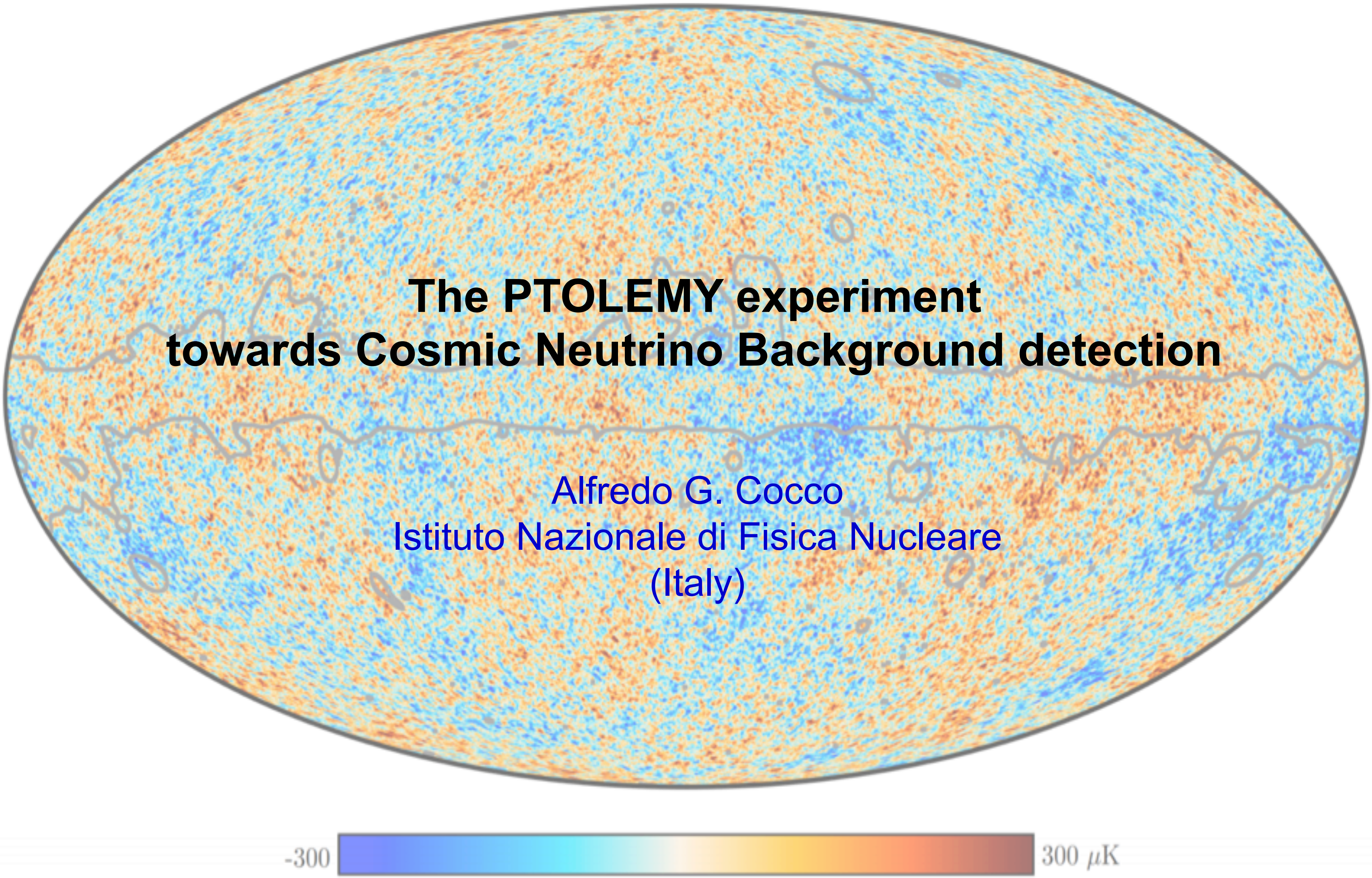
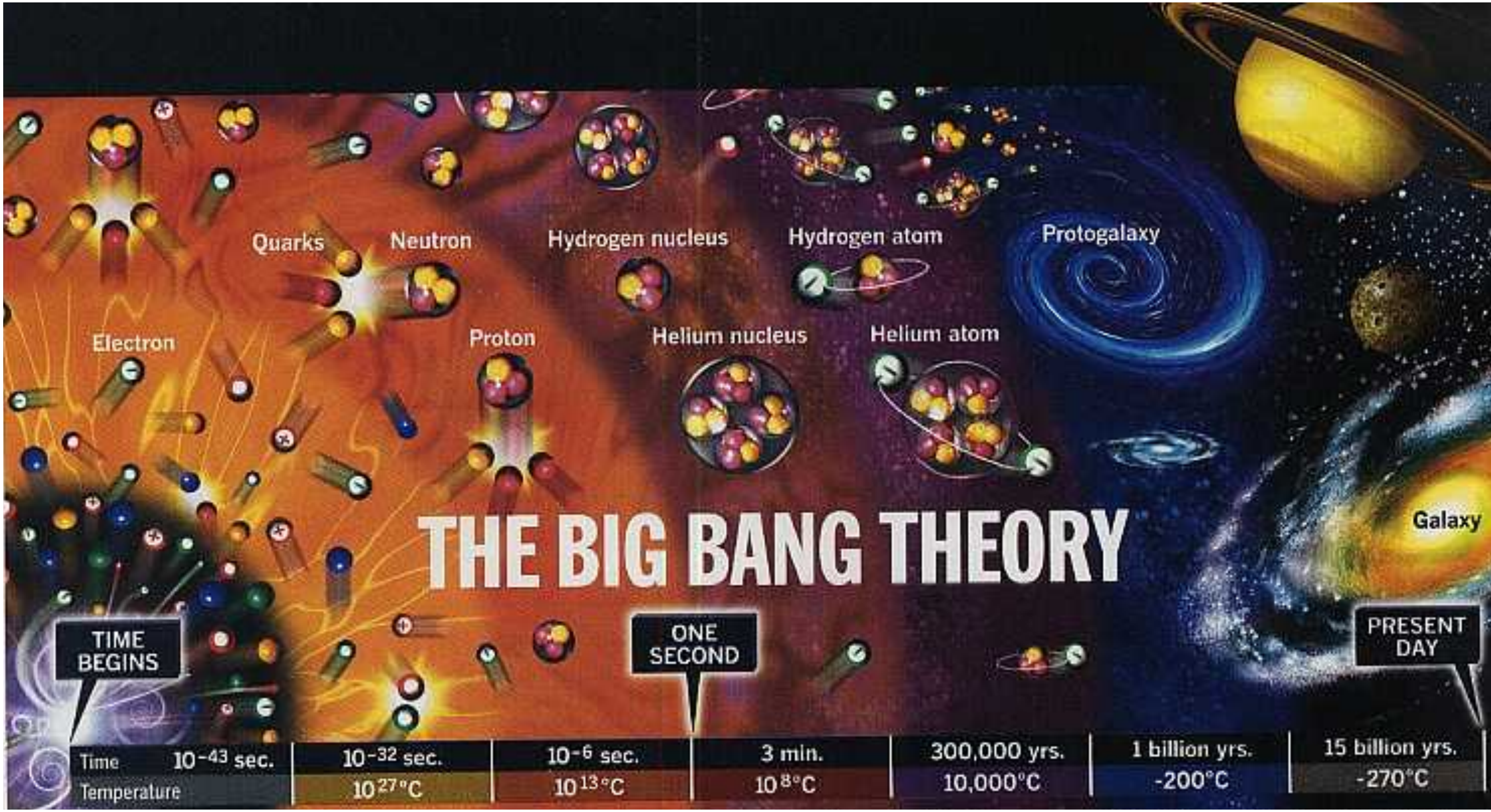
NEPLES 2019 – Korea Institute for Advanced Study (KIAS)

