# The PTOLEMY project

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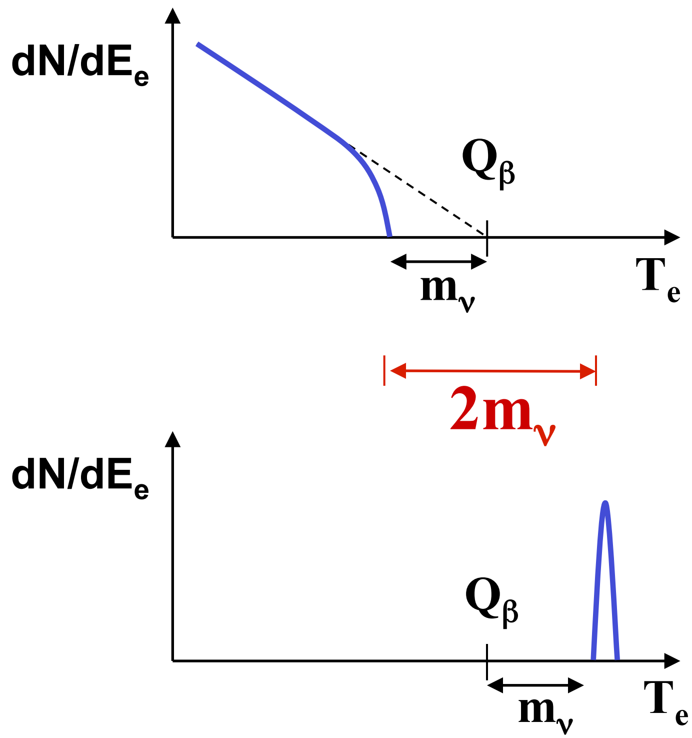
exploiting $m_\nu \neq 0$

# Neutrino capture on $\beta^\pm$ decaying nuclei

**Nuclear Beta decay**

**Neutrino Capture on a Beta Decaying Nucleus**




The events induced by Neutrino Capture have a unique signature: there is a gap of $2m_\nu$ (centered at $Q_\beta$) between “signal” and “background”

As s “side result”: measurement of the neutrino mass !

# C$\nu$B detection using Tritium

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

Signal to background ratio depends crucially on the energy resolution ($\Delta$) at the beta decay endpoint: detection is possible only if $\Delta < m_\nu$

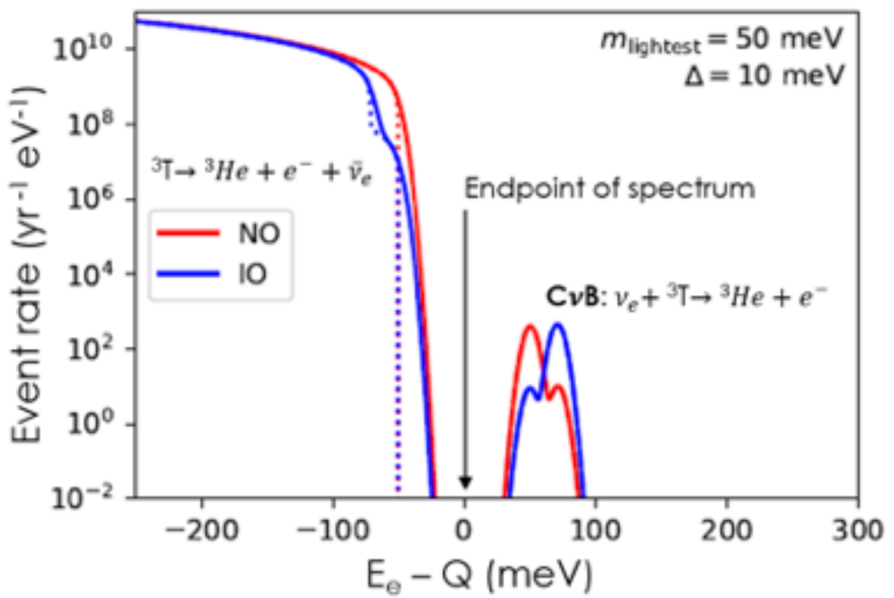
As an example, given a neutrino mass of 0.7 eV and an energy resolution at the beta decay endpoint of $\Delta$=0.2 eV a signal to background ratio of 3 is obtained.

In the case of 100 g mass target of Tritium we expect about 7 capture events per year

More details in: AGC, M.Messina and G.Mangano JCAP 06(2007)015

# Why tritium target ?

- High cross section ($\sim 10^{-44}$ cm$^2$)
- Sizeable lifetime ($T_{1/2}$ = 12 y)
- Low Q value (18.6 keV)
- Nuclear and atomic physics effects can be evaluated analytically




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

# PTOLEMY
arXiv:1307.4738v2

**P** rinceton
**T** ritium
**O** bservatory for
**L** ight,
**E** arly-universe,
**M** assive-neutrino
**Y** ield

Development of a Relic Neutrino Detection Experiment at PTOLEMY:
Princeton Tritium Observatory for Light, Early-Universe, Massive-Neutrino Yield

S. Betts[1], W. R. Blanchard[1], R. H. Carnevale[1], C. Chang[2], C. Chen[3], S. Chidzik[3], L. Ciebiera[1], P. Cloessner[4], A. Cocco[5], A. Cohen[1], J. Dong[1], R. Klemmer[3], M. Komor[3], C. Gentile[1], B. Harrop[3], A. Hopkins[1], N. Jarosik[3], G. Mangano[5], M. Messina[6], B. Osherson[3], Y. Raitses[1], W. Sands[3], M. Schaefer[1], J. Taylor[1], C. G. Tully[3], R. Woolley[1], and A. Zwicker[1]

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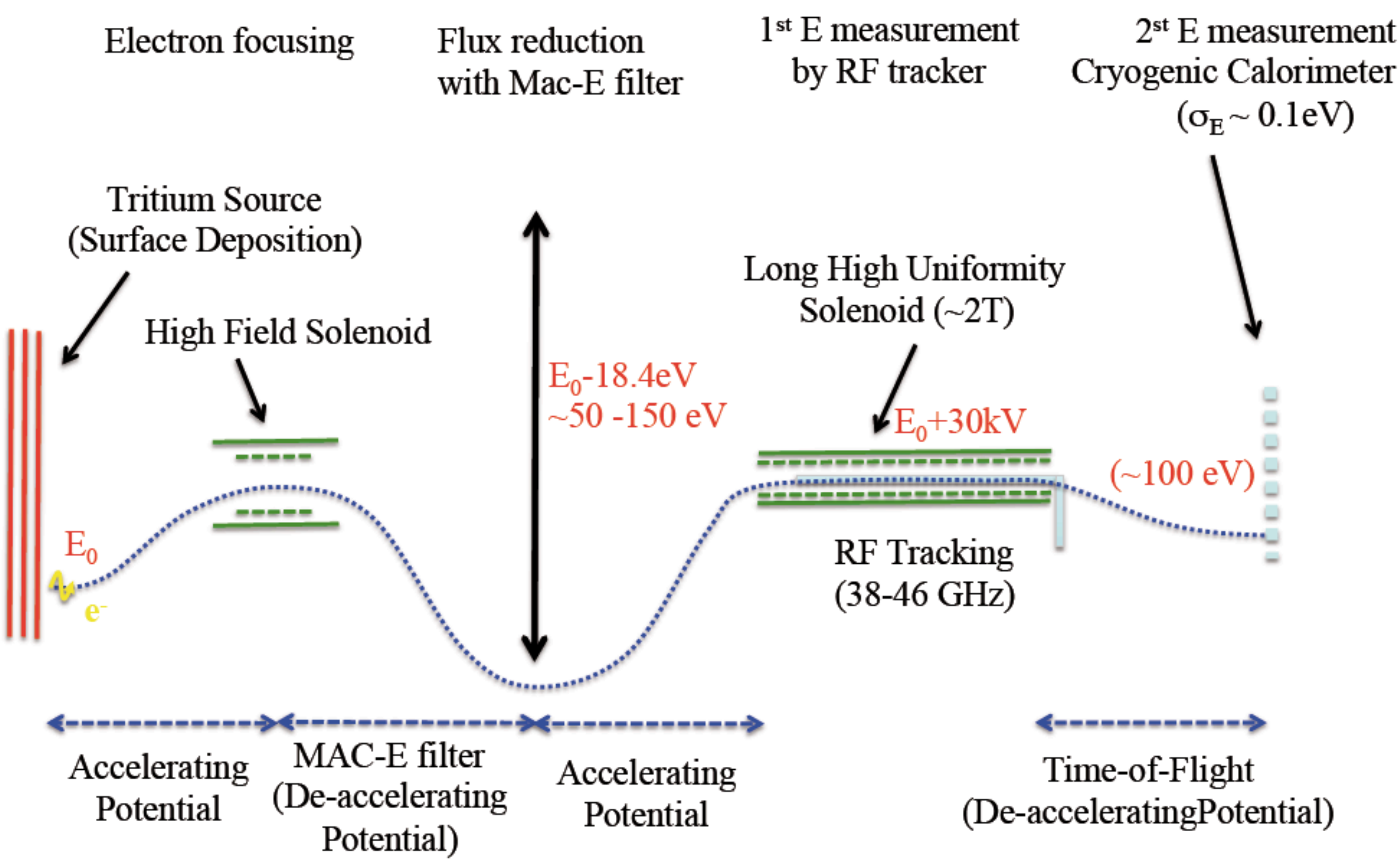
[6]Department of Physics, Columbia University



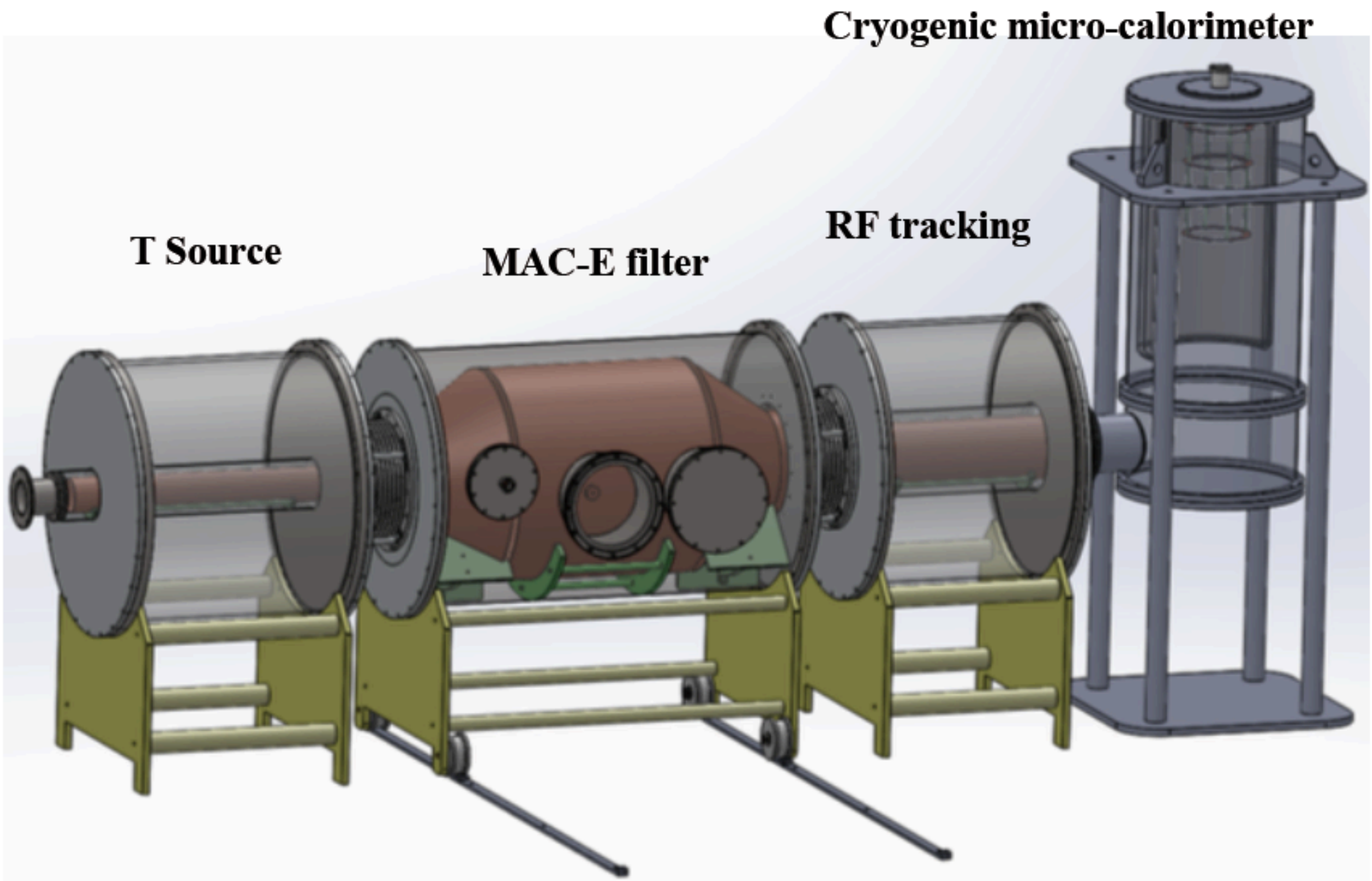
100 g T source + EM filter + RF tagging + sub-eV resolution μ-cal

