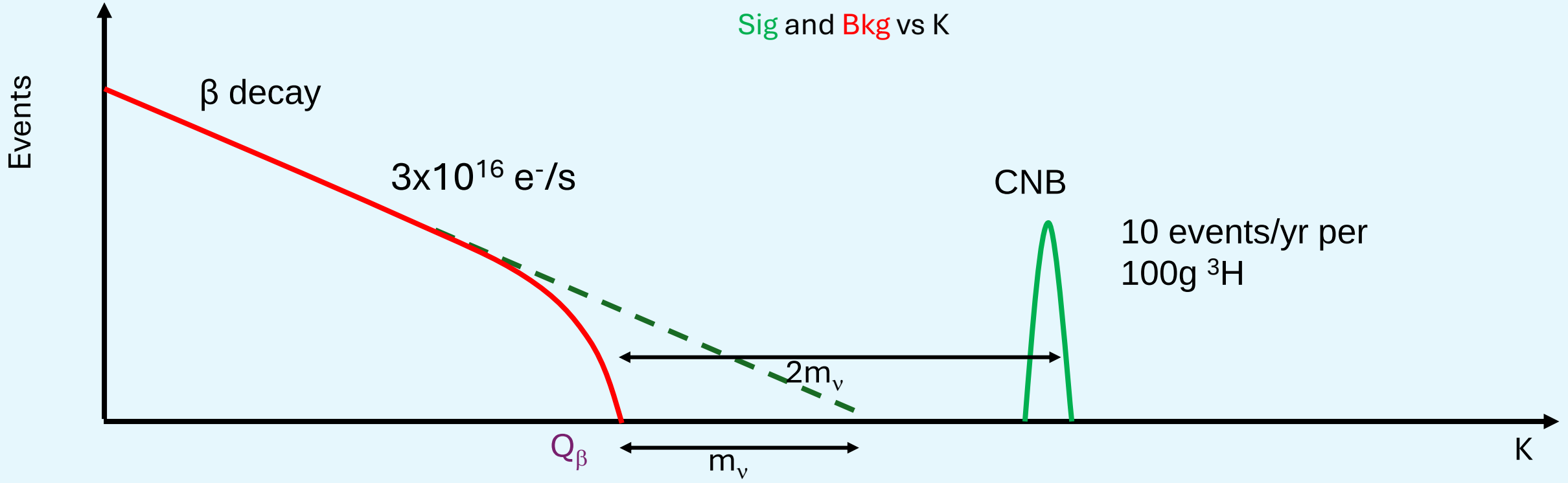
We want to use them as microcaloremeters for electrons

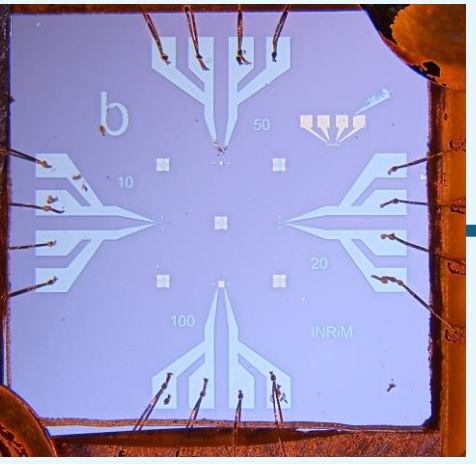
Dedicated talk on fresh results by Francesco Pandolfi
18 july 2024, 08:47 R&D parallel session



arXiv:2405.19475v1 [physics.ins-det] 29 May 2024

PTOLEMY Energy measurement





You need

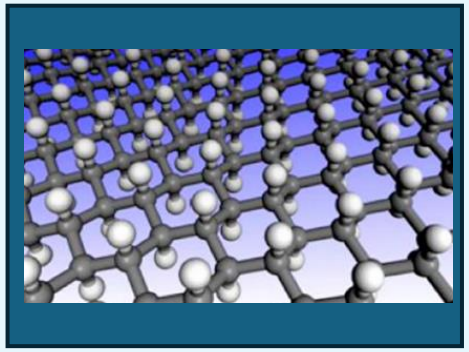
Low electron rate

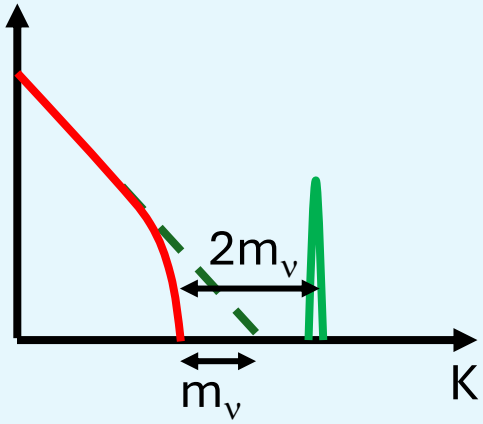
Decrease energy from 18.6keV to O(100eV)

PTOLEMY's novel Dynamic Filter

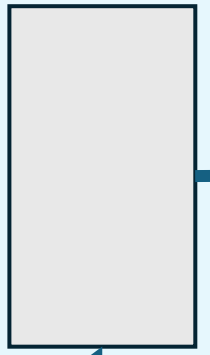
PTOLEMY concept II

Tritium target

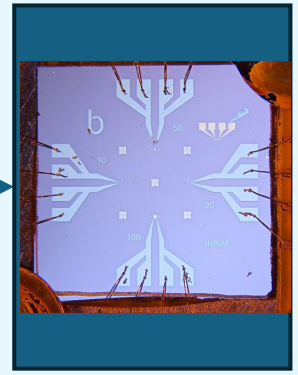




Filter



TES

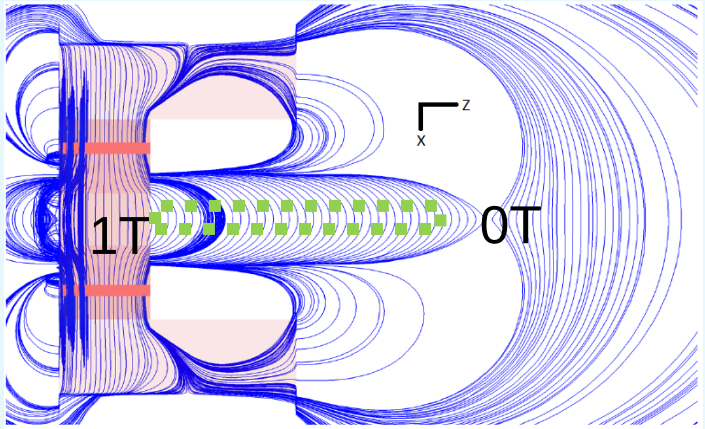


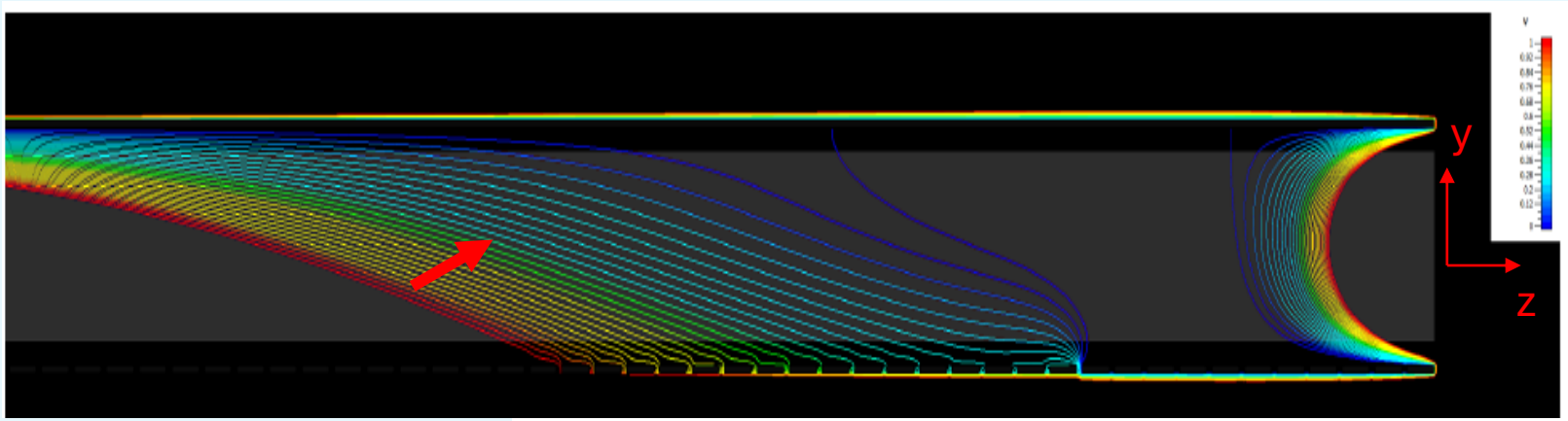
How?