The PTOLEMY experiment towards Cosmic Neutrino Background detection

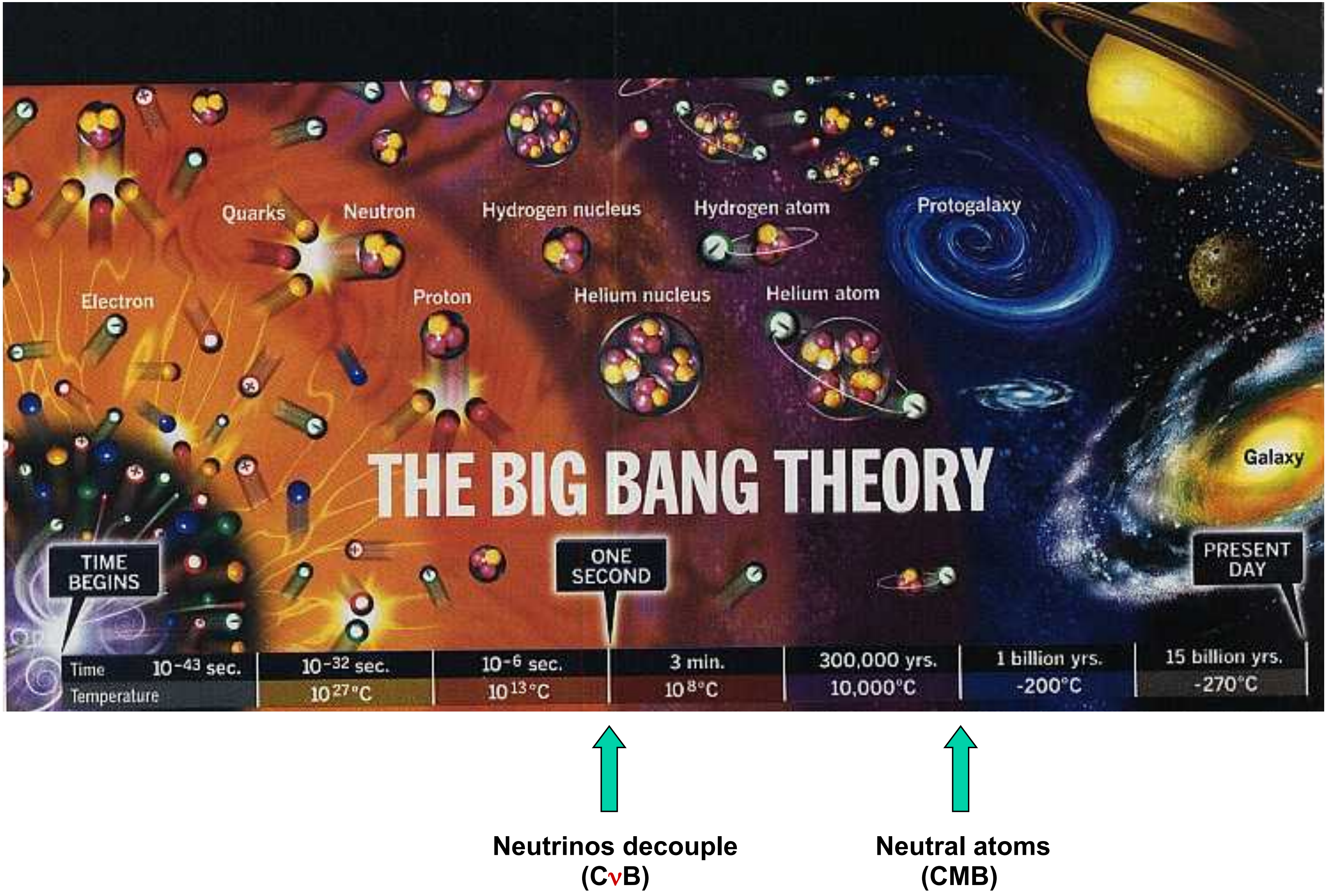
Alfredo G. Cocco
Istituto Nazionale di Fisica Nucleare
(Italy)



Seoul, September 26th 2019



Neutral atoms (CMB)


THE BIG BANG THEORY
Quarks
Neutron
Hydrogen nucleus
Hydrogen atom
Protogalaxy
Electron
Proton
Helium nucleus
Helium atom
Galaxy
TIME BEGINS
ONE SECOND
PRESENT DAY
Time
Temperature
10-43 sec.
10-32 sec.
10²⁷°C
10-6 sec.
10¹³°C
3 min.
10⁸°C
300,000 yrs.
10,000°C
1 billion yrs.
-200°C
15 billion yrs.
-270°C
Neutrinos decouple
(CνB)
Neutral atoms
(CMB)

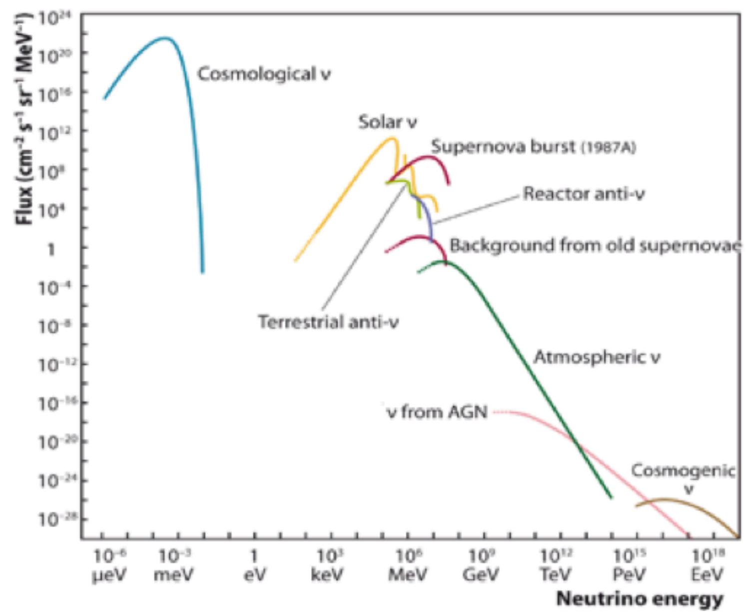
Cosmic Neutrino Background (CνB)

In the Big-Bang scenario neutrinos decoupled when T ~ MeV

This happened about 1 s after the Universe was born
$\Rightarrow$ ν are the oldest "detectable" relics !!