# 100 g T source + MAC-E filter + RF tagging + sub-eV resolution μ-cal



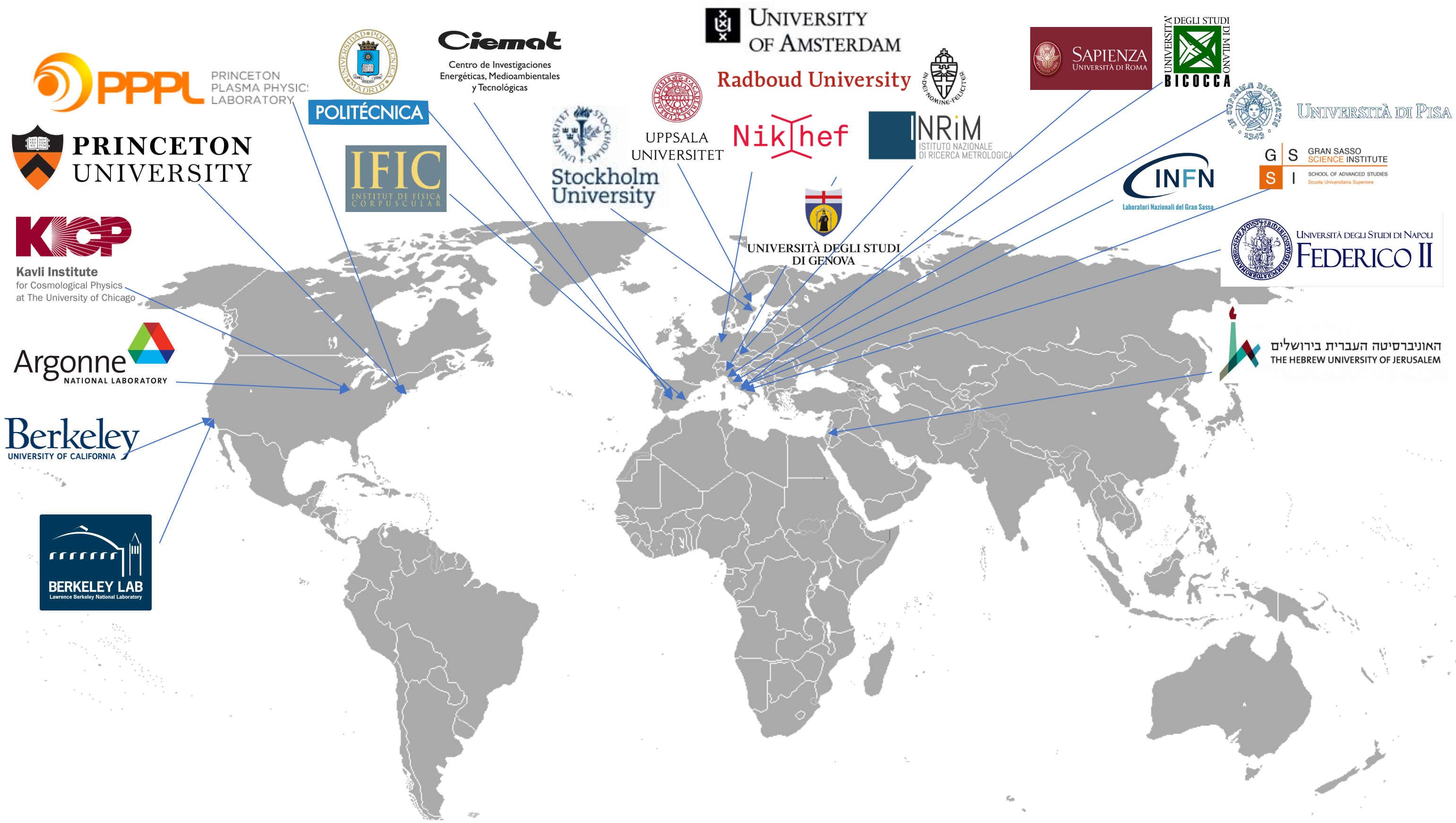
# PTOLEMY prototype






PTOLEMY R&D in 2016
R&D Prototype @ PPPL
CRYOFAB, INC
Supported by:
The Simons Foundation
The John Templeton Foundation

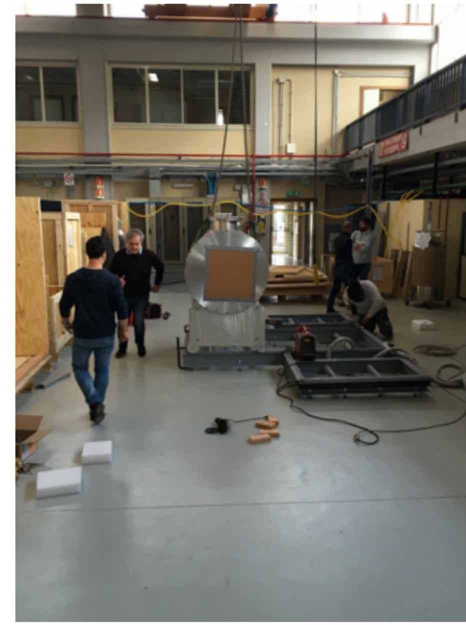
# The PTOLEMY Collaboration

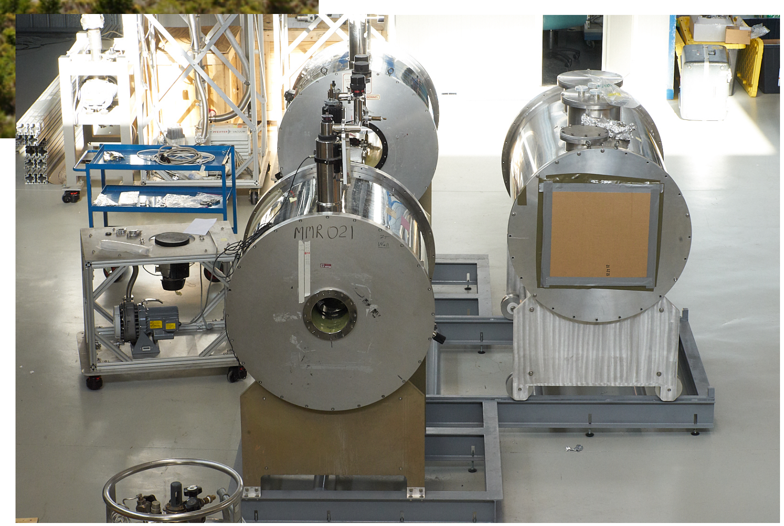



**M.G.Betti, M.Biasotti, A.Bosca, F.Calle, J.Carabe-Lopez, G.Cavoto, C.Chang, W.Chung, A.G.Cocco, A.P.Colijn, J.Conrad, N.D'Ambrosio, P.F.de Salas, M.Faverzani, A.Ferella, E.Ferri, P.Garcia-Abia, G.Garcia Gomez-Tejedor, S.Gariazzo, F.Gatti, C.Gentile, A.Giachero, J.Gudmundsson, Y.Hochberg, Y.Kahn, M.Lisanti, C.Mancini-Terracciano, G.Mangano, L.E.Marcucci, C.Mariani, J.Martinez, M.Messina, A.Molinero-Vela, E.Monticone, A.Nucciotti, F.Pandolfi, S.Pastor, J.Pedros, C.Perez de los Heros, O.Pisanti, A.Polosa, A.Puiu, Y.Raitses, M.Rajteri, N.Rossi, R.Santorelli, K.Schaeffner, C.F.Strid, C.G.Tully, F.Zhao, K.M.Zurek, A. Kievsky, M. Viviani, I. Rago, A. Ruocco**

# PTOLEMY @ LNGS in 2018

we are here





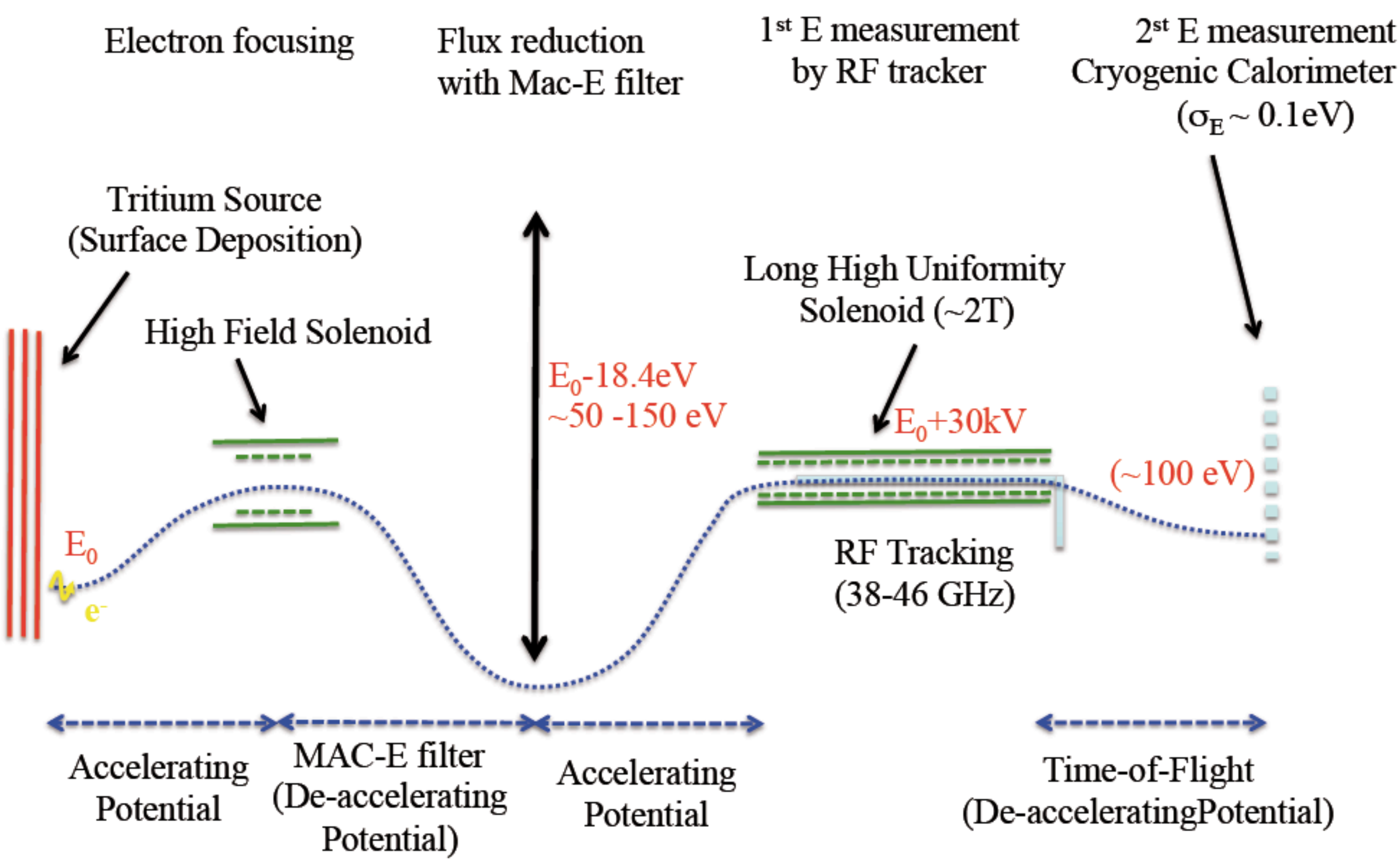
Underground area not needed
for the time being