σ_E=50 meV

PTOLEMY filter

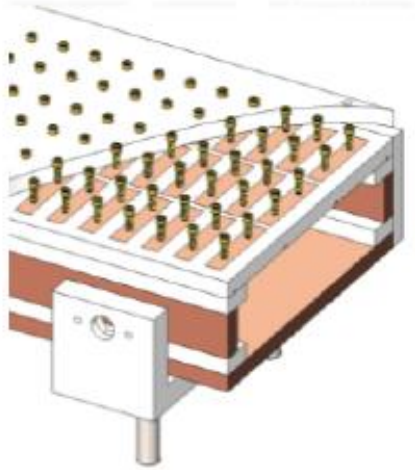
- Exponential decaying magnetic field
- Exponential decaying electric field





$$B_x = B_0 \cos\left(\frac{x}{\lambda}\right) e^{-z/\lambda},$$
$$B_y = 0,$$
$$B_z = -B_0 \sin\left(\frac{x}{\lambda}\right) e^{-z/\lambda}.$$

$$E_x = 0,$$
$$E_y = E_0 \cos\left(\frac{y}{\lambda}\right) e^{-z/\lambda},$$
$$E_z = -E_0 \sin\left(\frac{y}{\lambda}\right) e^{-z/\lambda}.$$



$$\boldsymbol{V}^{y}_{E\times B}(z)|_{x,y=0} = \frac{\boldsymbol{E}\times\boldsymbol{B}}{B_x^2} = \frac{E_z B_x \hat{\boldsymbol{y}}}{B_x^2} = \frac{E_z}{B_x}\hat{\boldsymbol{y}}$$

$$\boldsymbol{V}_{\nabla B-C} = \frac{1}{2} m(v_\perp^2 + 2v_\parallel^2)\frac{\boldsymbol{B}\times\boldsymbol{\nabla}_\perp B}{qB^3} = (T_\perp + 2T_\parallel)\frac{\boldsymbol{B}\times\boldsymbol{\nabla}_\perp B}{qB^3}$$

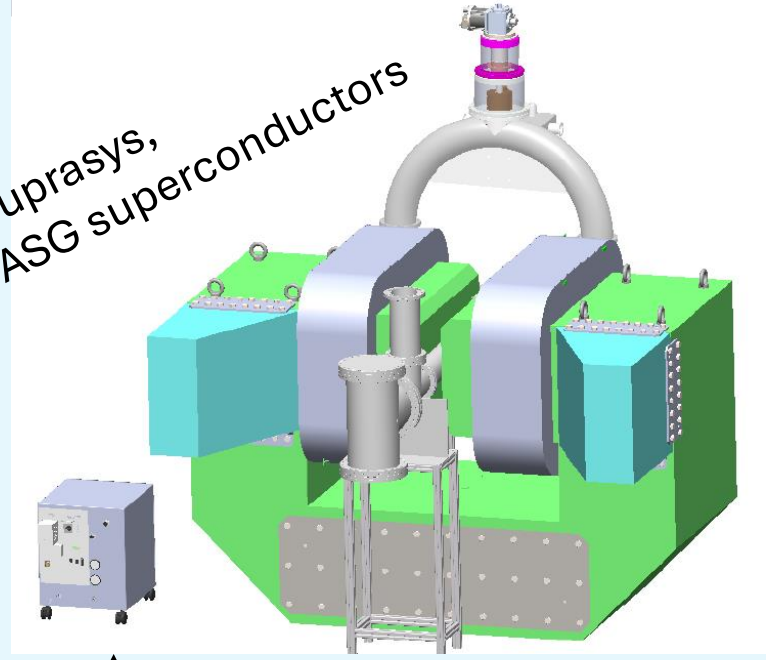
arXiv:2108.10388v2 [physics.ins-det] 24 Jan 2022

Dynamic EM Filter

Pitch angle Θ =angle between e^- velocity and B

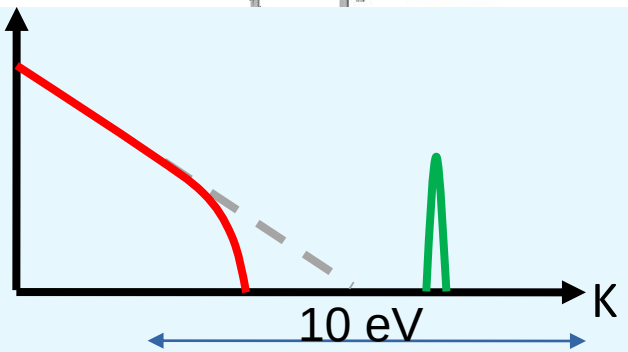
- Electron decelleration:
  Drain K, Θ
  K up to O(100 eV) on TES

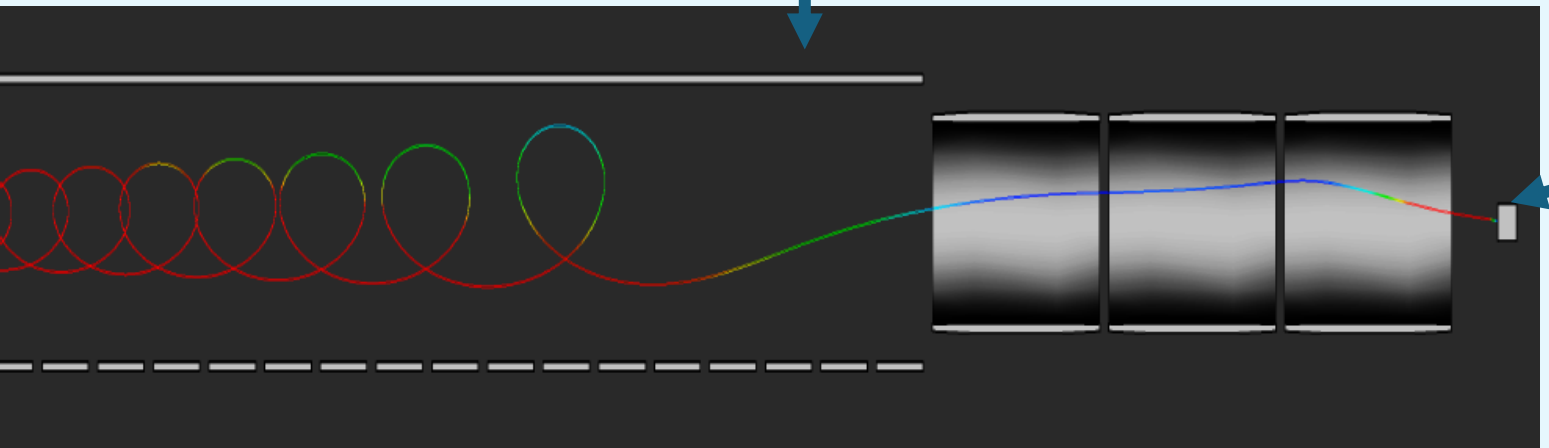
Energy Drain ✓



- If electron has:
  $K<Q_\beta$ → Discarded TES
  $K \sim Q_\beta$ →

Background rejection ✓



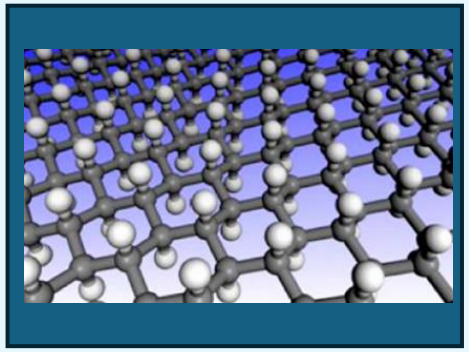


Event by event basis
If K , Θ known

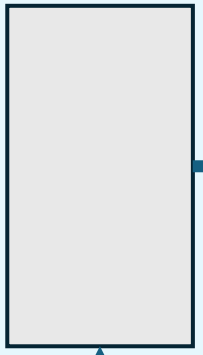
RF Region

PTOLEMY concept III

Tritium target

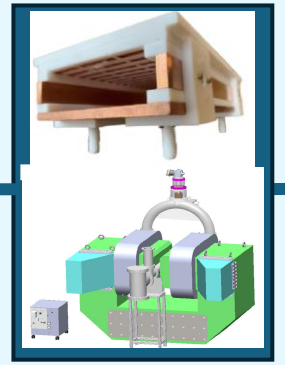


RF region



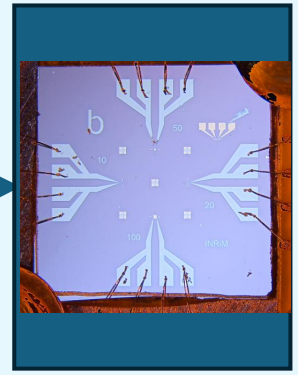
How?