"Thermal" spectrum $p_\nu \approx 10^{-3}$ eV

Number density today $n_\nu = 56$ cm^{-3}

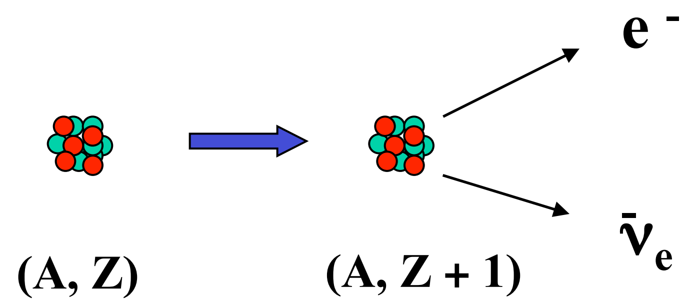


Energy is not enough to induce CC interactions
"Collective" NC effects are undetectable

Neutrino capture on $\beta^{\pm}$ decaying nuclei

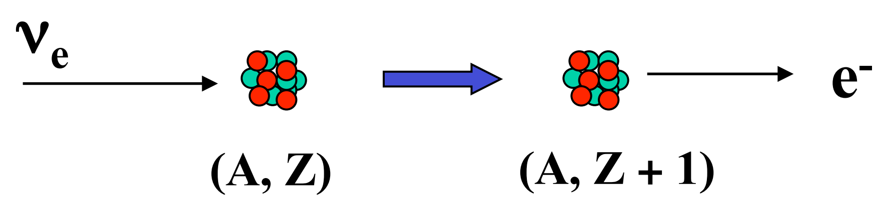
Known

Nuclear Beta decay



Possible

Neutrino Capture on a Beta Decaying Nucleus (NCB)



This process has no energy threshold !
Cross section is non vanishing !
e^- in final state has fixed energy (2 body decay) !

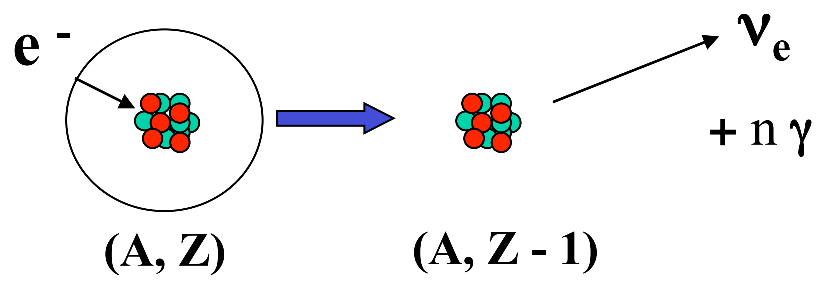
Direct detection IS possible !!

A.G.Cocco, G.Mangano and M.Messina JCAP 06(2007)015

Antineutrino capture on EC decaying nuclei (a)

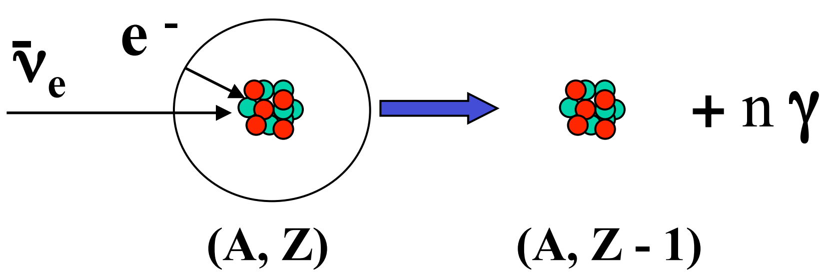
Known

Electron Capture



Possible

Simultaneous $\bar{\nu}$ and electron Capture



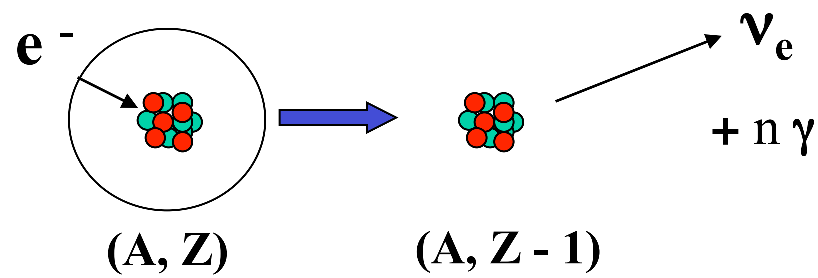
This process has no energy threshold !

A.G.Cocco, G.Mangano and M.Messina Phys. Rev. D79 (2009) 053009

Antineutrino capture on EC decaying nuclei (b)

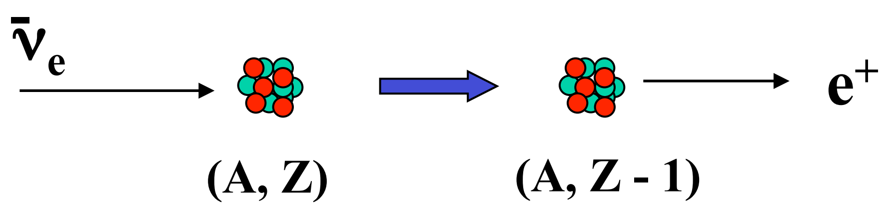
Known

Electron Capture



Possible

Antineutrino Capture



$E_{\nu} > 2m_e - Q_{EC}$

A.G.Cocco, G.Mangano and M.Messina Phys. Rev. D79 (2009) 053009

NCB Cross Section

a new parametrization

$$\sigma_{\mathrm{NCB}} v_\nu = \frac{2\pi^2 \ln 2}{\mathcal{A}\, t_{1/2}}$$

This is valid for both $\beta^\pm$ and EC decaying nuclei

$$\mathcal{A} = \int_{m_e}^{W_o} \frac{C(E'_e, p'_\nu)_\beta}{C(E_e, p_\nu)_\nu} \frac{p'_e}{p_e} \frac{E'_e}{E_e} \frac{F(E'_e, Z)}{F(E_e, Z)} E'_\nu p'_\nu dE'_e$$

$\overset{(-)}{\nu}$ capture on $\beta^\pm$ nuclei

$$\mathcal{A} = \frac{\sum_x n_x C_x(q_\nu) f_x(q_\nu)}{p_e E_e F(Z, E_e) C(p_e, p_\nu)_\nu}$$

$\bar{\nu}$ capture on EC nuclei

$$\mathcal{A}' = \frac{\sum_x n_x C_x(q_\nu) f_x(q_\nu)}{\sum_x n_x C_x(E_\nu) g_x \rho_x(E_\nu)}$$