# Recent papers

M.G. Betti et al.
"*A design for an electromagnetic filter for precision energy measurements at the tritium endpoint*"
Prog. Part. Nucl. Phys. 106 (2019) 120-131

M.G. Betti et al.
"*Neutrino Physics with the PTOLEMY project: active neutrino properties and the light sterile case*"
JCAP 07(2019)047

## 100 g T source + MAC-E filter + RF tagging + sub-eV resolution μ-cal



# Major technological challenges
## towards the full scale PTOLEMY detector

- Assemble a 100 g ($35 \times 10^6$ GBq) tritium target
- Reduce target induced $E_e$ smearing due to molecular effects
- Decimate the huge background event rate ($10^{14}$ Hz/g)
- Compress a 70m spectrometer length (KATRIN) down to meter scale
- Measure the electron energy with $\sigma_E$ better than O(0.05 eV)

## Challenge I

100 g of Tritium = 35 Million GBq = 1 Mega Curie

Procurement (probably) easy

World inventory of tritium hundreds of kilograms

Handling requires special permissions and dedicated infrastructures

## Challenge II

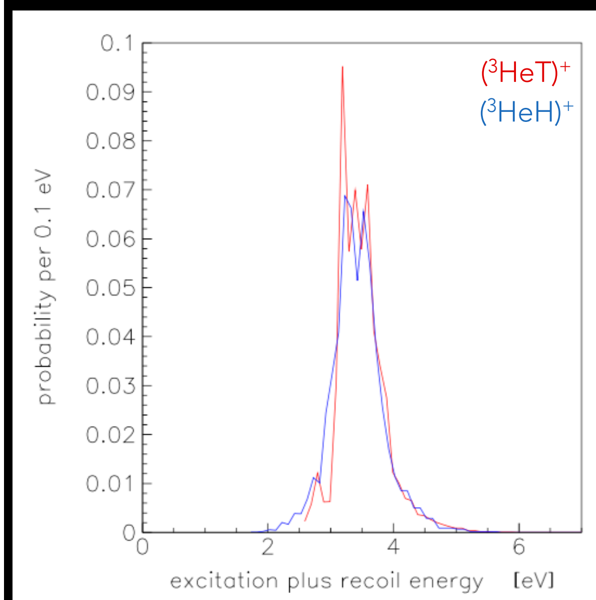
Tritium must undergo a <u>clean</u> decay/capture process

(molecular binding, final states density)

# Tritium target

Characteristics:

- High density and packing factor
- Weakly bound to substrate
- Low interaction probability
- Electron focusing to the EM filter




Advances in High Energy Physics 2013 (2013) 39

Molecular excitations in daughter molecule

- blur tritium endpoint

→ fundamental limit to measurement of $\nu$-mass

Need atomic tritium for ultimate experiment!

# Tritiated graphene

Single atomic layer weakly bound in sp-3 configuration (2D structure)

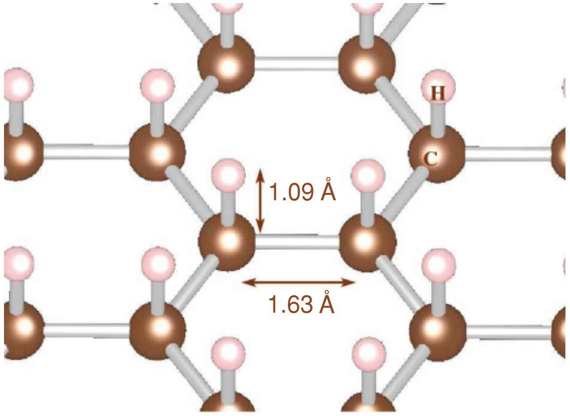
Single-sided (loaded on substrate) and planar (uniform bond length)

Binding Energy < 3 eV (exact value to be measured)

Source strength with surface densities of ~2 Ci/m$^2$ (200 μg/m$^2$)

Semiconductor (Voltage Reference)

Polarized tritium (directionality?)



## Challenge III

Transport each single electron ($10^{16}$ Hz) to the EM filter unperturbed

$\Delta E < 0.05$ eV

## Challenge IV

Select and measure only electrons at the beta decay endpoint

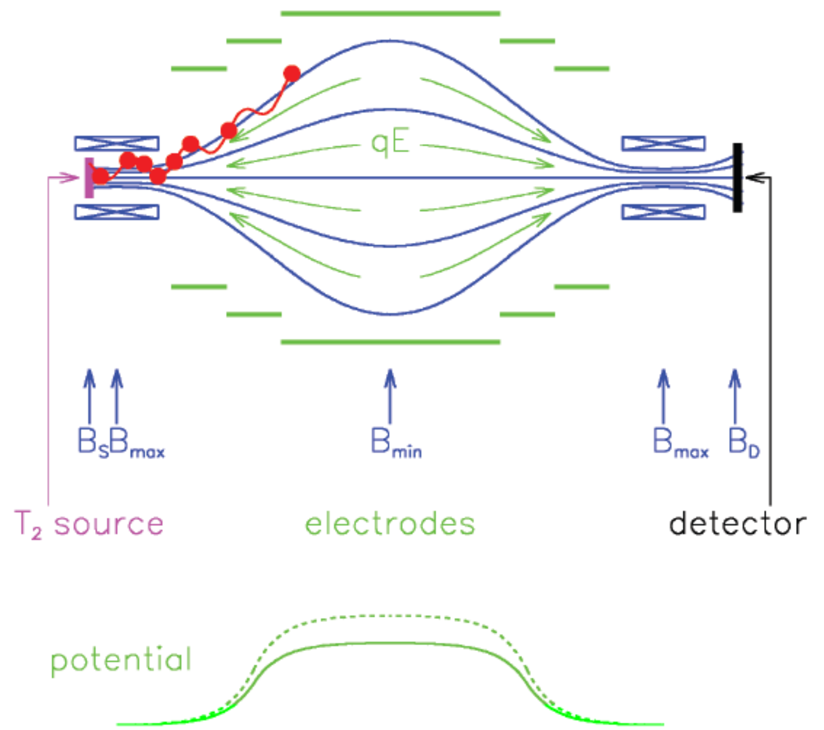
(reject $10^{16}$ events per second)

# KATRIN
# Karlsruhe Tritium Neutrino Experiment

Aim at direct neutrino mass measurement through the study of the $^3$H endpoint ($Q_\beta$ =18.59 keV, $t_{1/2}$=12.32 years)

Phase I

- Energy resolution: 0.93 eV
- Tritium mass: ~ 0.1 mg
- Noise level 10 mHz
- Sensitivity to $\nu_e$ mass: 0.2 eV