Filter

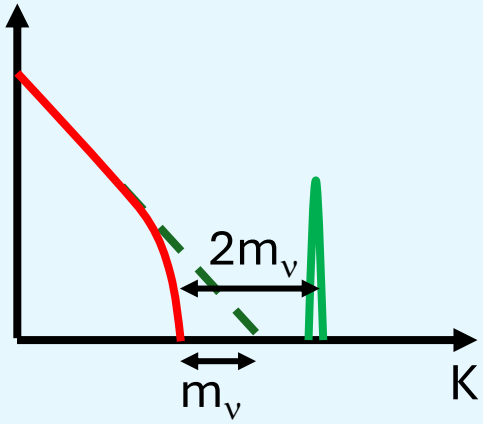


Energy Drain
+filter

TES



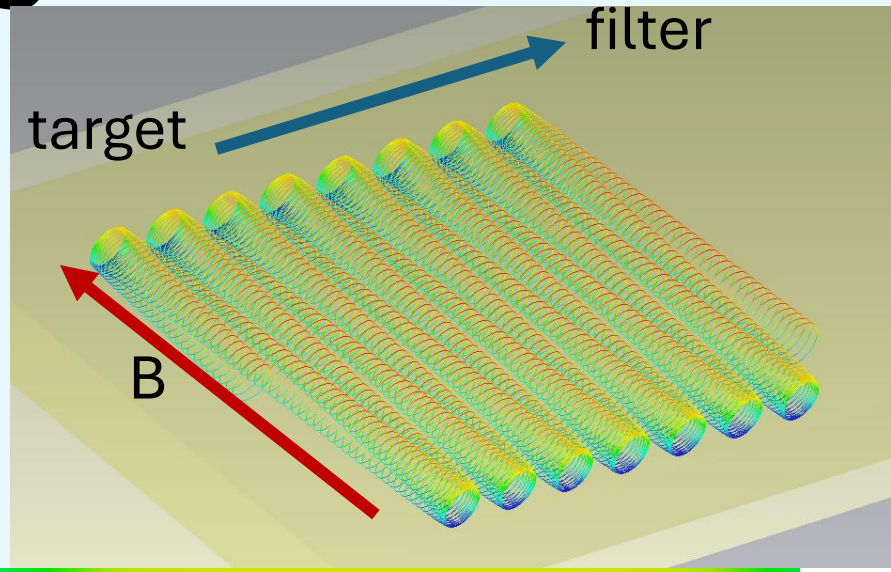
σ_E=50 meV

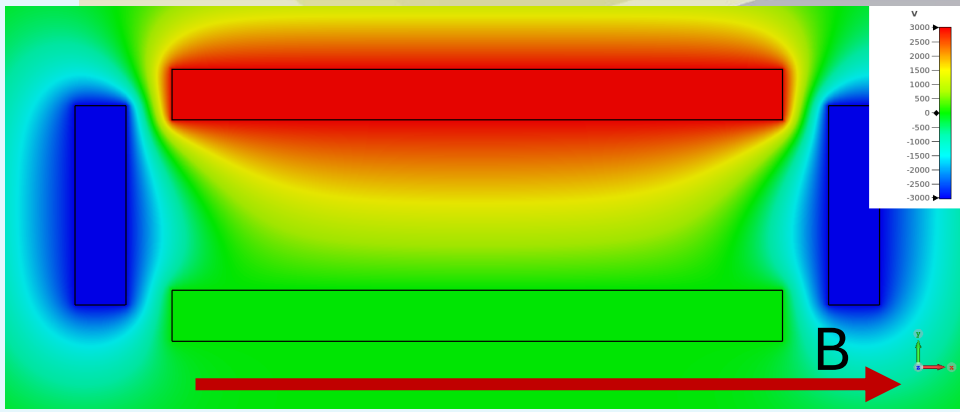


RF region: filter trigger

Requirements:

- Measurement K , Θ for each electron in the ROI
- O(10 eV) energy resolution ← Rough mesurement
- In O(100 μs) ← Very fast!
- Non destructive measurement
- Uniform 1T field





How? → Electron spectroscopy with cyclotron radiation (CRES)

PROJECT 8

Thank you!

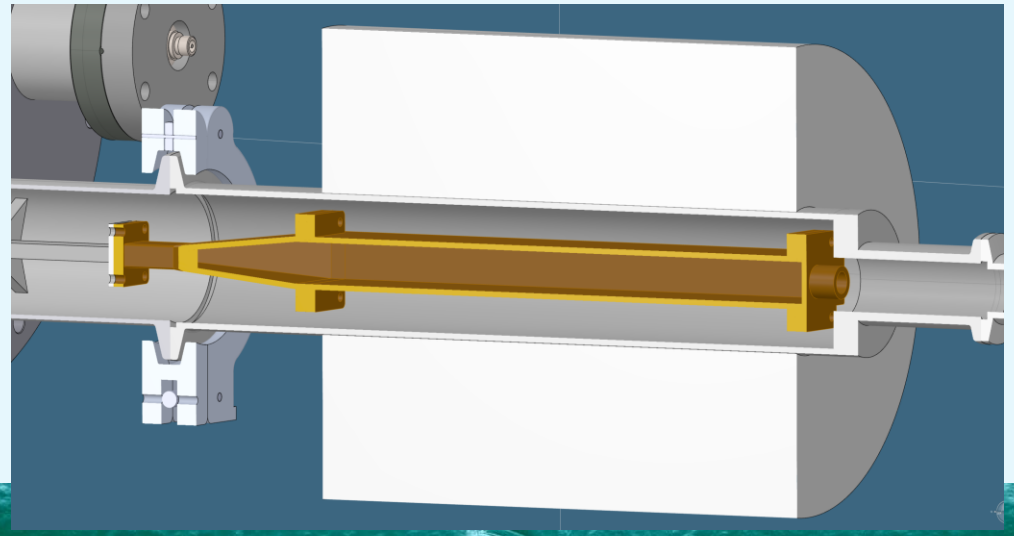
$$f_c = \frac{1}{2\pi}\frac{|q|B}{m}\frac{1}{K/m+1}$$

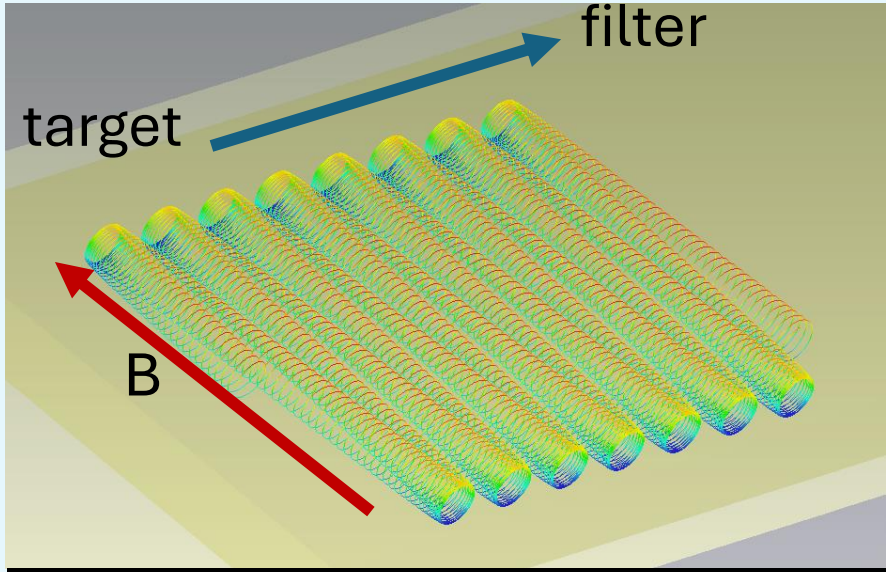
Cyclotron radiation
In uniform 1T
Bouncing motion → TOF information combined with TES

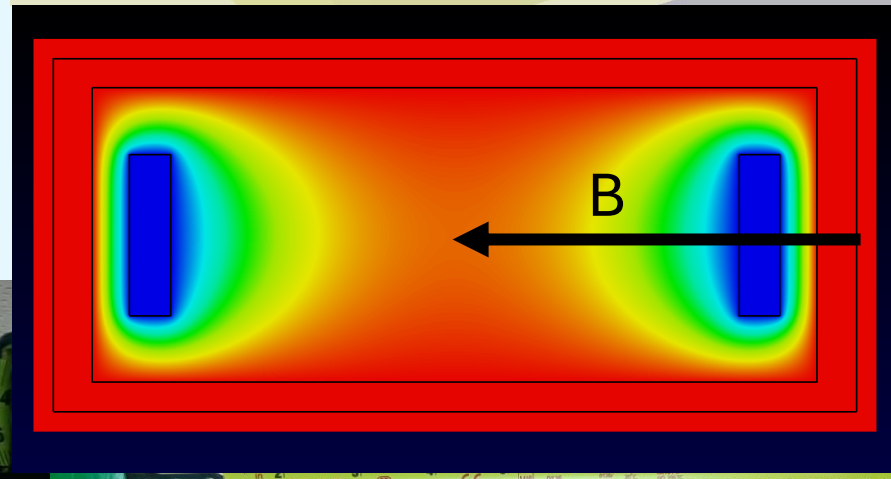
Electron Trap: test setup for RF Region

Ongoing measurements at LNGS

- Kr source
- 0.98T permanent magnet
- Detection of RF emitted by electron in bouncing motion

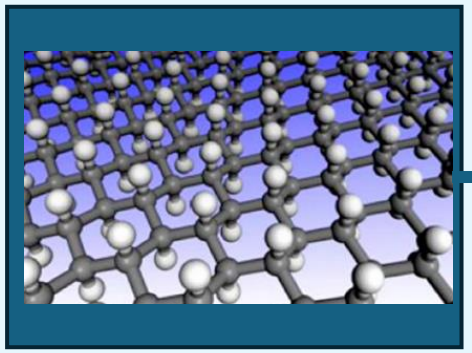




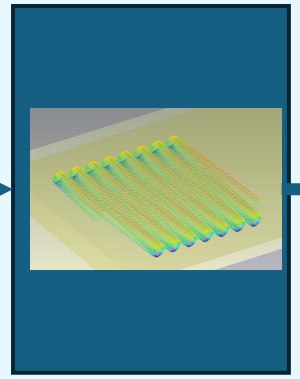


PTOLEMY concept IV

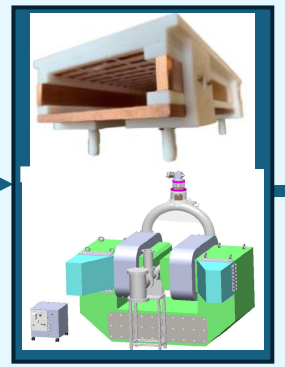
Tritium target



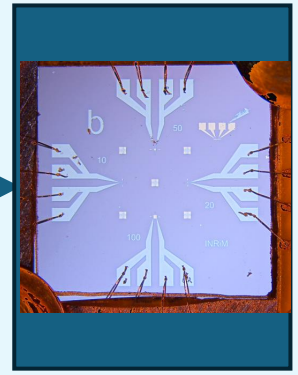
RF region

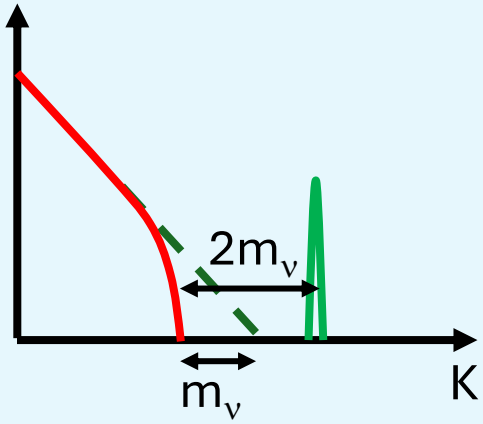


Filter



TES





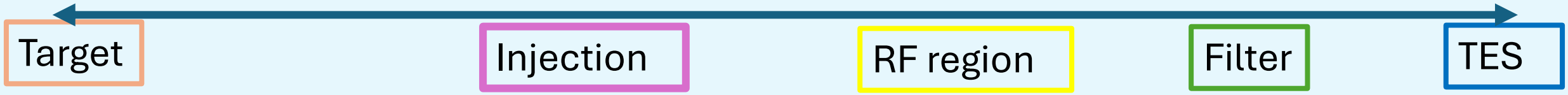
Filter trigger
K and Θ, fast and
rough measurement