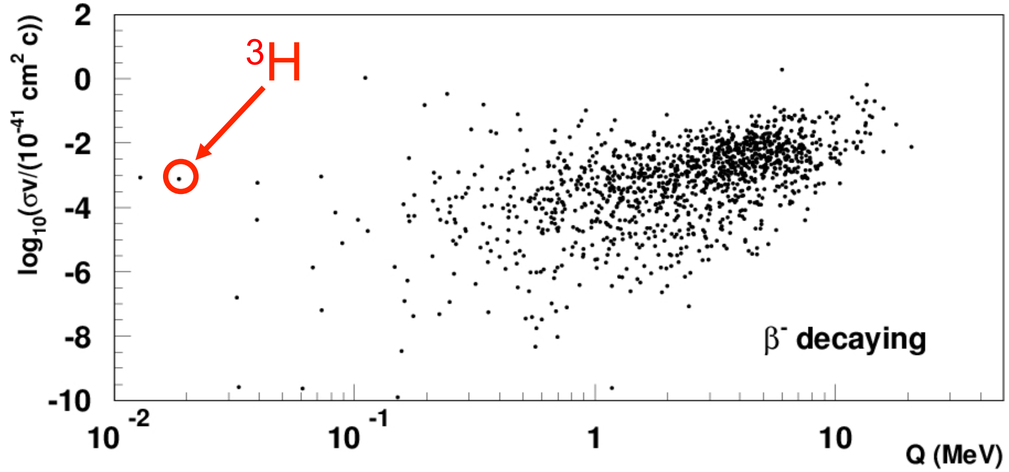
$\bar{\nu}$ + e^- capture on EC nuclei

In a large number of cases $\mathcal{A}$ can be evaluated in an exact way and NCB cross section depends only on Q_β and $t_{1/2}$ (measurable)

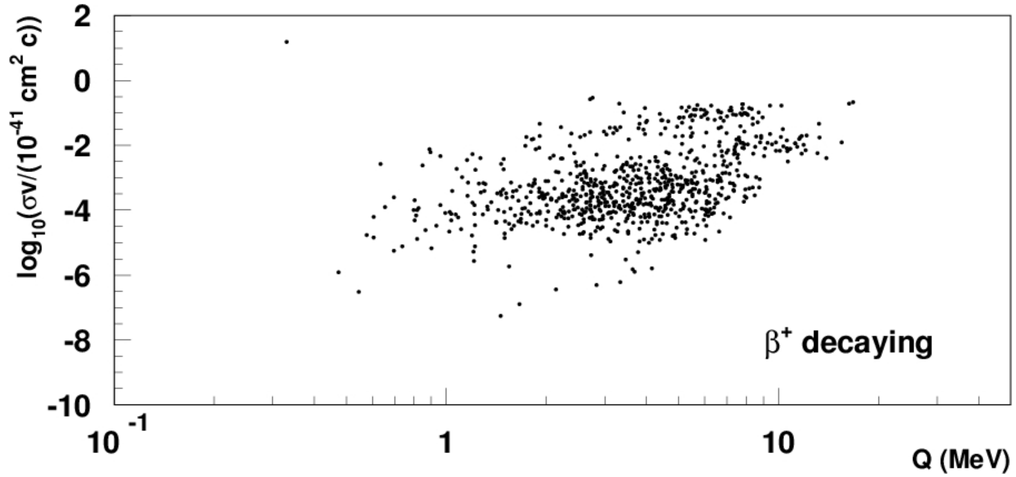
NCB Cross Section Evaluation

using measured values of Q_β and $t_{1/2}$

1272 β^- decays



799 β^+ decays



Beta decaying nuclei having BR($\beta^\pm$) > 5 %
selected from 14543 decays listed in the ENSDF database

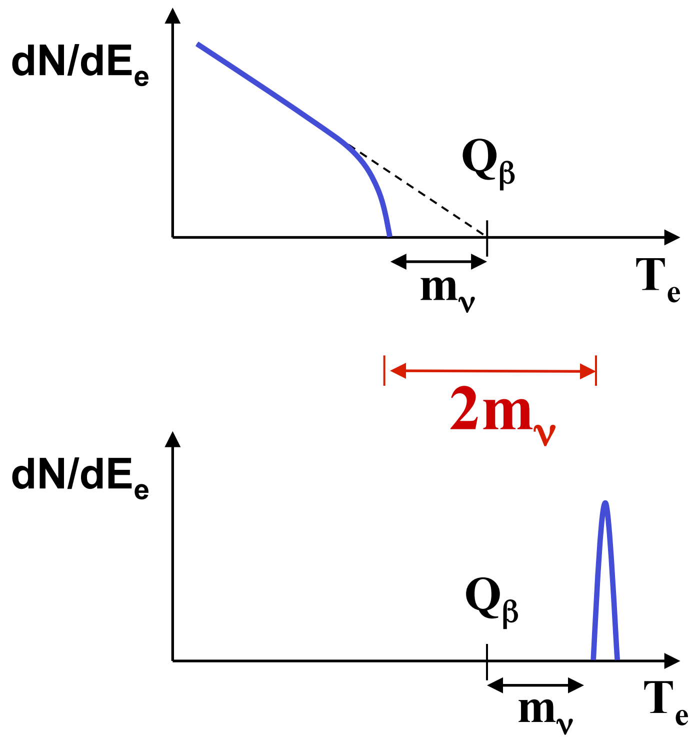
The effect of $m_\nu \neq 0$

(Neutrino masses of the order of eV are still compatible with the present picture of our Universe) 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_β) between "signal" and "background"

As s "side result": measurement of the neutrino mass !

CνB detection using Tritium

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

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

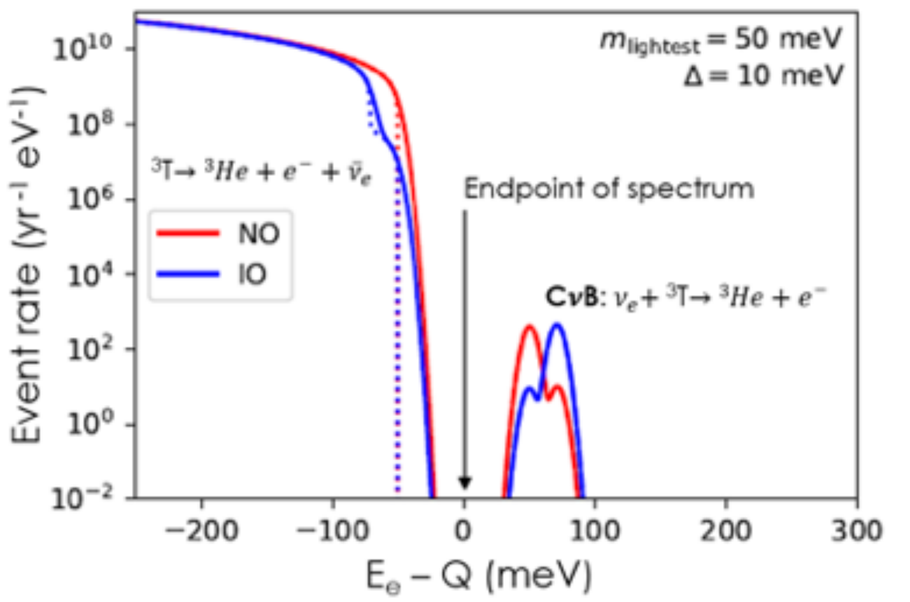
As an example, given a neutrino mass of 0.7 eV and an energy resolution at the beta decay endpoint of Δ=0.2 eV a signal to background ratio of 3 is obtained.