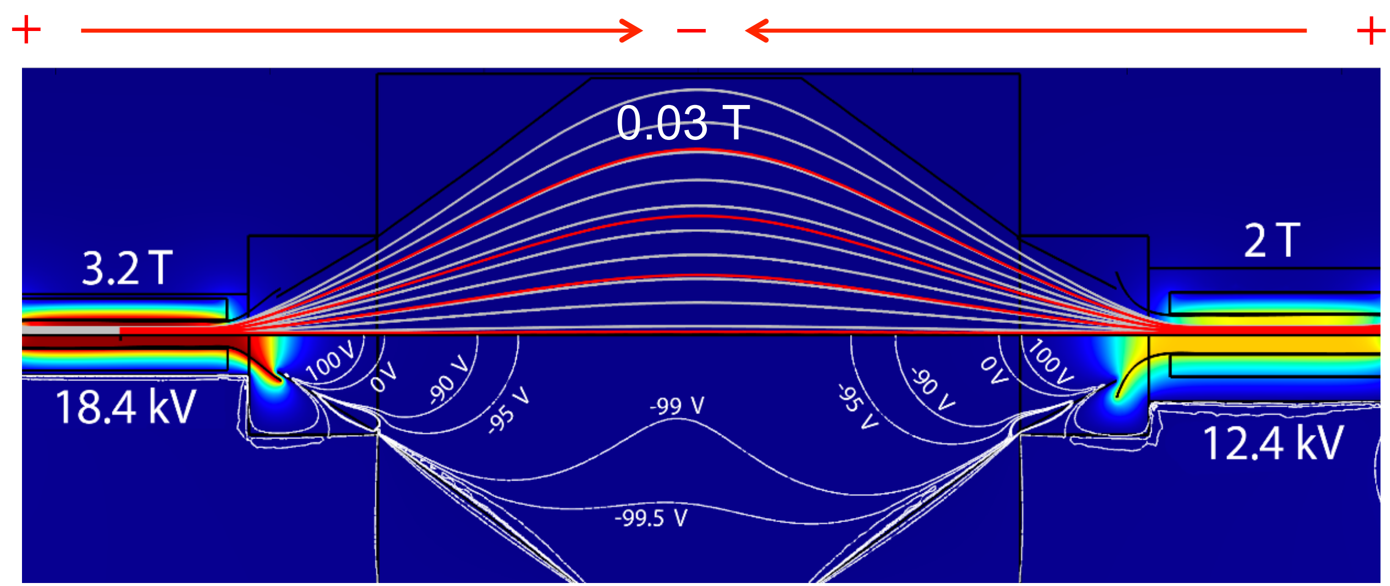

Magnetic Adiabatic Collimator + Electrostatic filter

# MAC-E filter

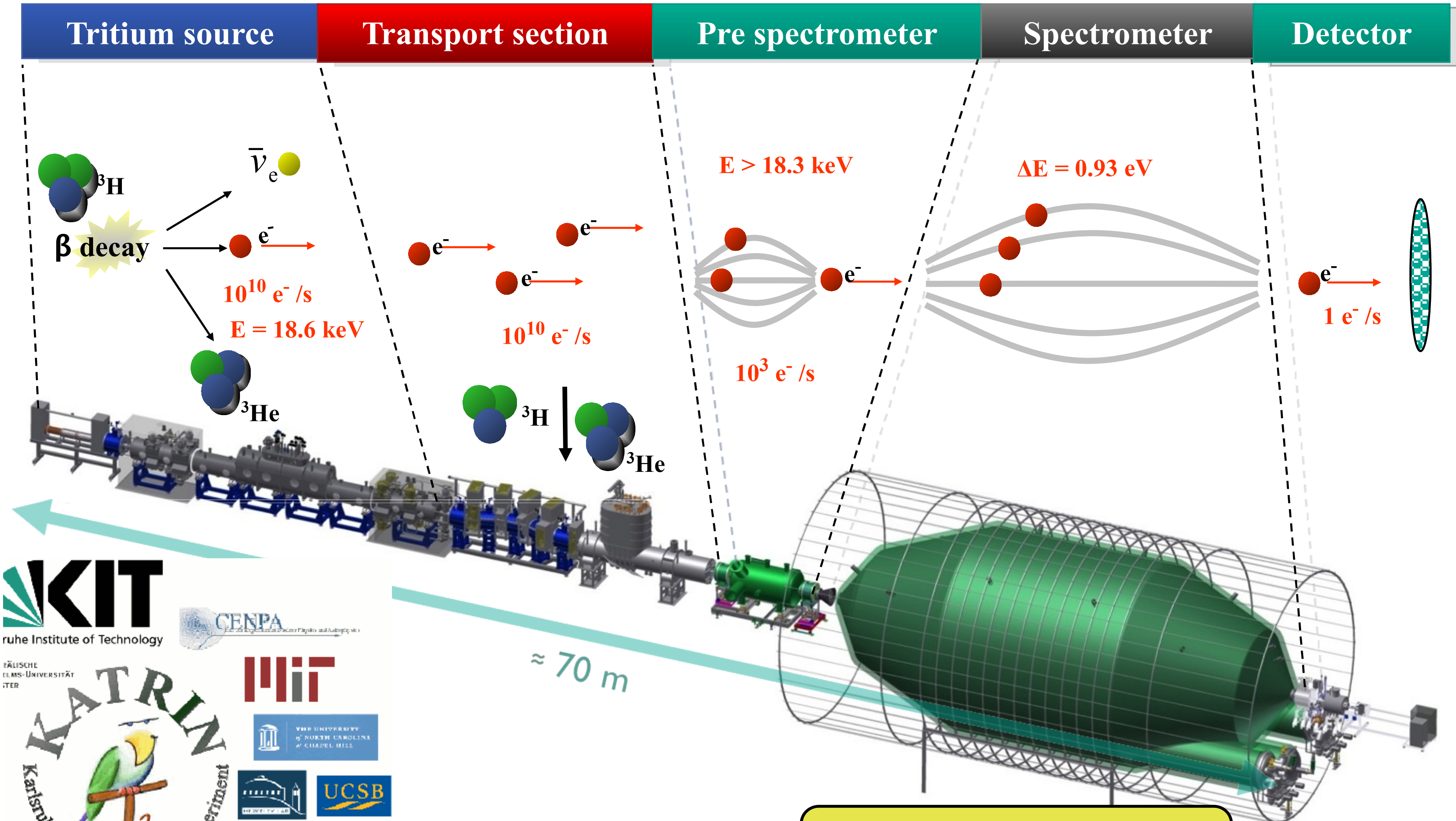
Low magnetic gradient adiabatically transforms cyclotron trajectories into longitudinal motion

$$\mu = \frac{E_\perp}{B} \qquad \frac{\Delta E}{E} = \frac{B_{min}}{B_{max}}$$

Electric field sets the energy cutoff




If the threshold is set at ~1eV the event rate reduction is ~ $(\Delta E/Q)^3 = 1.55\ 10^{-13}$
(for comparison, the activity of 1 g of T is of $3.6\ 10^{+14}$ Hz)




new

**Sensitivity on $m(\nu_e)$:**

**2 eV → 200 meV**

70m length for a target of $10^{11}$ Bq (about 300 μg !!!)

# KATRIN
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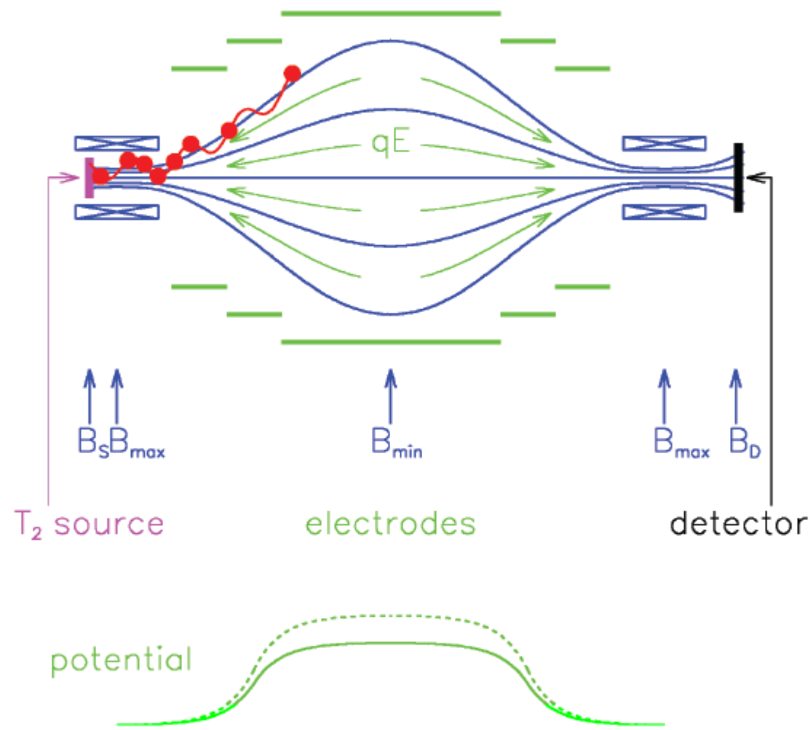



Magnetic Adiabatic Collimator + Electrostatic filter

~~**Challenge IV**~~

~~Select and measure only electrons at the beta decay endpoint~~

~~(reject $10^{16}$ events per second)~~

**Challenge IV**

Select only electrons at the beta decay endpoint

(reject $10^{16}$ events per second)

**Challenge V**

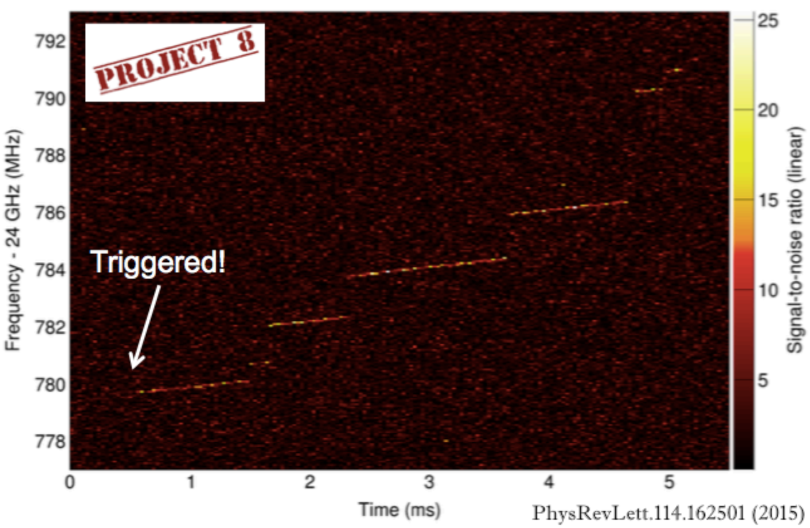
Measure electrons with very good resolution

$\sigma(E) < 0.05$ eV

# RF triggering and EM filter "tune"

Thread electron trajectories through an array of RF antennas with wide bandwidth (few x$10^{-5}$) in order to identify cyclotron RF signal (~26 GHz @ 1T) with few eV resolution (transit times of order 0.2 msec)

In case of candidate event set the EM filter voltages accordingly (see next slides)




First detection of single electron cyclotron radiation
Phys.Rev.Lett. 114(2015)162501

$$2\pi f_c = \frac{qB}{m_e c^2} \cdot \frac{1}{\gamma} \rightarrow E_e$$

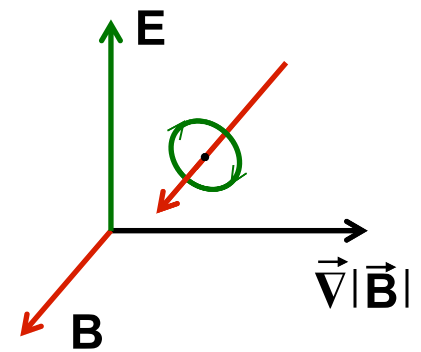
$$P_{tot} = \frac{1}{4\pi\epsilon_0} \frac{8\pi^2 q^2 f_c^2}{3c} \frac{\beta_\perp^2}{1-\beta^2} \rightarrow k_T$$

# New concept EM filter

Magnetic drifts: $$\mathbf{V}_D = \mathbf{V}_\perp = \left( \underbrace{qE}_{\vec{E} \times \vec{B} \text{ drift}} + F - \underbrace{\mu \nabla B}_{\nabla B \text{ drift}} - m\frac{d\mathbf{V}}{dt} \right) \times \frac{\mathbf{B}}{qB^2}$$

First adiabatic invariant: $$\mu = \frac{m v_\perp^{*2}}{2B}$$

Static fields configuration




M.G. Betti et al., Prog. Part. Nucl. Phys. 106 (2019) 120-131

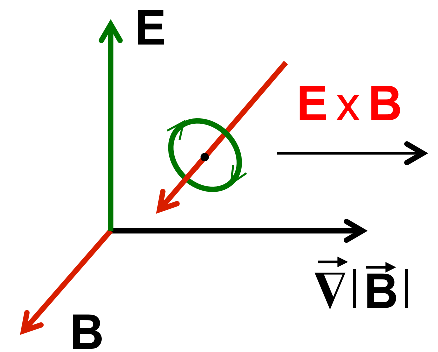
# New concept EM filter

Magnetic drifts: $$\mathbf{V}_D = \mathbf{V}_\perp = \left( qE + F - \mu \nabla B - m\frac{d\mathbf{V}}{dt} \right) \times \frac{\mathbf{B}}{qB^2}$$

**$\vec{E} \times \vec{B}$ drift** **$\nabla B$ drift**

First adiabatic invariant: $$\mu = \frac{m v_\perp^{*2}}{2B}$$

Static fields configuration




M.G. Betti et al., Prog. Part. Nucl. Phys. 106 (2019) 120-131

# New concept EM filter

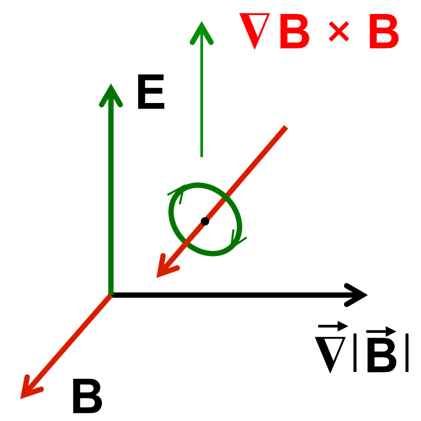
Magnetic drifts: $\mathbf{V}_D = \mathbf{V}_\perp = \left( qE + F - \mu \nabla B - m\frac{d\mathbf{V}}{dt} \right) \times \frac{\mathbf{B}}{qB^2}$