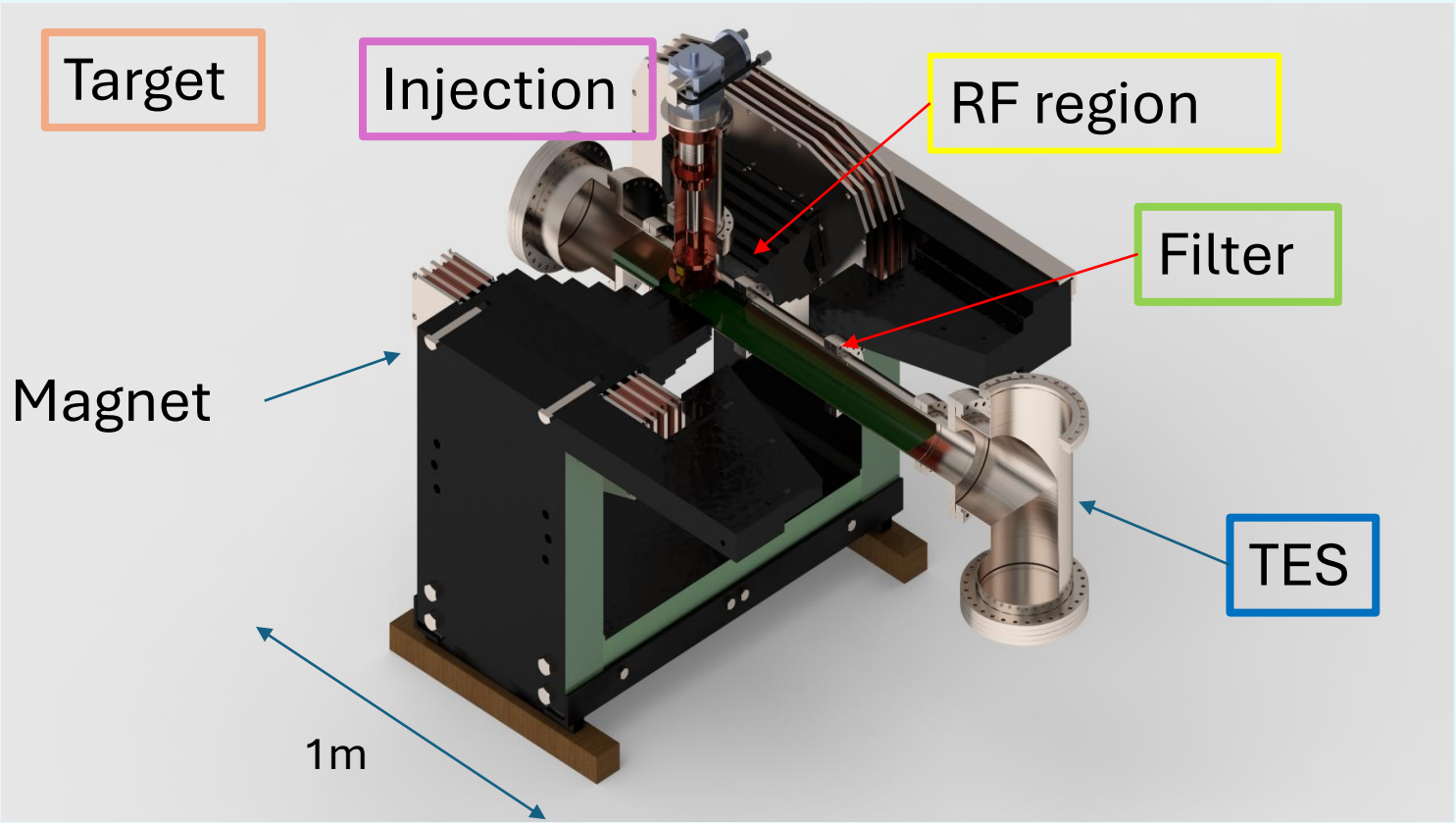
Energy Drain
+filter

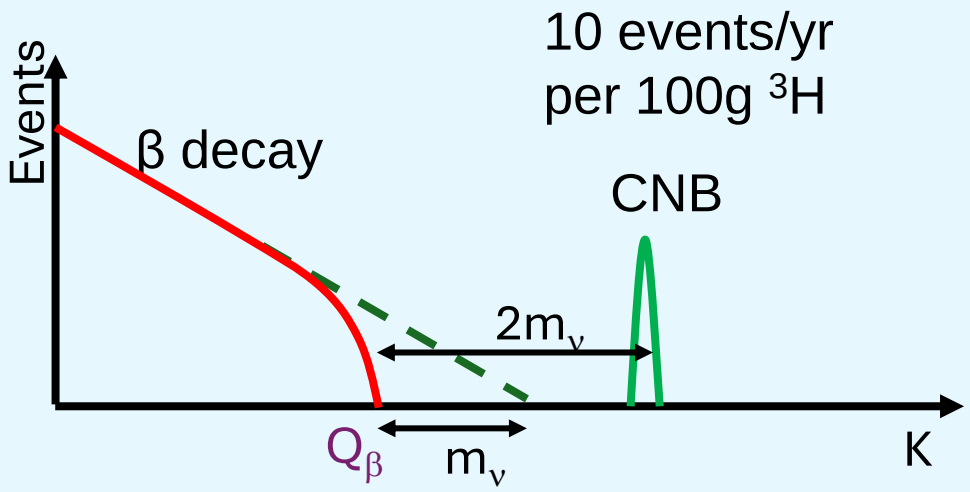
σ_K=50 meV

PTOLEMY Concept

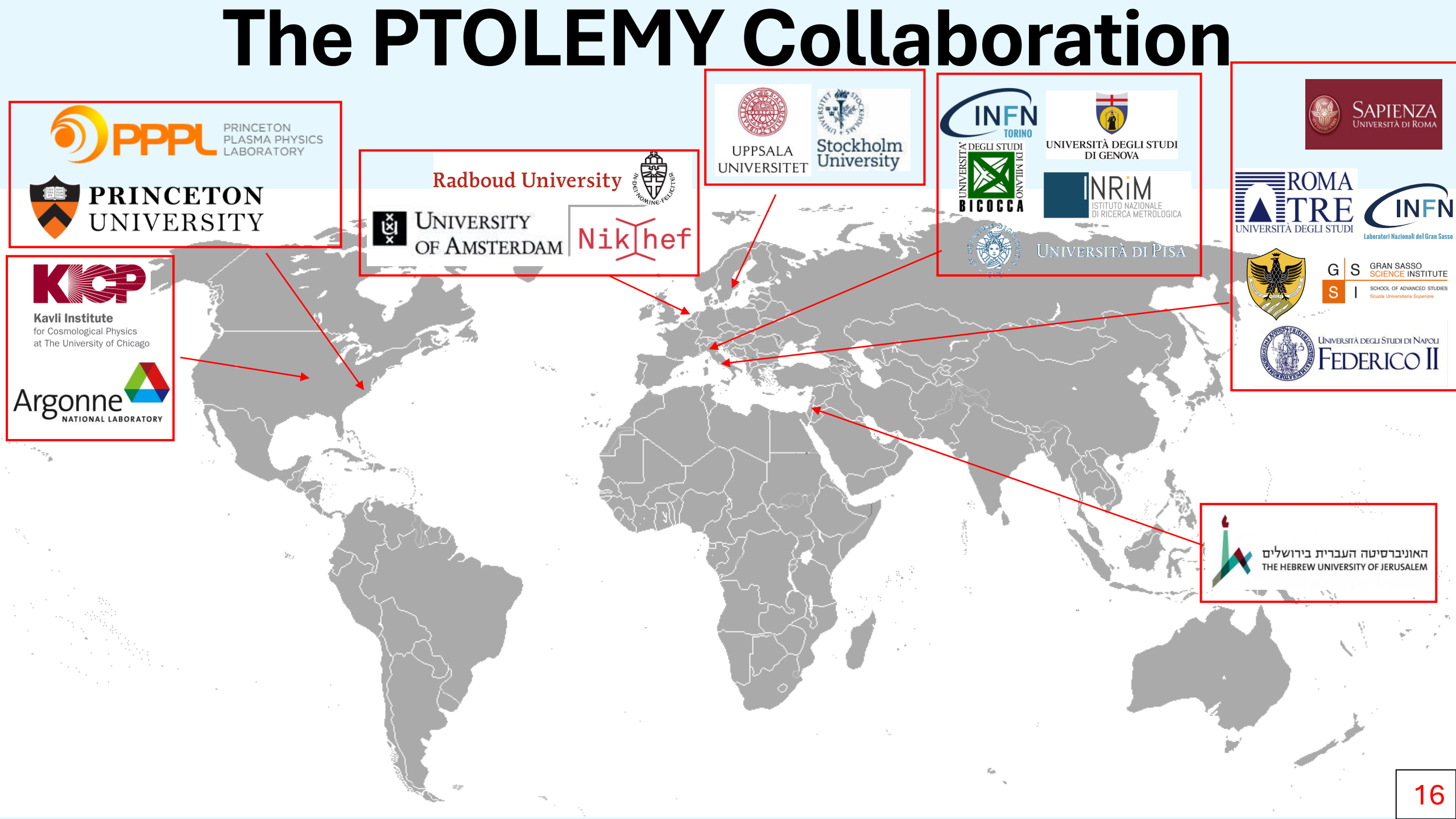
How to reconstruct target's electron kinetic energy K_i? → $K_i = q\Delta V + E_{RF,corr} + E_{TES}$