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 (~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

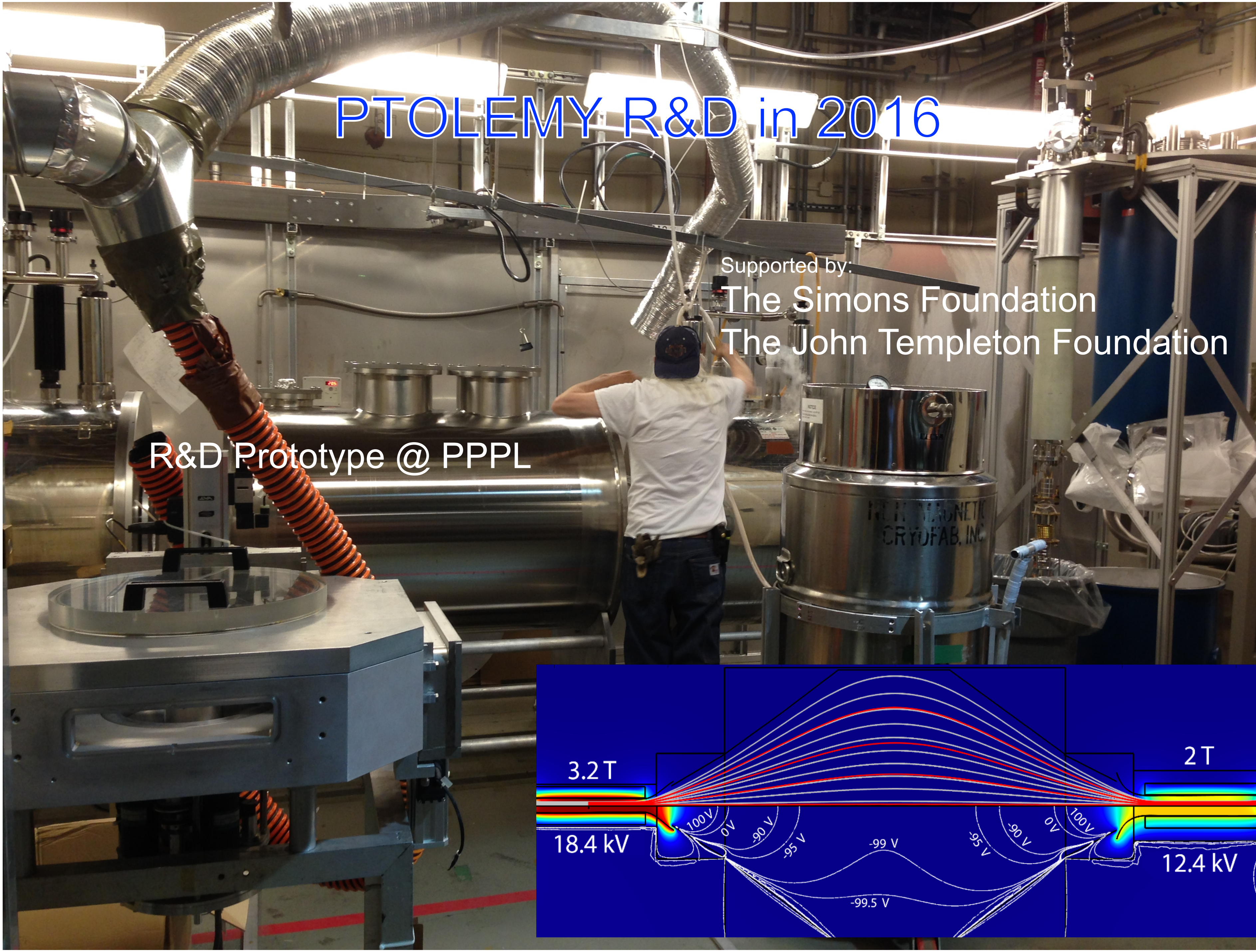
S. Betts[1], W. R. Blanchard[1], R. H. Carnevale[1], C. Chang[2], C. Chen[3], S. Chidzik[3], L. Ciebiera[1], P. Cloessner[4], A. Cocco[5], A. Cohen[1], J. Dong[1], R. Klemmer[3], M. Komor[3], C. Gentile[1], B. Harrop[3], A. Hopkins[1], N. Jarosik[3], G. Mangano[5], M. Messina[6], B. Osherson[3], Y. Raitses[1],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

[1]Princeton Plasma Physics Laboratory
[2]Argonne National Laboratory and University of Chicago
[3]Department of Physics, Princeton University
[4]Savannah River National Laboratory
[5]Istituto Nazionale di Fisica Nucleare – Sezione di Napoli
[6]Department of Physics, Columbia University