$\downarrow$ **$\vec{\mathbf{E}} \times \vec{\mathbf{B}}$ drift**

$\downarrow$ **$\nabla \mathbf{B}$ drift**

First adiabatic invariant: $\mu = \frac{m v_\perp^{*2}}{2B}$

Static fields configuration




M.G. Betti et al., Prog. Part. Nucl. Phys. 106 (2019) 120-131

# New concept EM filter

$$E_x = 0 \ ,$$

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

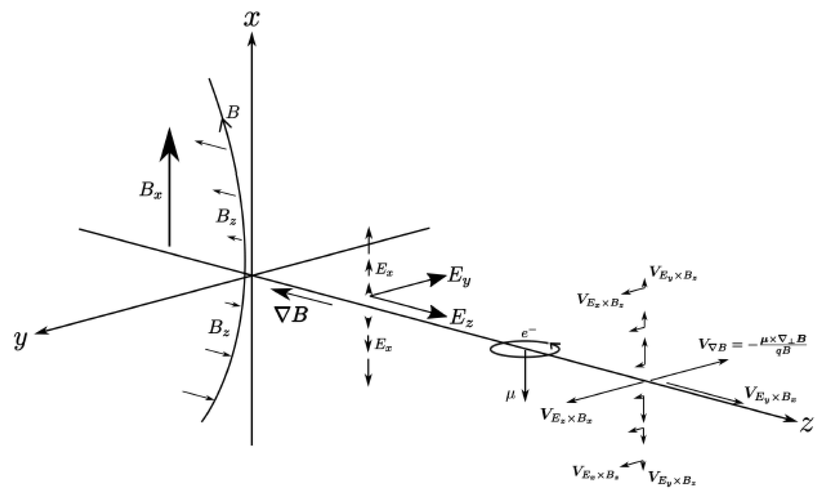
$$E_z = -E_0 \sin\left(\frac{y}{\lambda}\right) e^{-z/\lambda} \ ,$$

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

$$B_y = 0 \ ,$$

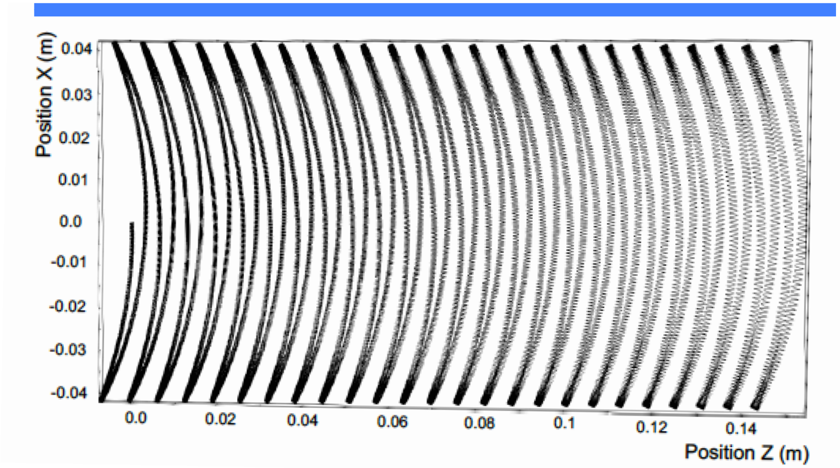
$$B_z = -B_0 \sin\left(\frac{x}{\lambda}\right) e^{-z/\lambda}$$

$$E_0 = -\frac{\mu B_0}{q\lambda \sin\left(y_0/\lambda\right)}$$

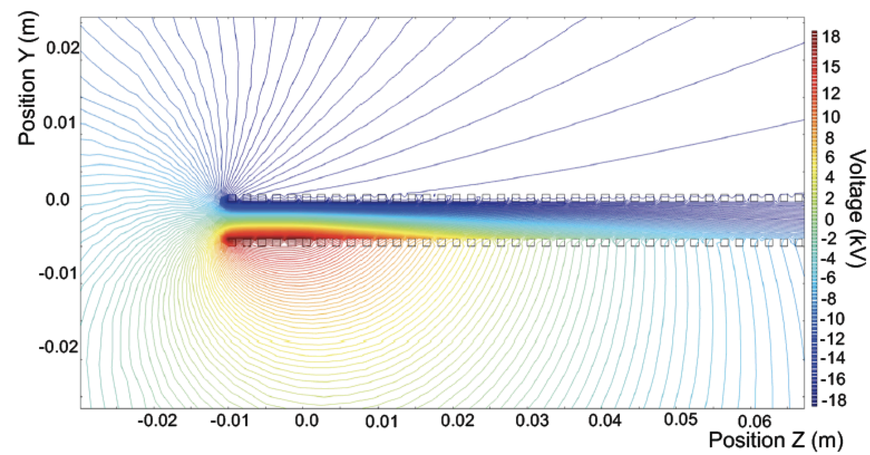



Top view

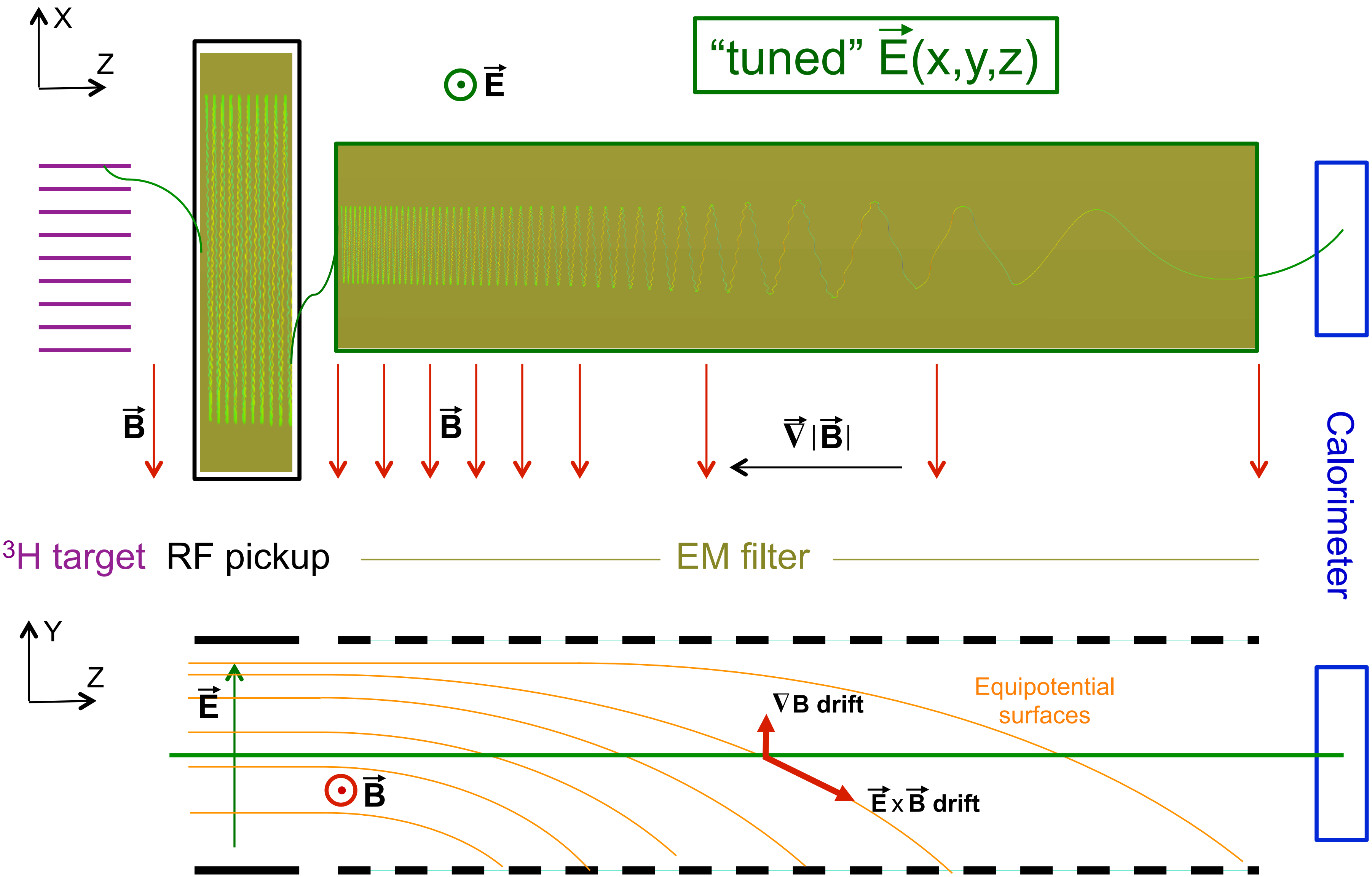
negative potential walls




Side view



# New concept EM filter
# Dynamic tuning



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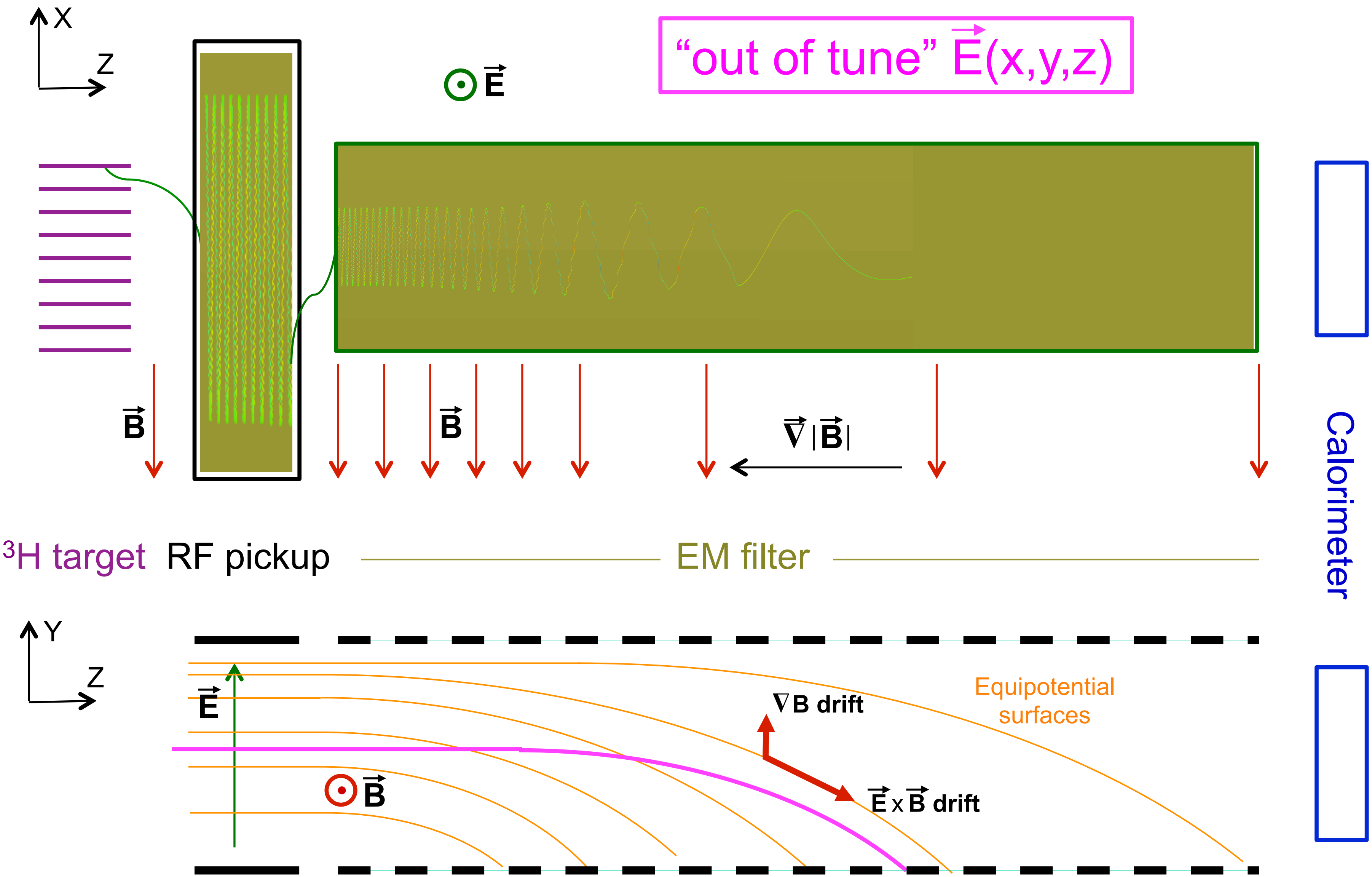
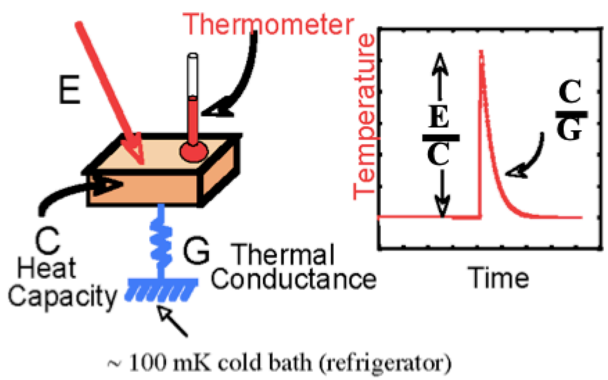