The PTOLEMY Collaboration

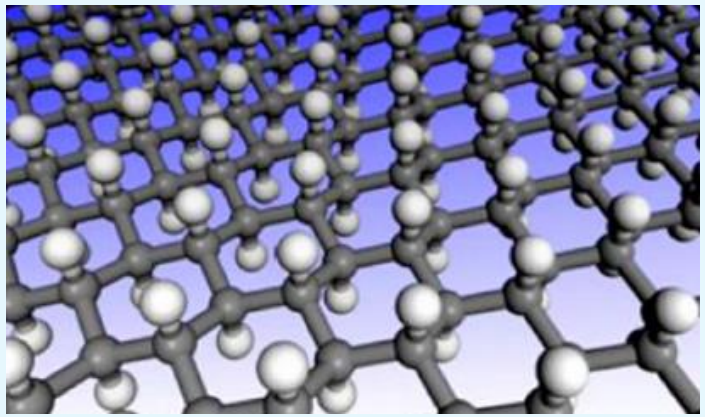


Conclusion and outlook

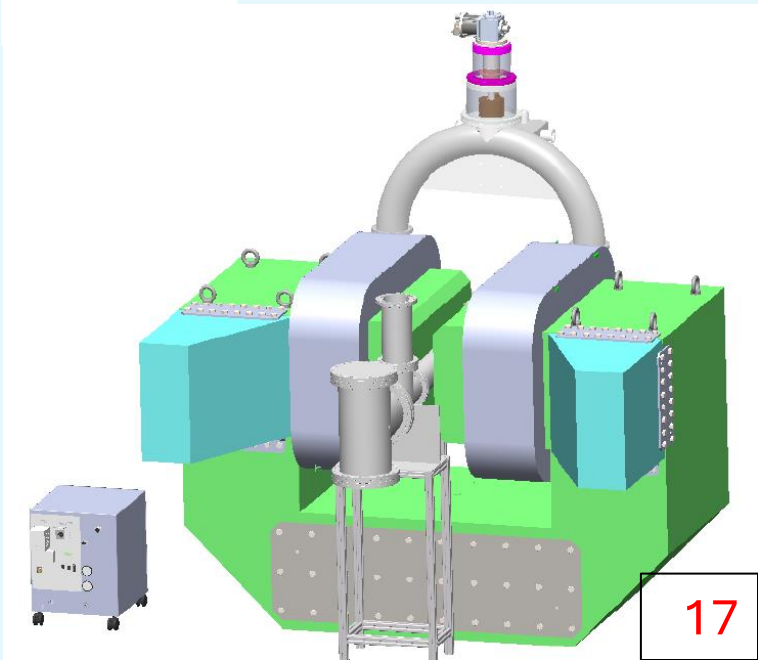
PTOLEMY experimental method

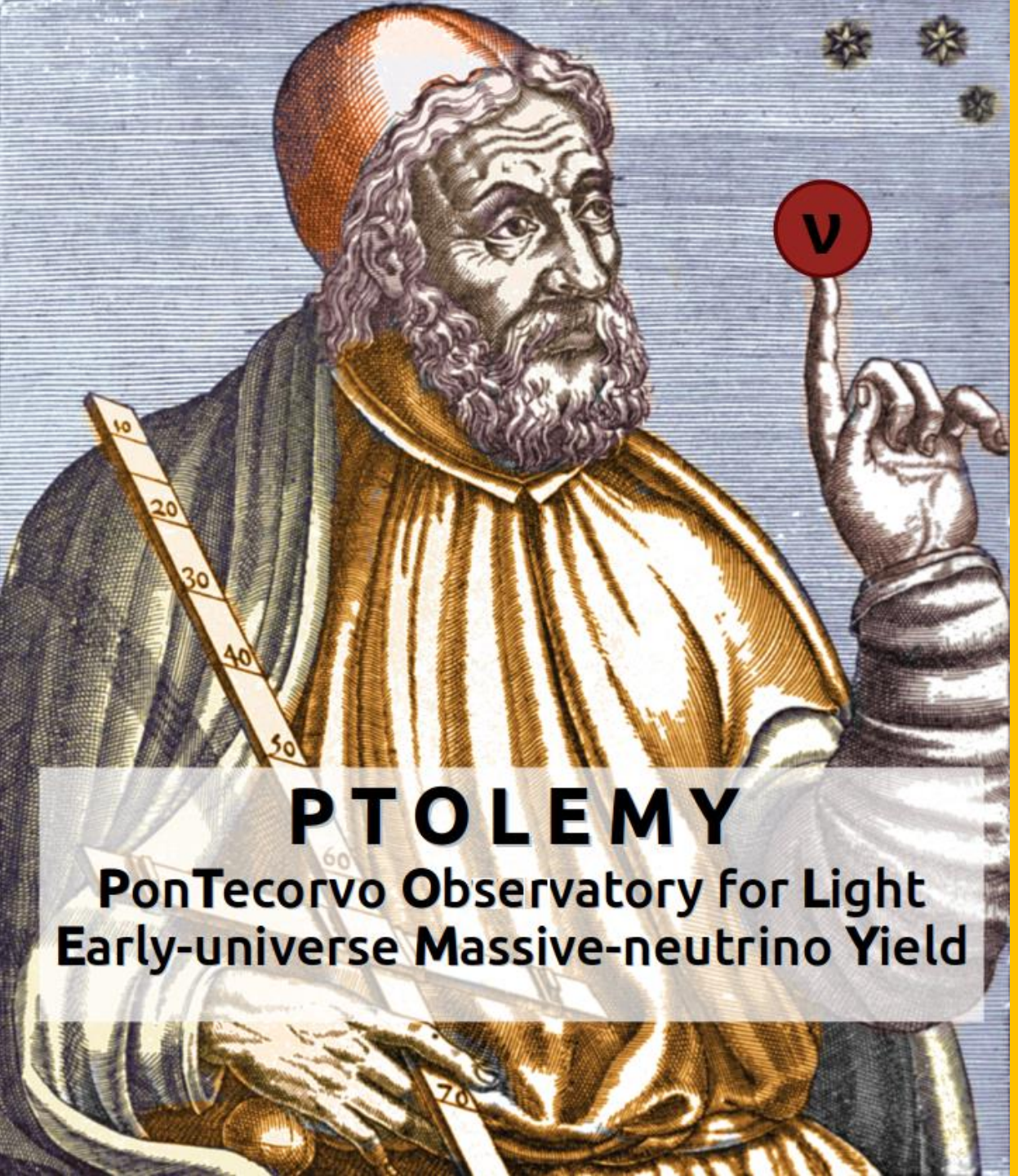
Atomic, solid Tritium target	Background rejection by realtime filter +bouncing motion geometry	High precision energy measurement

Key for future high tritium mass experiment



Phase 0) Demonstrator
Phase 1) Measurement m_ν
Phase 2) Mid Scale demonstrator
Phase 3) Measurement CNB