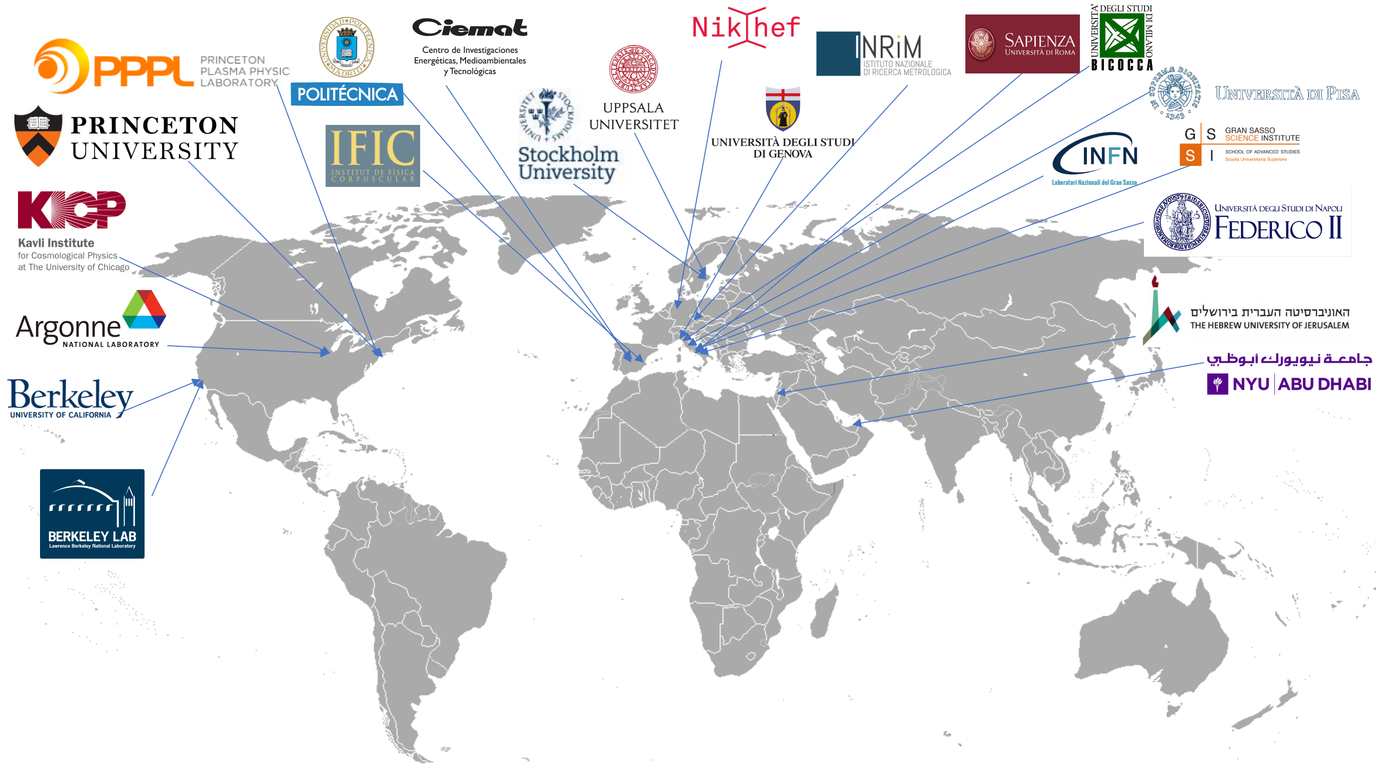
100 g T source + EM filter + RF tagging + sub-eV resolution μ-cal

Major technological challenges
towards the full scale PTOLEMY detector

- Assemble a 100 g (35×10^6 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 σ_E better than O(0.05 eV)


PTOLEMY R&D in 2016
Supported by:
The Simons Foundation
The John Templeton Foundation
R&D Prototype @ PPPL
3.2 T
18.4 kV
2 T
12.4 kV
100 V
0 V
-90 V
-95 V
-99 V
-99.5 V
-95 V
-90 V
0 V
100 V

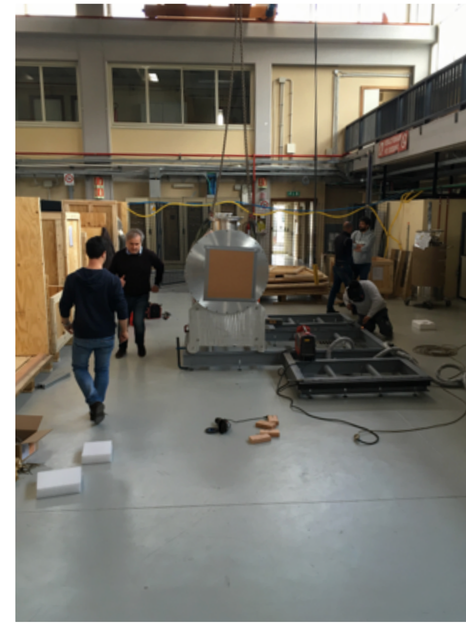
The PTOLEMY Collaboration

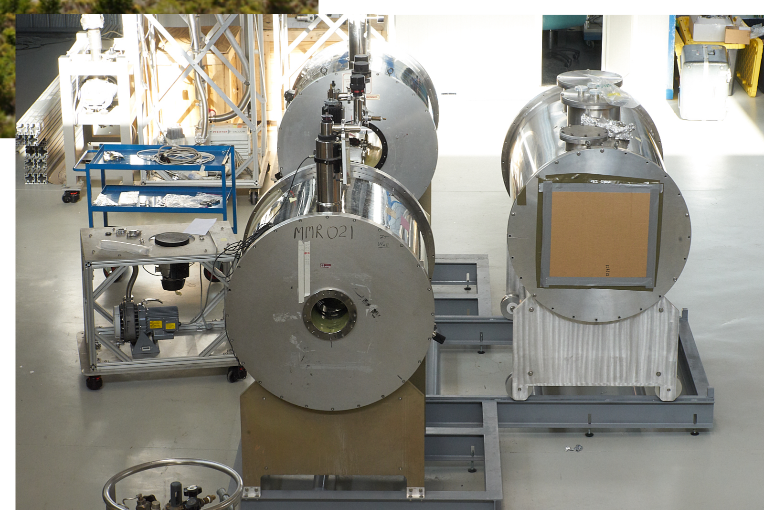


M.G.Betti, M.Biasotti, A.Bosca, F.Calle, J.Carabe-Lopez, G.Cavoto, C.Chang, W.Chung, A.G.Cocco, A.P.Colijn, J.Conrad, N.D'Ambrosio, P.F.de Salas, M.Faverzani, A.Ferella, E.Ferri, P.Garcia-Abia, G.Garcia Gomez-Tejedor, S.Gariazzo, F.Gatti, C.Gentile, A.Giachero, J.Gudmundsson, Y.Hochberg, Y.Kahn, M.Lisanti, 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