# Electron calorimeter with an energy resolution good enough to resolve the neutrino mass

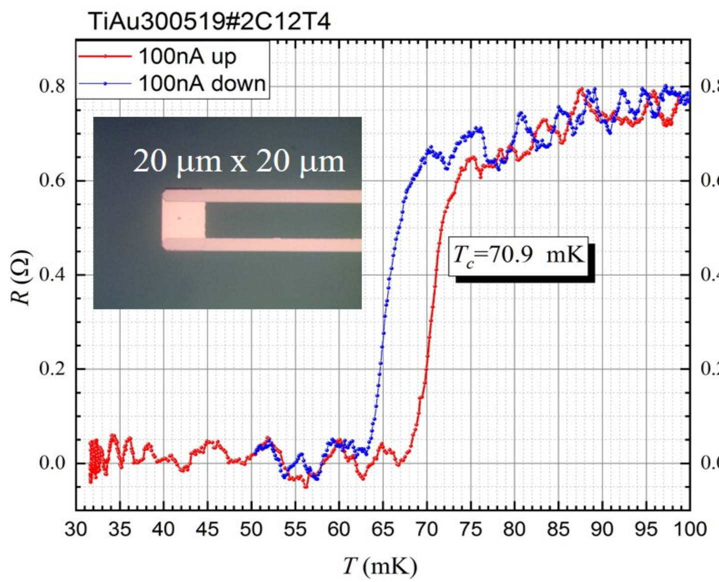
## Cryogenic Transition Edge Sensors (TES)




10÷100eV electron can be stopped with very small C ($10^4$ smaller than for X-ray)

$$\Delta E \propto T_c^{3/2} t^{1/2}$$

ΔE=0.11 eV for 0.8 eV IR photon already achieved @ 106 mK (10x10 μm$^2$) at INRiM




Large area, low $T_C$, 38 nm thickness ($t$) TiAu TES produced, tests ongoing

# Major technological challenges
## towards the full scale PTOLEMY detector

- Assemble a 100 g ($35 \times 10^{15}$ Bq) tritium target
  - Modular design highly packed source and E x B drift
- Reduce target induced $E_e$ smearing due to molecular effects
  - New source: Tritiated-Graphene or Cryogenic Au(111)
- Decimate the huge background event rate ($10^{14}$ Hz/g)
  - RF detection can provide $10^{10}$ reduction factor
- Compress a 70m spectrometer length (KATRIN) down to meter scale
  - New concept EM filter
- Measure the electron energy with $\sigma_E$ better than O(0.05 eV)
  - TES array with SQUID multiplexing read-out

A lot of R&D is still needed but
building blocks are there...

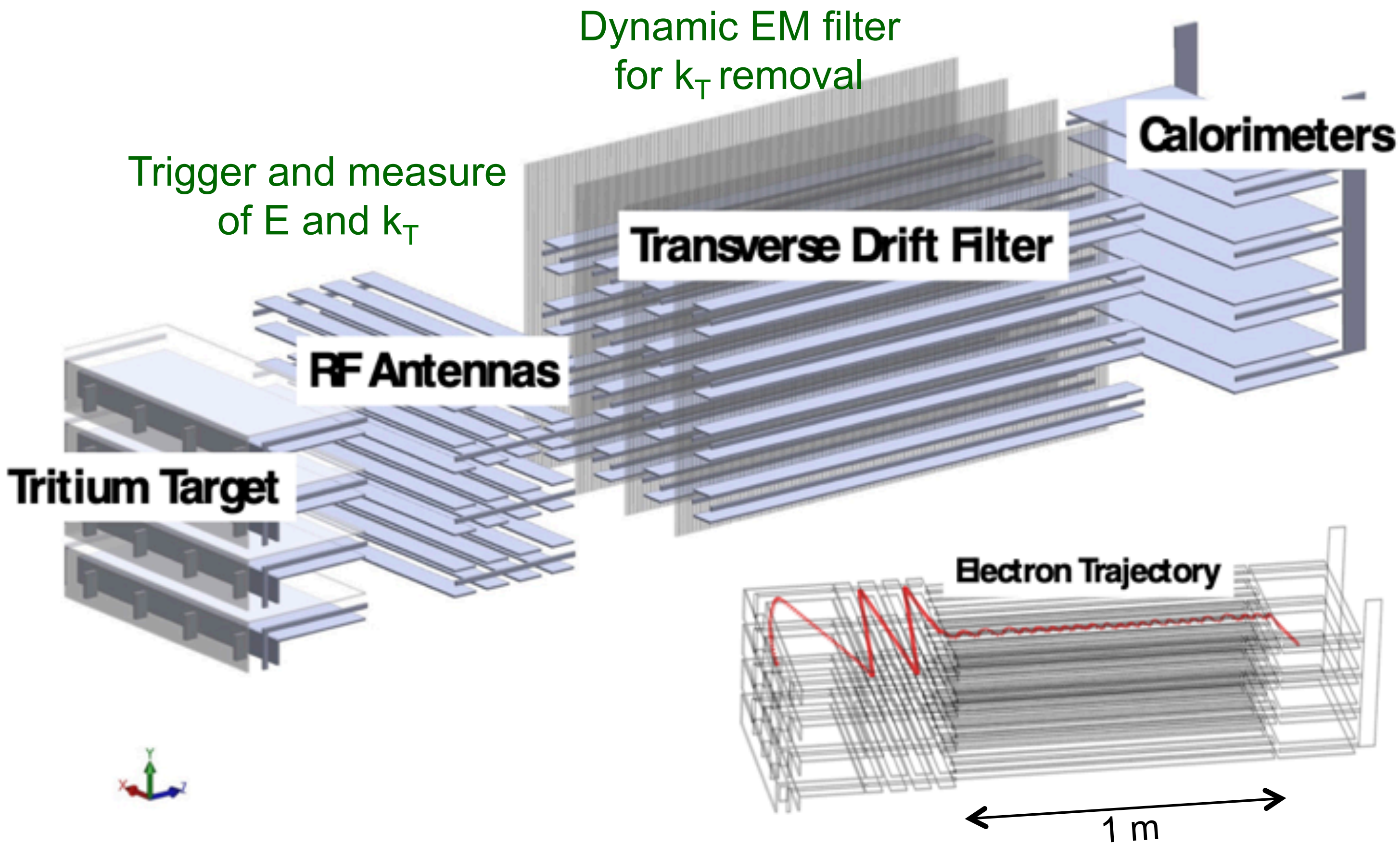
…and…

A lot of R&D is still needed but building blocks are there...

…see next talk !