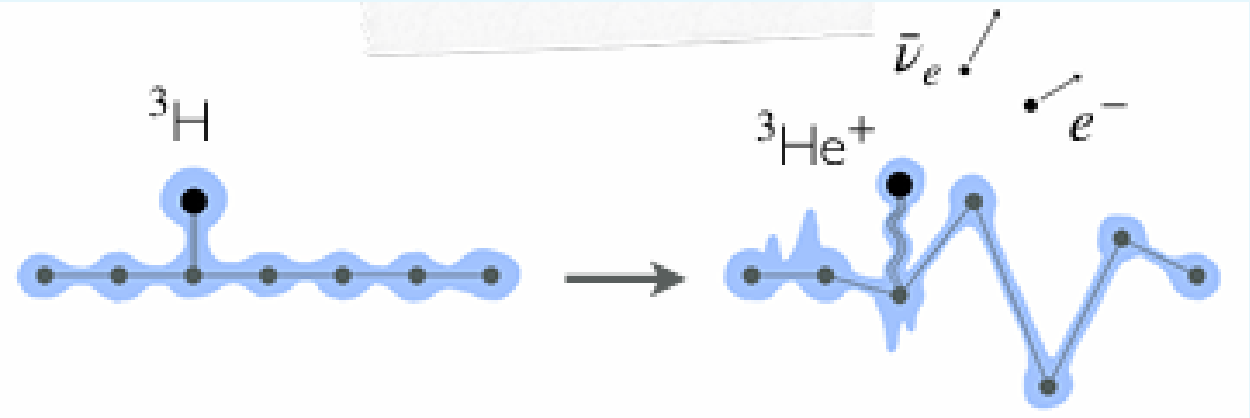


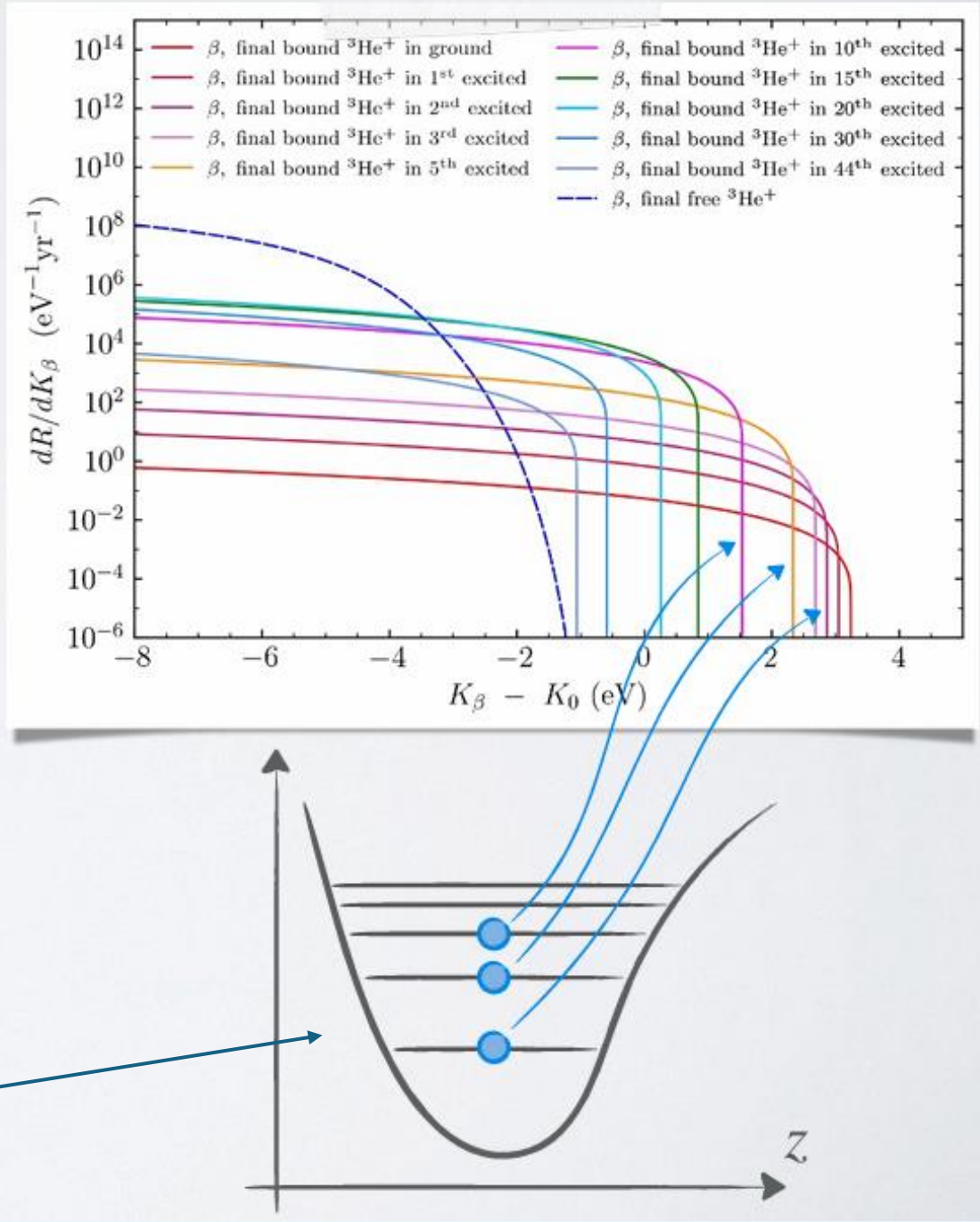


Backup slides

Tritium-graphene binding

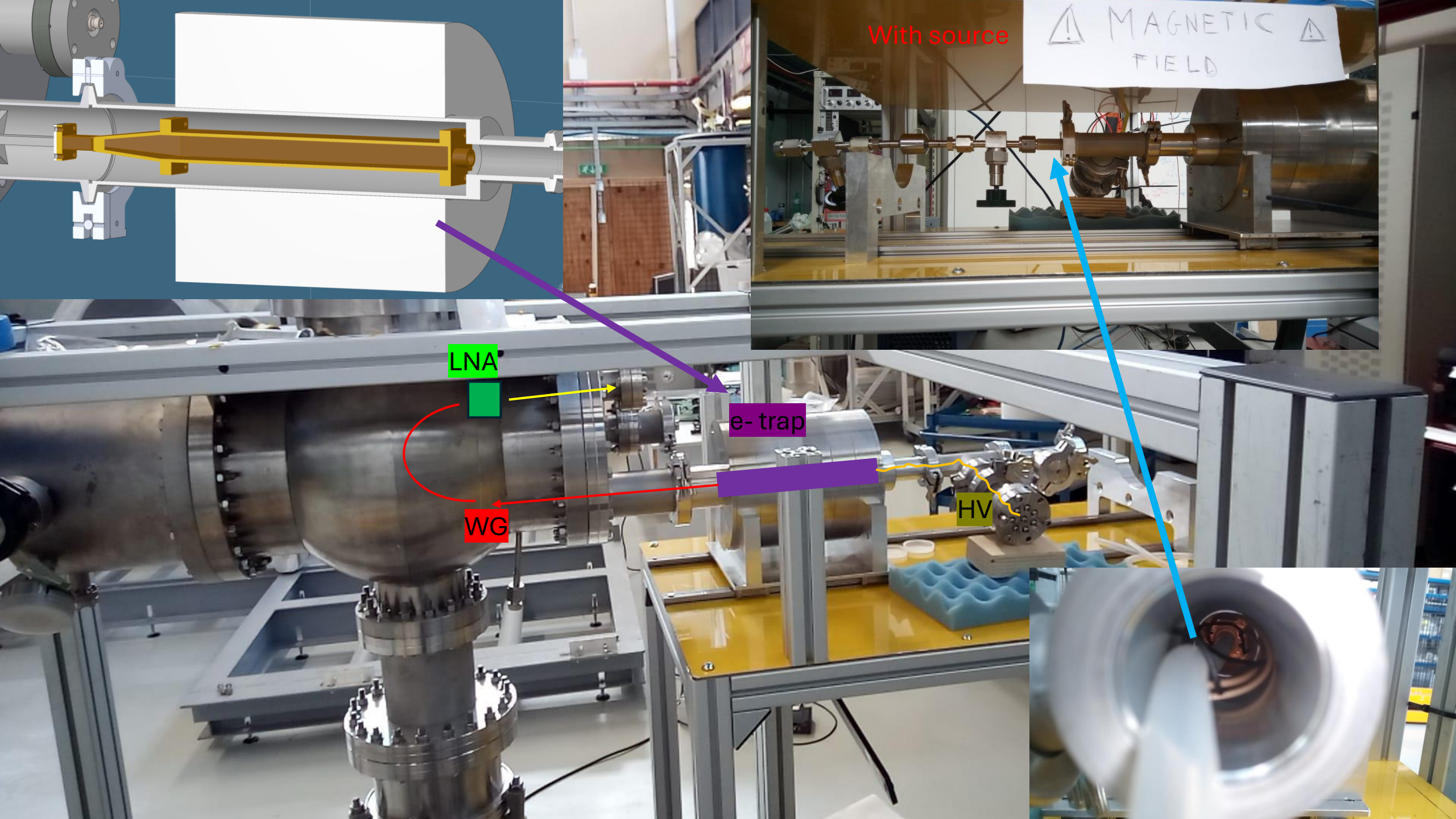
- Quantum spread
- Lattice recoil





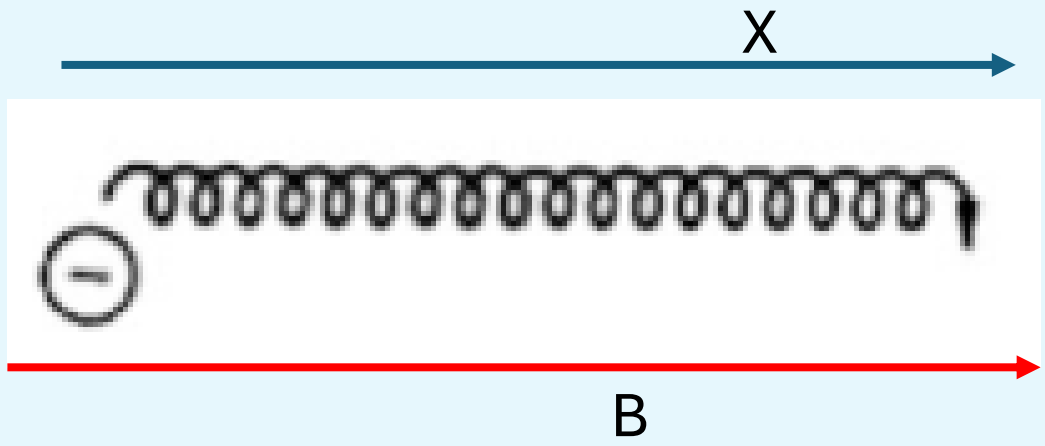
Helium in different final eigenstates

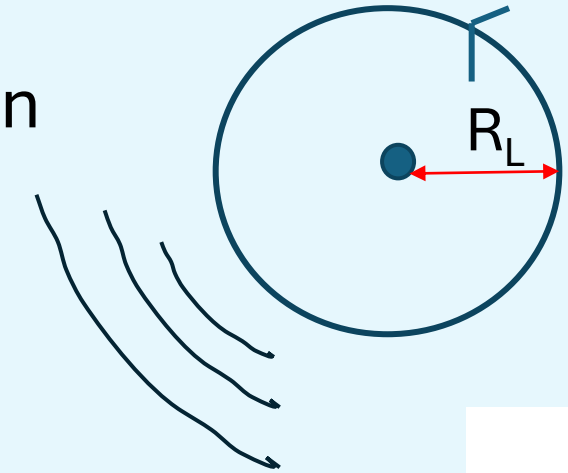
arXiv:2203.11228v1 [hep-ph] 21 Mar 2022


With source
MAGNETIC
FIELD
LNA
e- trap
HV
WG

Electron motion: uniform B, E=0

- Start with electron with velocity v_0
- Uniform B:
  electron in cyclotron motion
  $+V_x$ drift
- Can approximate circular motion with circle's center motion
- Cyclotron radiation emission