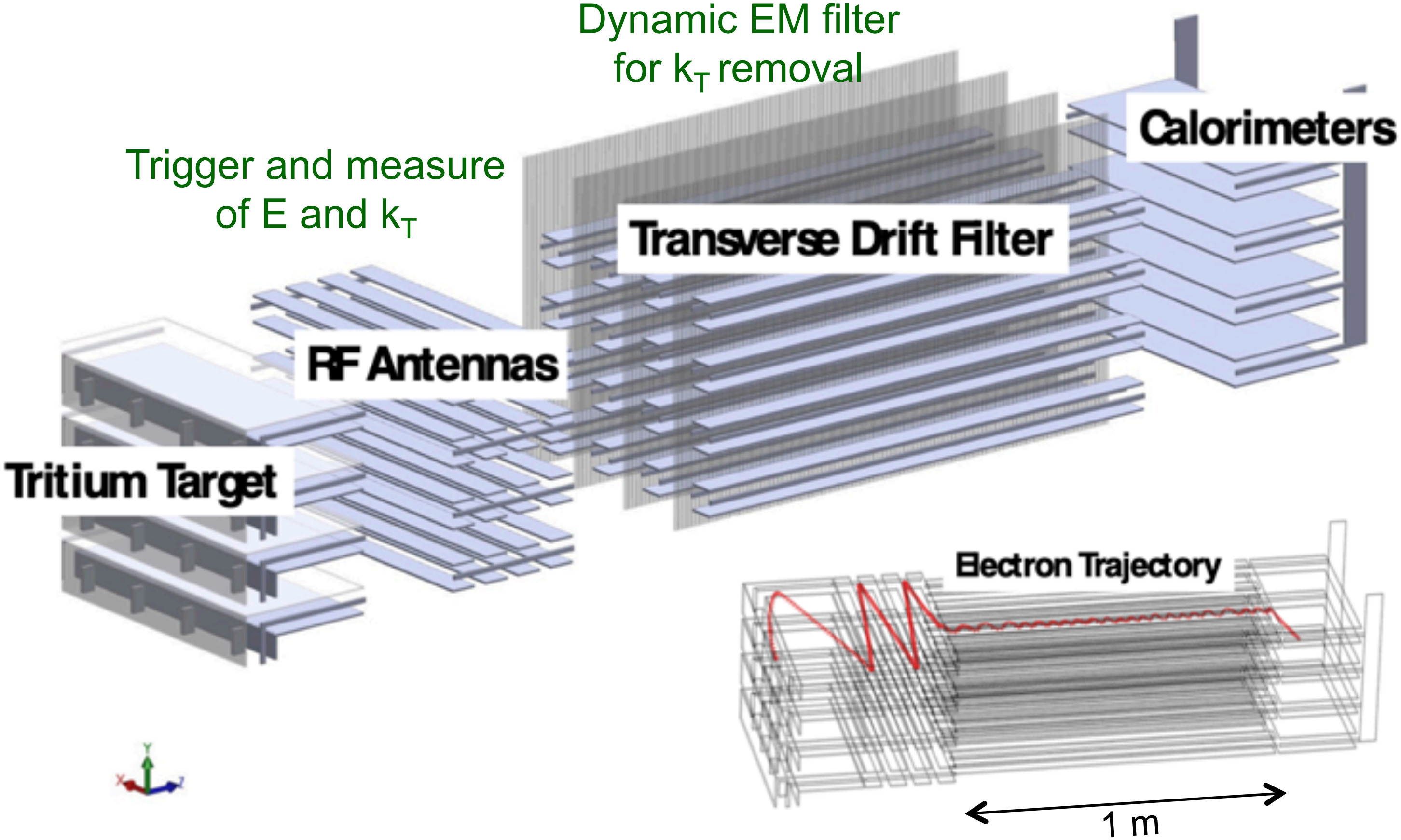
Underground area not needed
for the time being

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

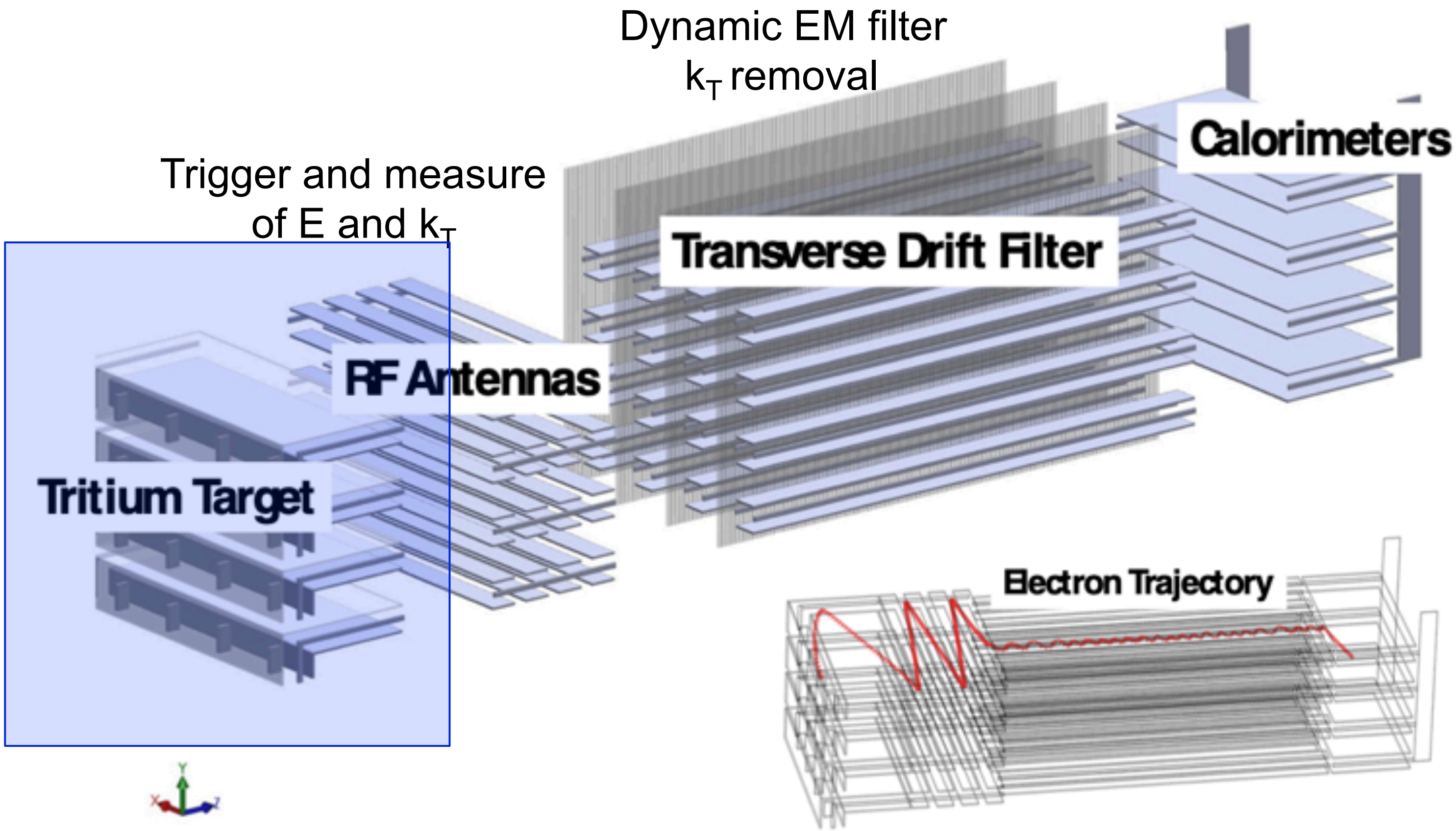
PTOLEMY prototype layout



Static electric and magnetic fields are used

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

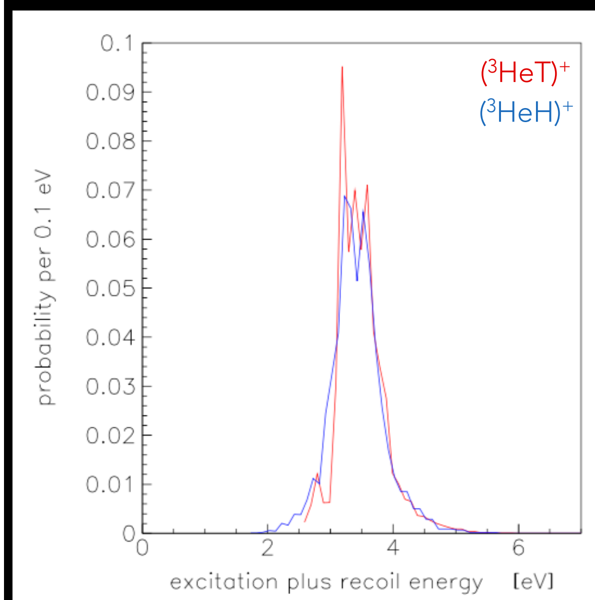
PTOLEMY prototype layout



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 ν-mass

Need atomic tritium for ultimate experiment!