Thank you

# PTOLEMY prototype layout



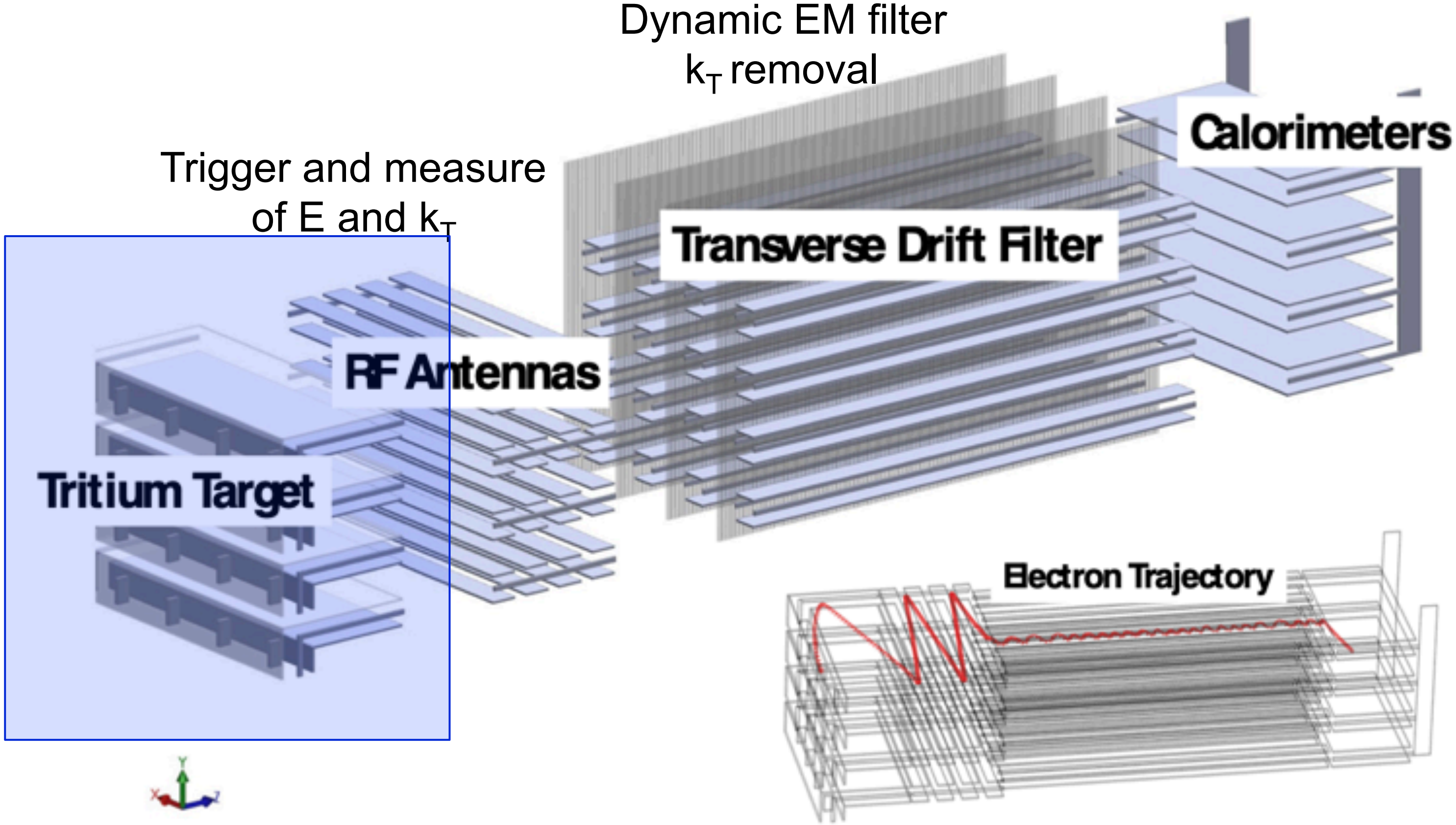

Static electric and magnetic fields are used

$$\boxed{E_{tot} = q(V_{cal} - V_{source}) + E_{cal}}$$

# PTOLEMY prototype layout

Dynamic EM filter
$k_T$ removal

Trigger and measure
of E and $k_T$



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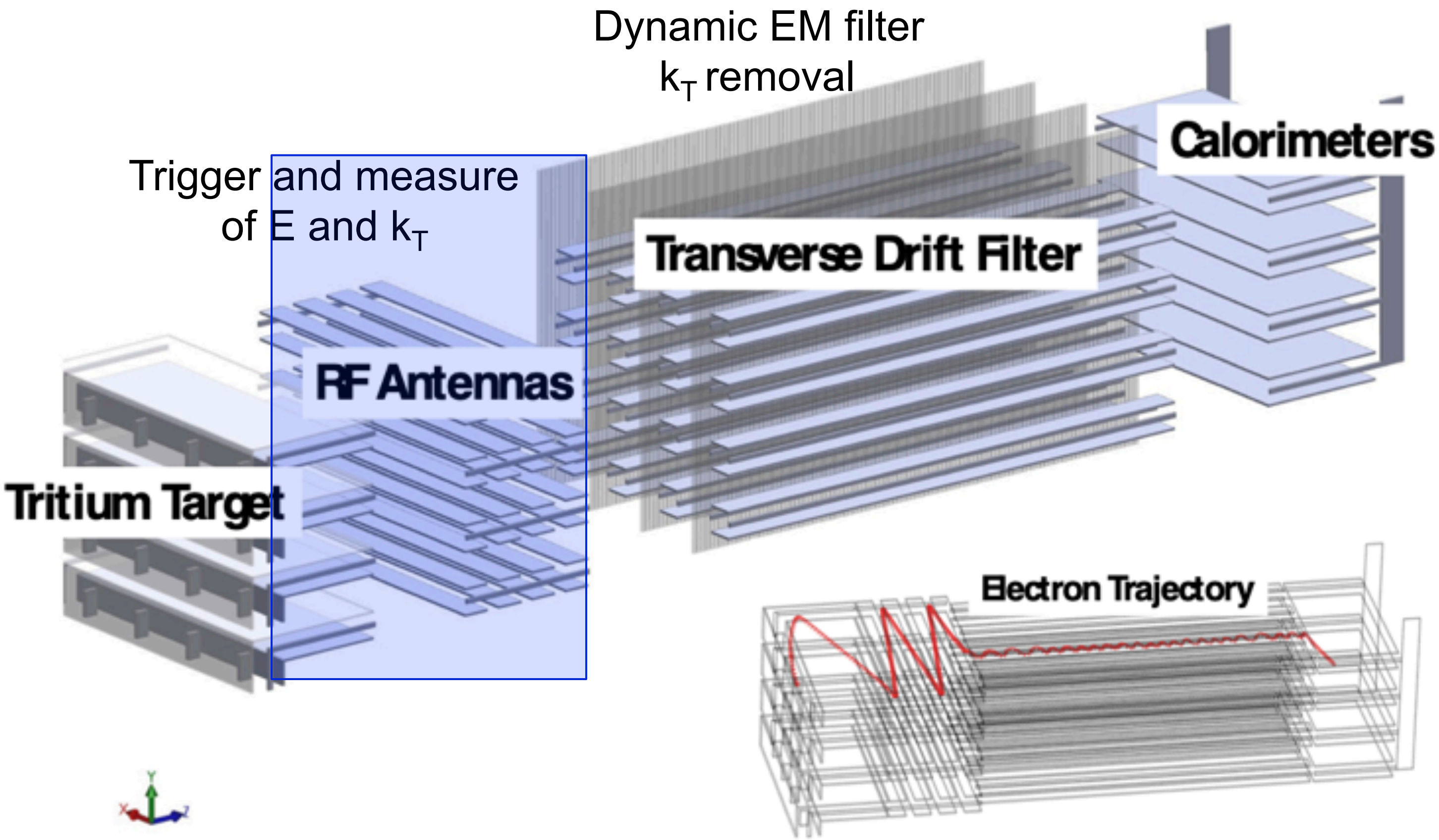

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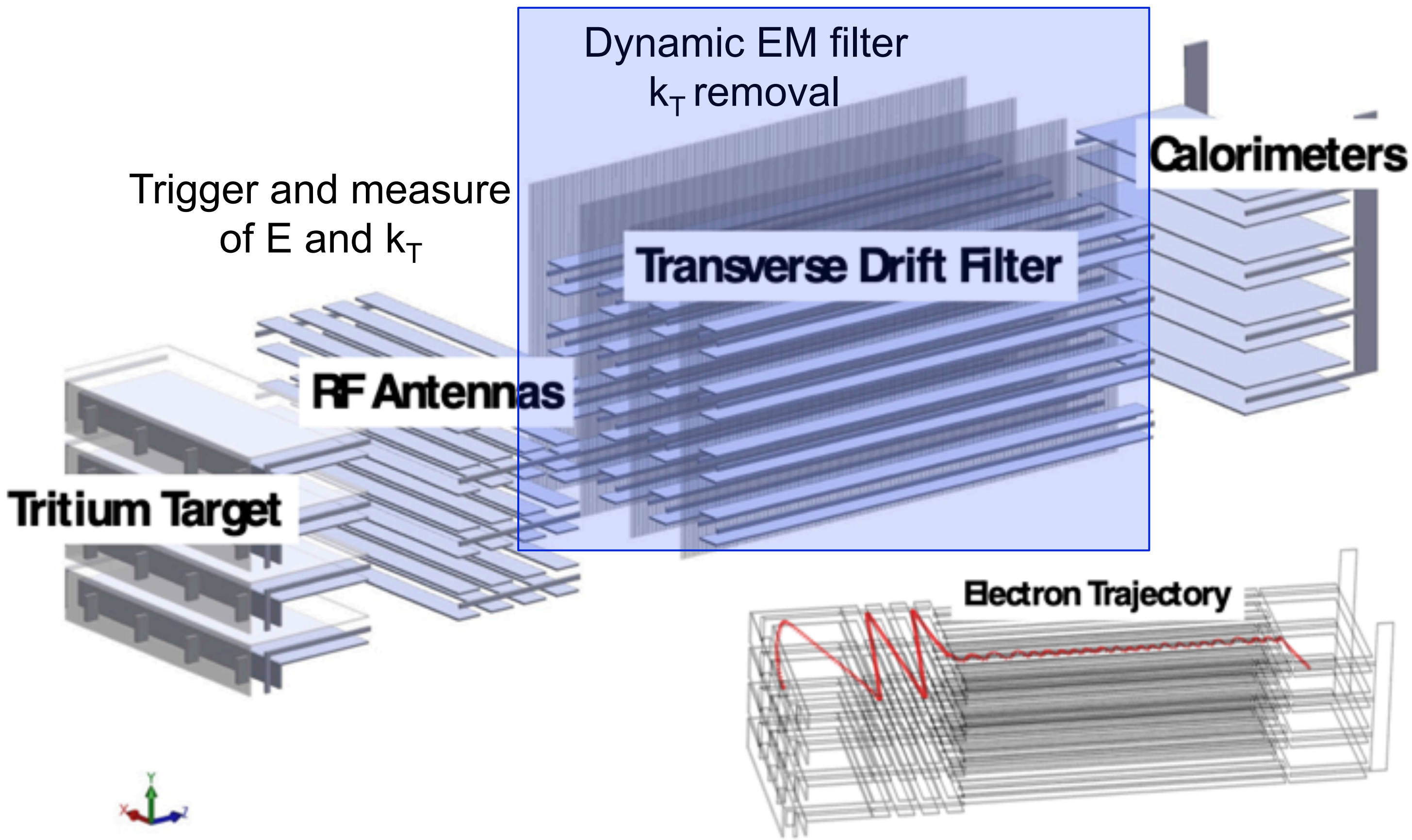

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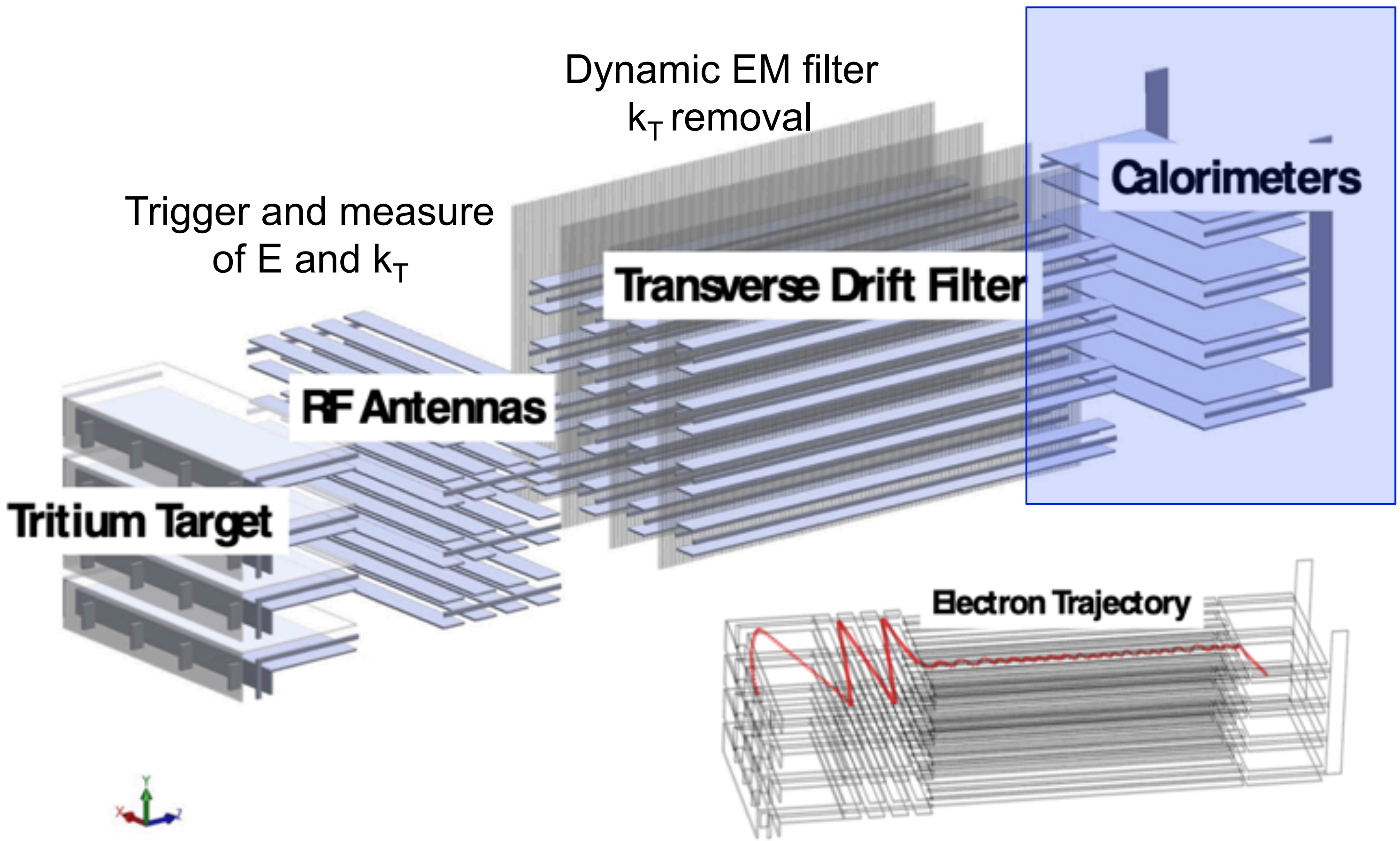


# PTOLEMY programme

A lot of R&D to be done but…

...what was “impossible” a few years ago is now merely “challenging”

The PTOLEMY Collaboration is actively working at LNGS and in local laboratories in order to produce a TDR for the detector prototype in three years from now

Many (interesting) activities are ongoing but many (smart) ideas are still needed !