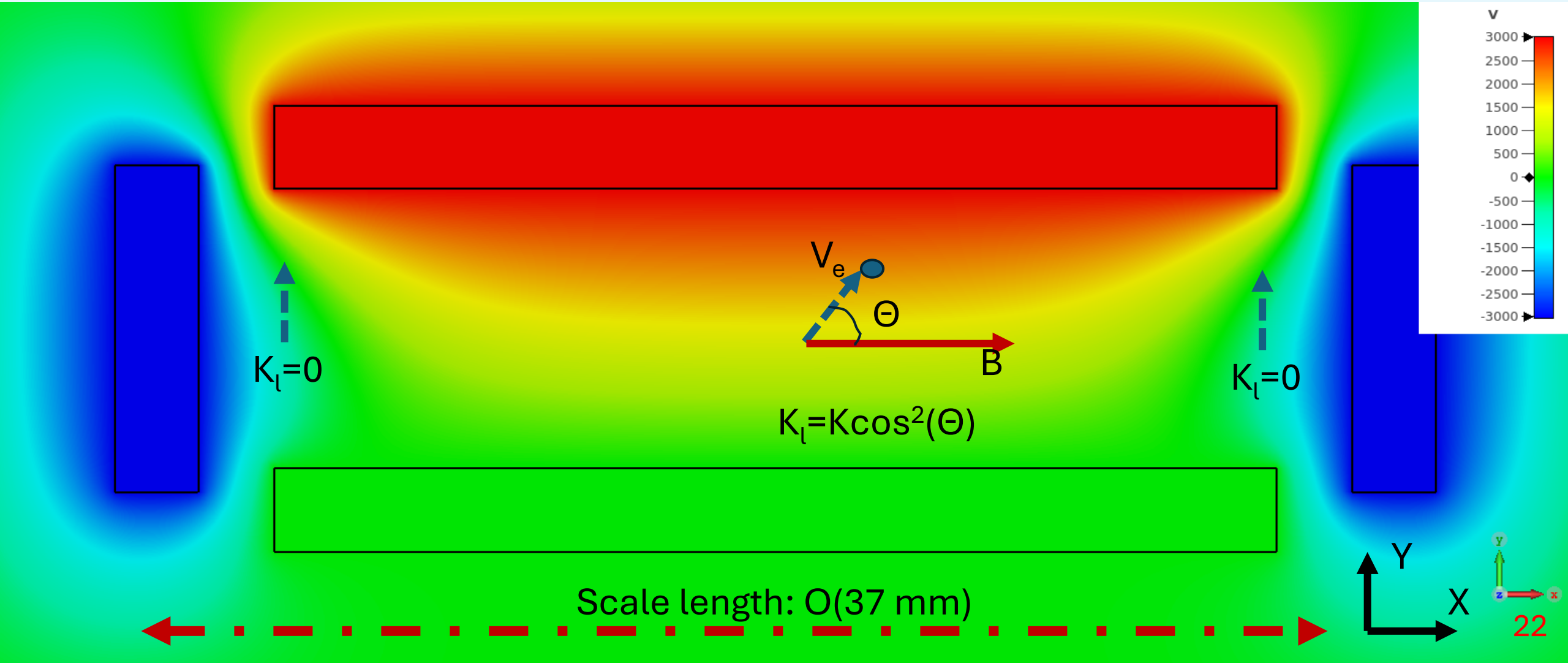
$$r_L \equiv \frac{v_\perp}{\omega_c} = \frac{mv_\perp}{|q|B}$$

Frequency of the motion

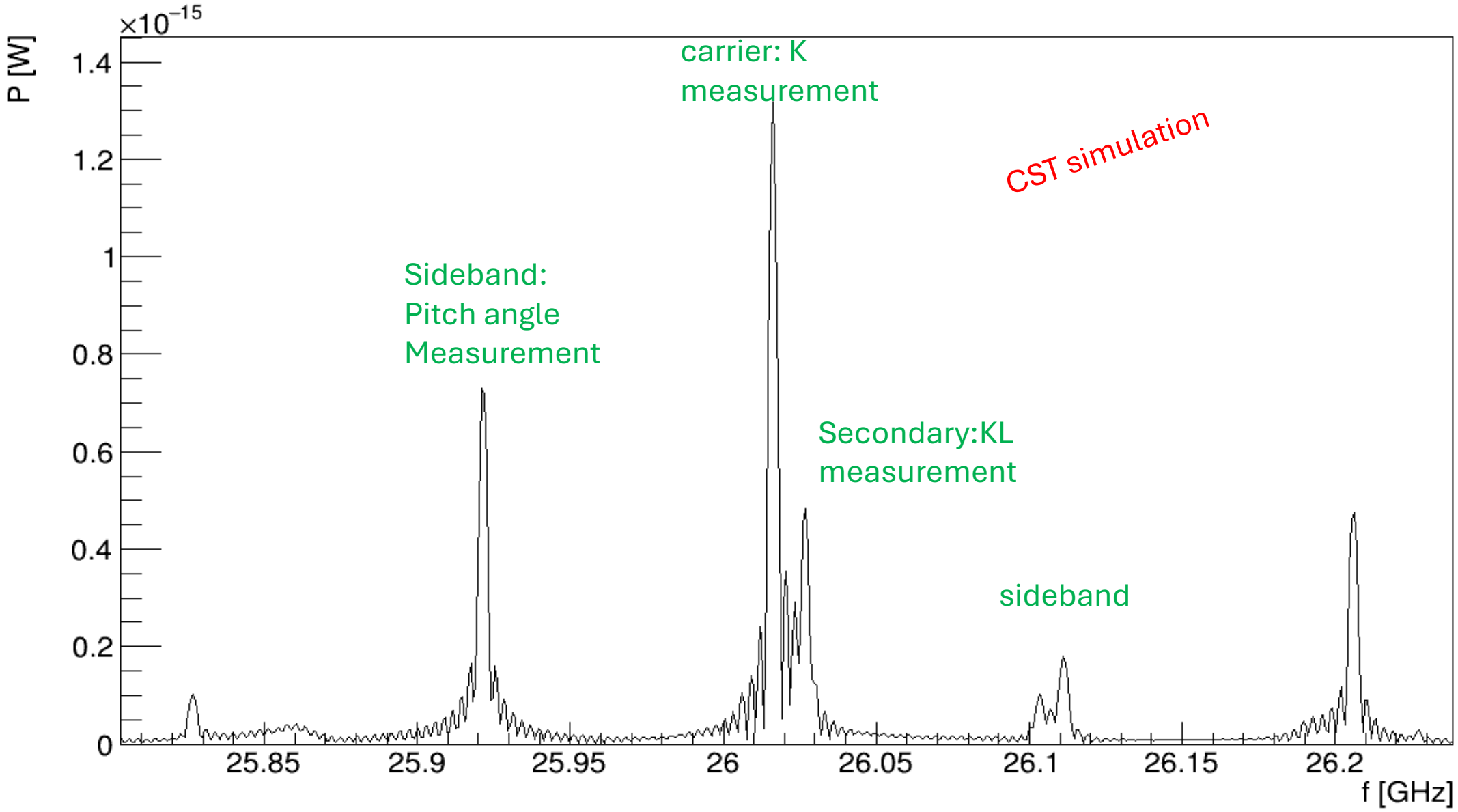
$$f_c = \frac{1}{2\pi}\frac{|q|B}{m}\frac{1}{K/m+1}$$

Electron Trap: electron motion

Cyclotron motion + X bouncing motion on potential well



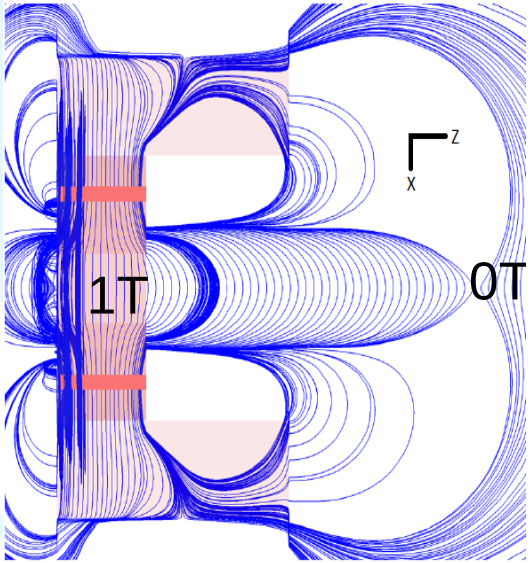
Electron Trap: How the expected signal looks like