# Relic Antineutrino Detection

## using EC decaying nuclei (a)

$\bar{\nu}_e + e^- + (A,Z) \rightarrow (A,Z\text{-}1) + X$

The lack of a suitable final state prevents the use of this reaction to detect C$\nu$B unless either:

1) there exist an excited level (either atomic or nuclear) with energy
$$E_o = Q_{EC} - E_K + m_\nu$$

2) the captured electron is "off-mass" shell $m_{eff} = m_e - E_o$

3) it exist a nucleus A (stable) for which $Q_{EC} = E_K - m_\nu$

# Relic Antineutrino Detection

## using EC decaying nuclei (b)

$\bar{\nu}_e$ + (A,Z) → (A,Z-1) + $e^+$

The energy threshold prevents the use of this reaction to detect C$\nu$B unless:

1) use C$\nu$B as a target for accelerated fully ionized beam

- EC decay is inhibited (no electrons to be captured)
- Ions should have $\gamma_{\min} = \dfrac{E_{\rm thr}}{m_\nu}$
- Interaction rate is given by $\lambda_{\rm NCB} = \dfrac{n_{\bar{\nu}}\, 2\pi^2 \ln 2}{\mathcal{A} \cdot t_{1/2}^{\rm EC}}\ \mathcal{N}$

For allowed transitions and using $n_\nu$= 56, $E_{thr}$=10 eV :

$$\mathcal{N} = 10^{13}$$
$$\gamma = 100$$

$$\lambda_{\rm NCB} \simeq 10^{-18}\ {\rm s}^{-1}$$

**Too slow to be detected !**

# Relic Antineutrino Detection

## using EC decaying nuclei (b)

$\bar{\nu}_e + (A,Z) \rightarrow (A,Z\text{-}1) + e^+$

2) there exist a nucleus for which

$$2m_e - m_\nu < Q_{EC} < 2m_e + m_\nu$$

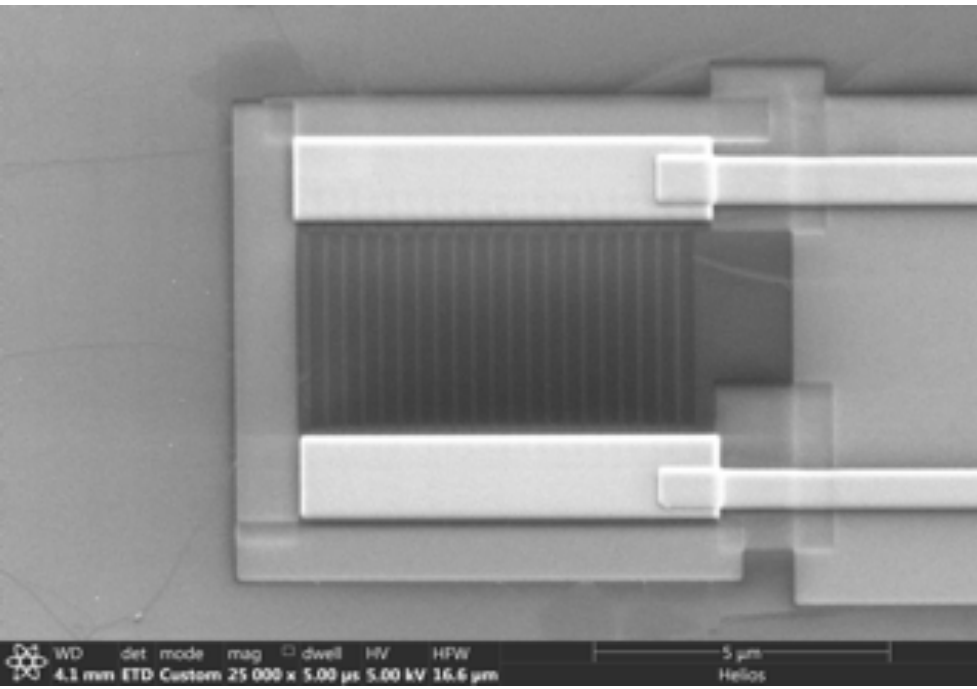
In this case:

- the reaction has no energy threshold on the incoming antineutrino
- unique signature since $\beta^+$ decay is forbidden
- cross section is evaluated using EC decay observables

More details in: AGC, M.Messina and G.Mangano Phys. Rev. D79(2009)053009

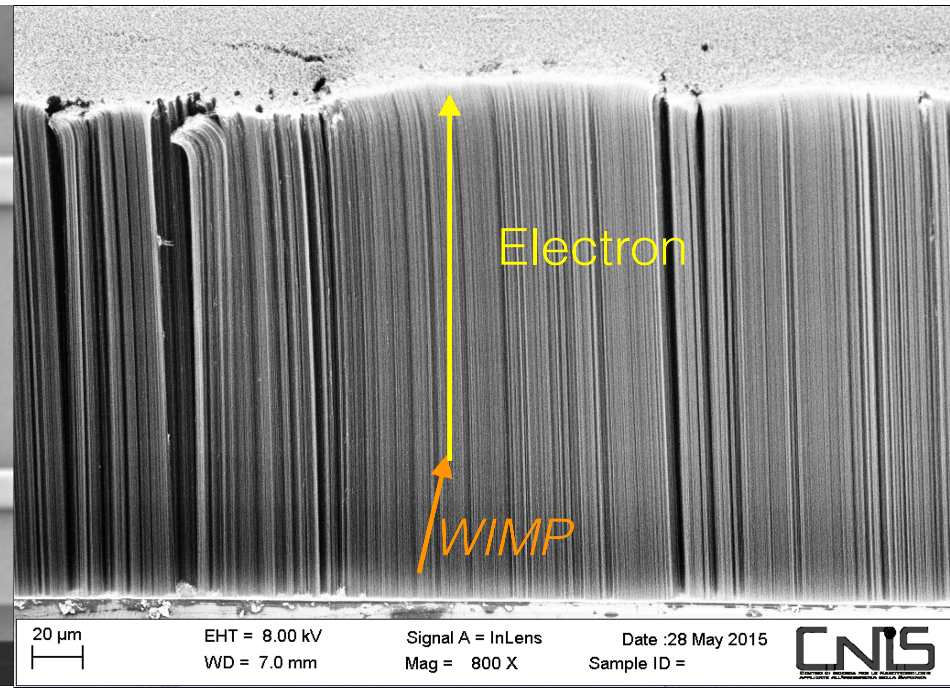
# Graphene Targets for directional DM detection
# Two Concepts

PTOLEMY-G$^3$




Self-instrumented with G-FETs

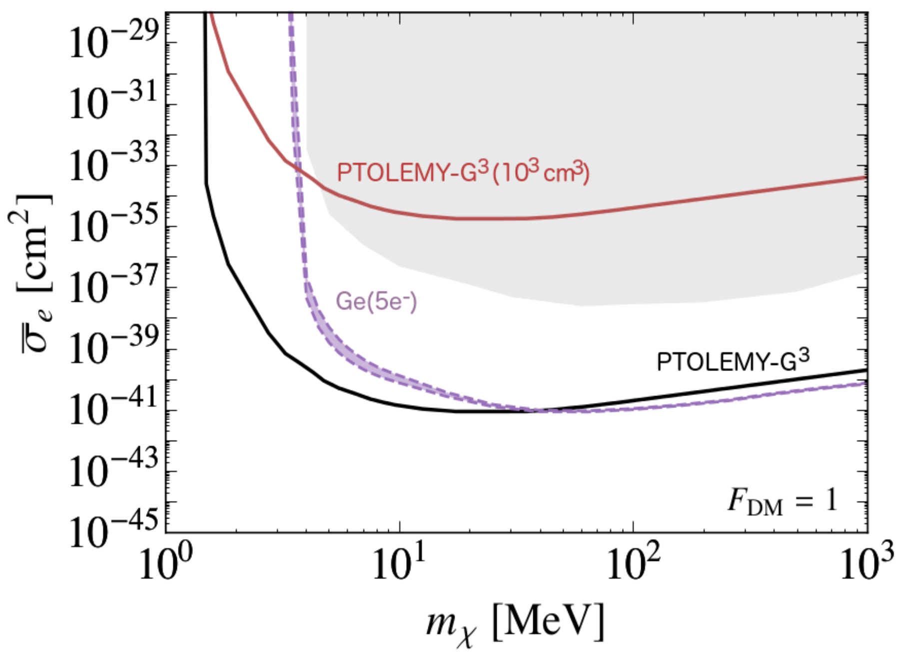
PTOLEMY-CNT




Anisotropy of aligned CNTs

# Direction Detection of MeV Dark Matter

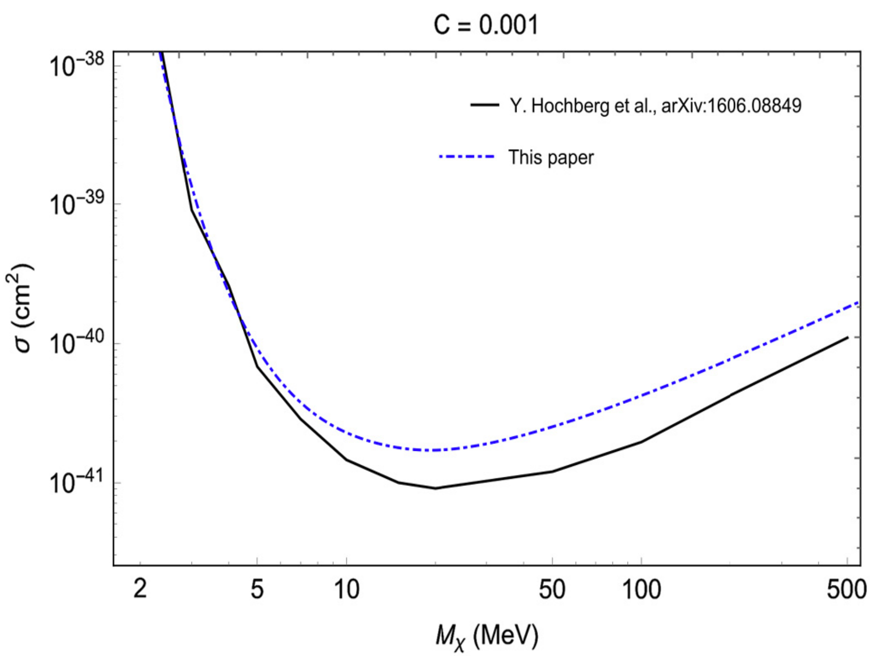
PTOLEMY-$G^3$




Self-instrumented with G-FETs

Physics Letters B772 (2017) 239

PTOLEMY-CNT




Anisotropy of aligned CNTs

Physics Letters B776 (2018) 338