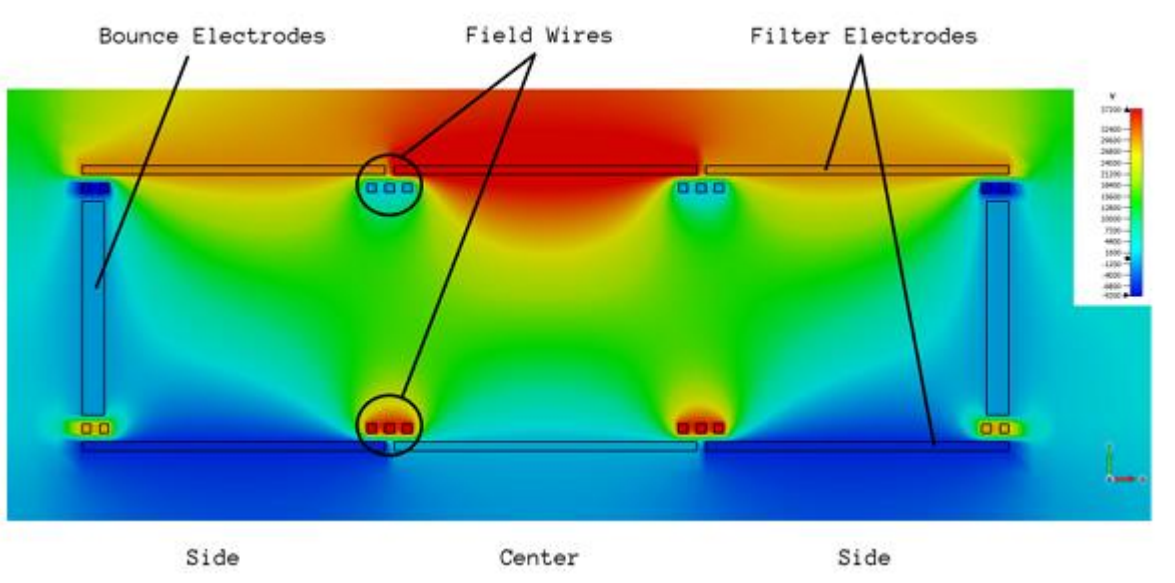


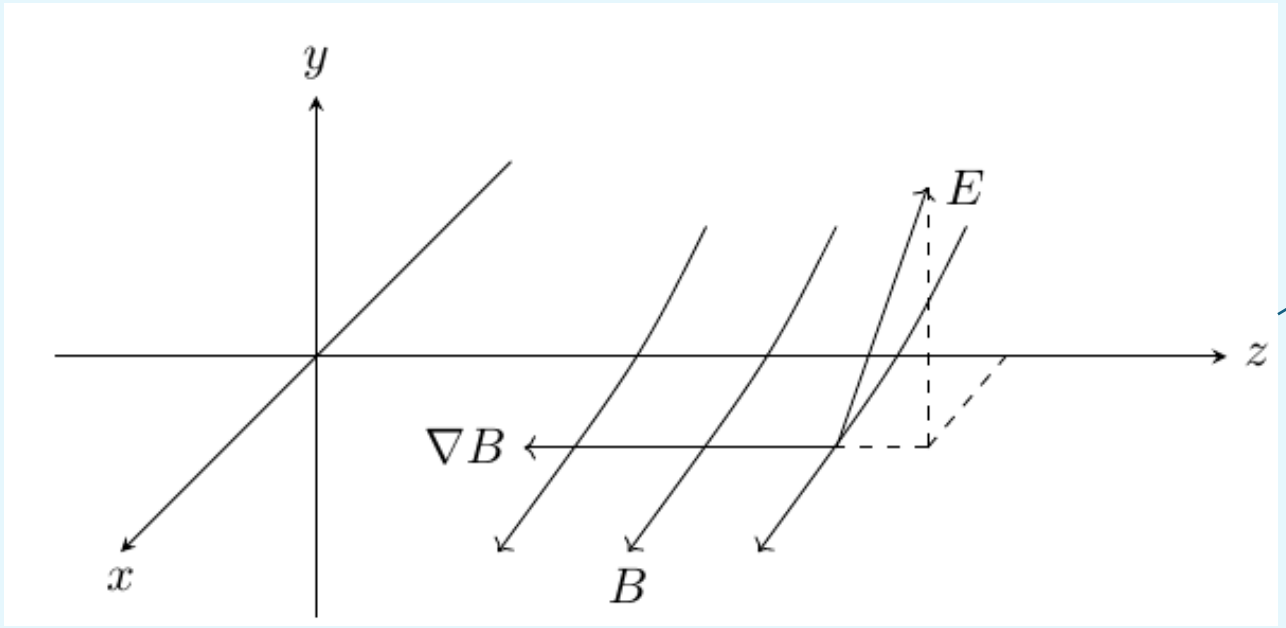
PTOLEMY filter

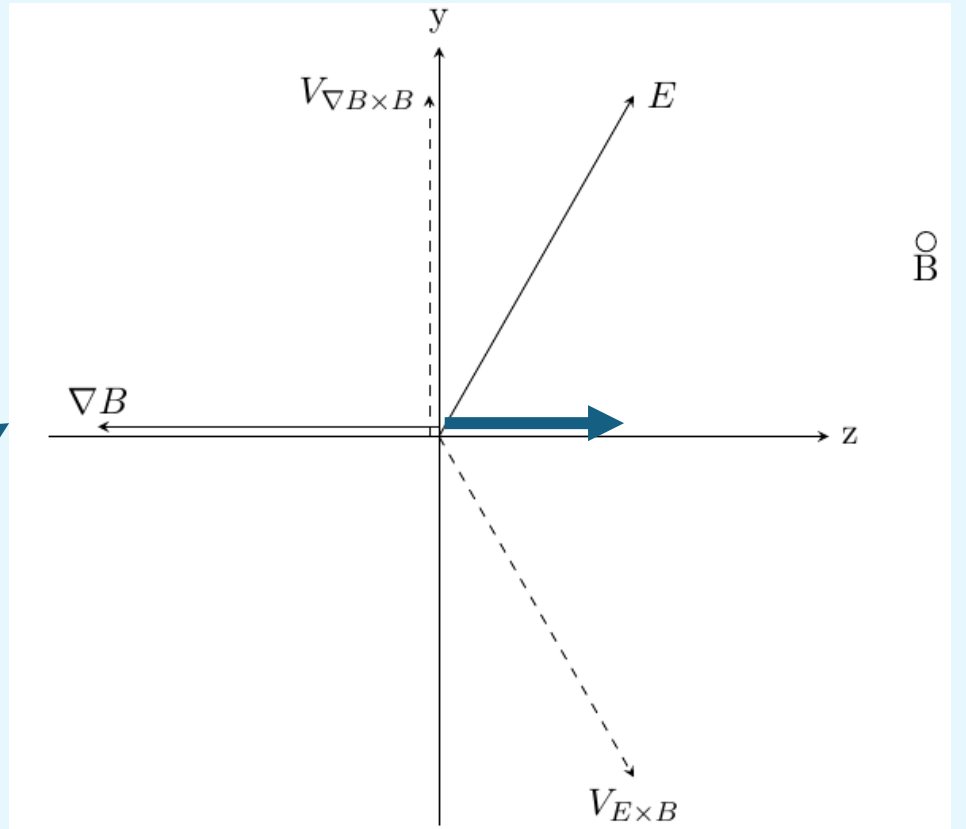
$$\vec{V}_{\nabla B} = +\frac{1}{2} V_{\perp} r_L \frac{\vec{\nabla} B \times \vec{B}}{B^2}$$

$$V_{\perp,E} = (\vec{E} \times \vec{B})/|\vec{B}|^2$$



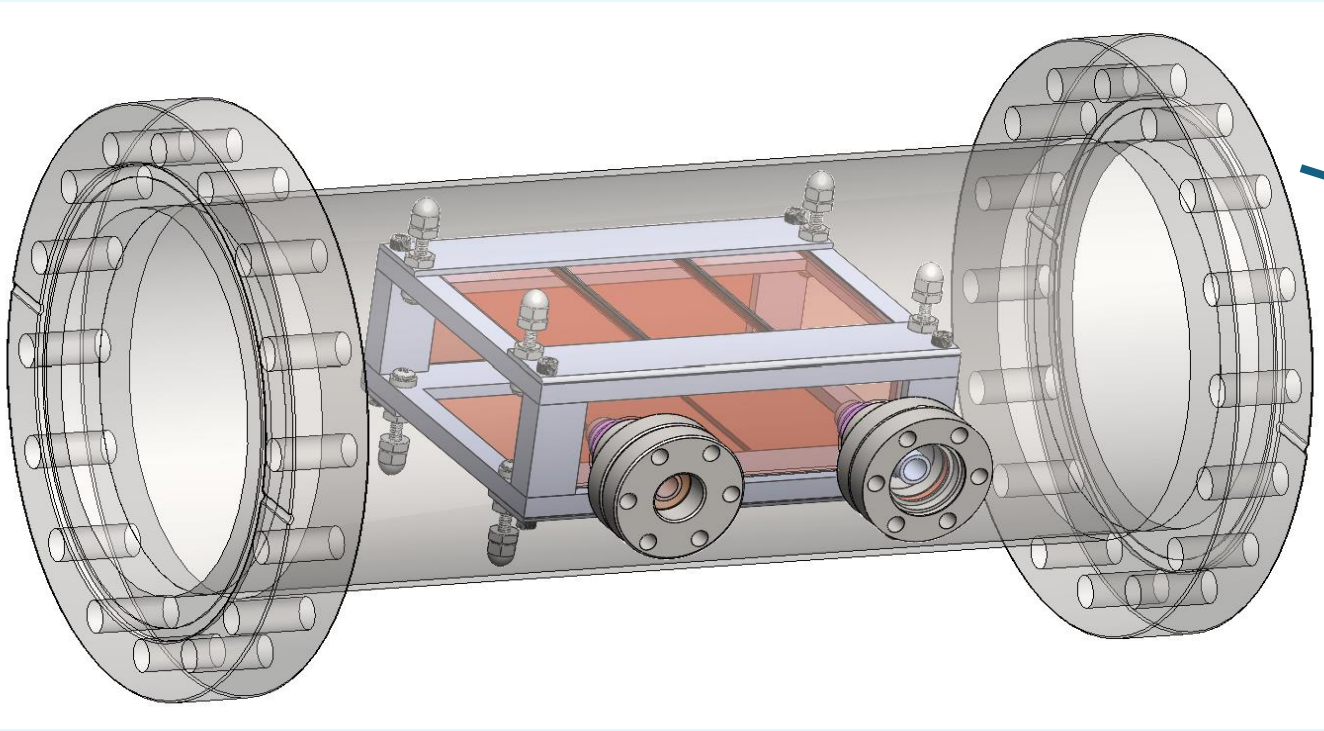






ExB demonstrator @ Princeton

- Test for PTOLEMY filter



Magnet prototype at Princeton