Tritiated graphene

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

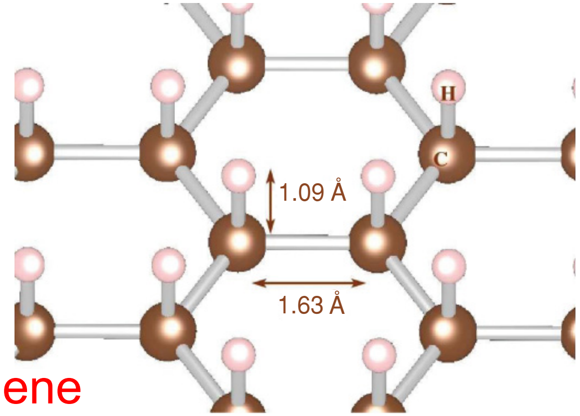
Single-sided (loaded on substrate) and planar (uniform bond length)

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

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

Semiconductor (Voltage Reference)

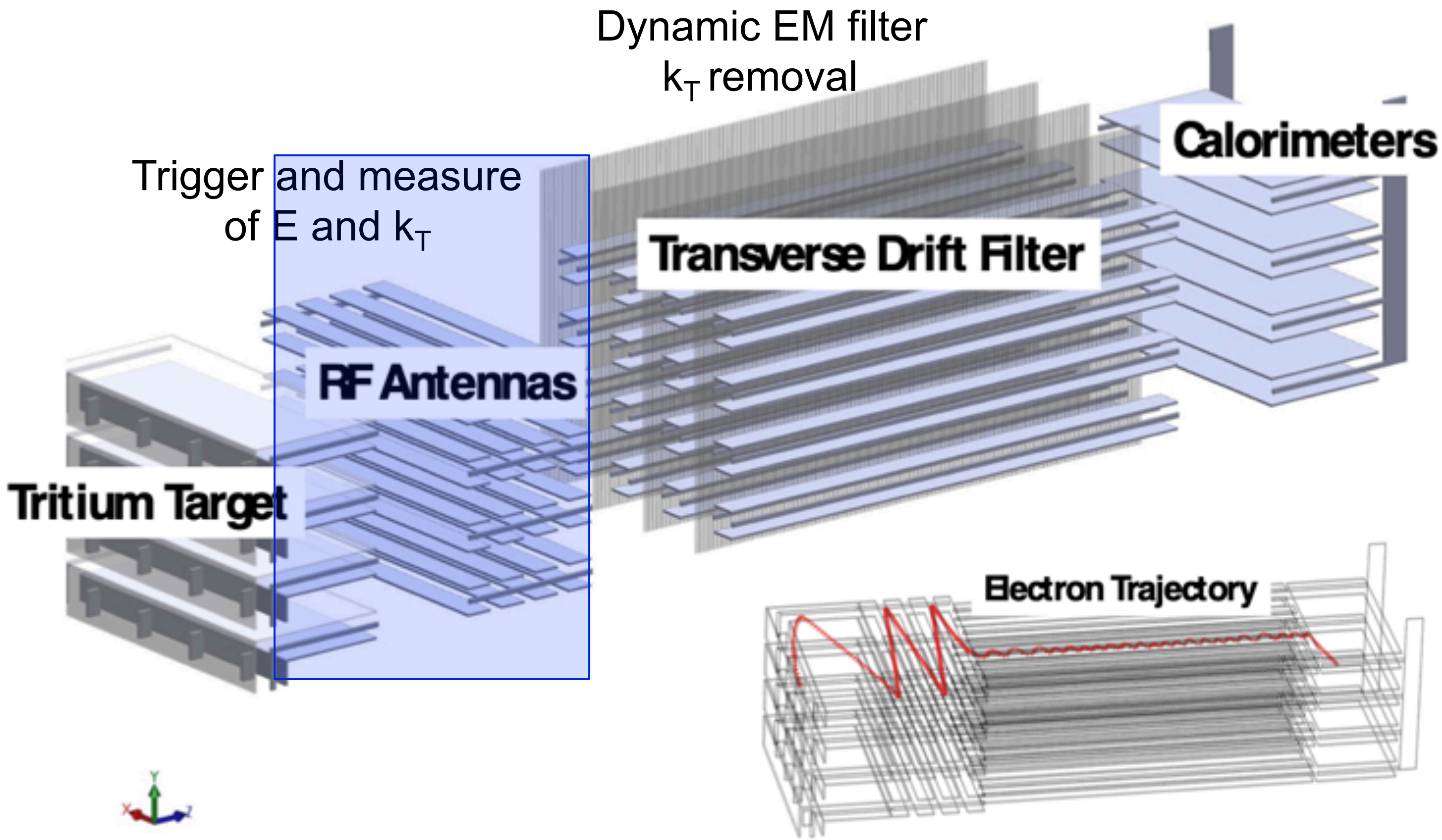
Polarized tritium (directionality?)



World record of 40% Hydrogen loading on graphene already achieved @ Princeton Univ. in 2016

Rome, Madrid, Princeton

PTOLEMY prototype layout



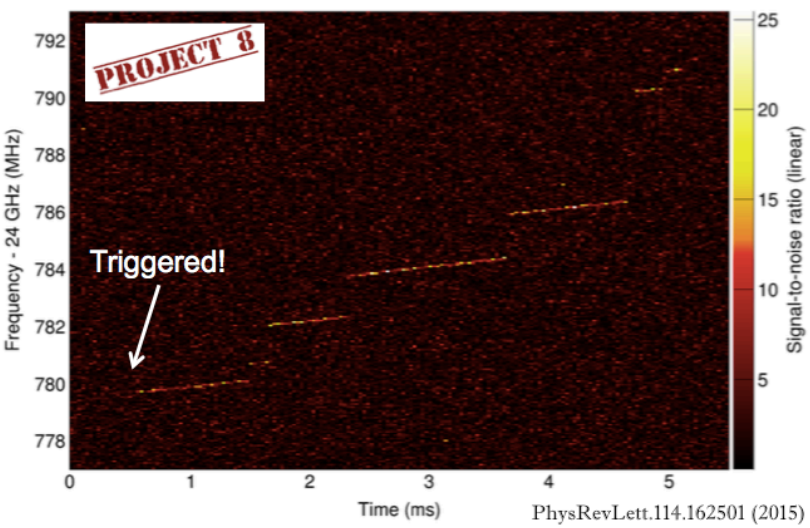
RF triggering and EM filter “tune”

Thread electron trajectories through an array of RF antennas with wide bandwidth (few x10^{-5}) in order to identify cyclotron RF signal (~26 GHz @ 1T) with few eV resolution (transit times of order 0.2 msec)

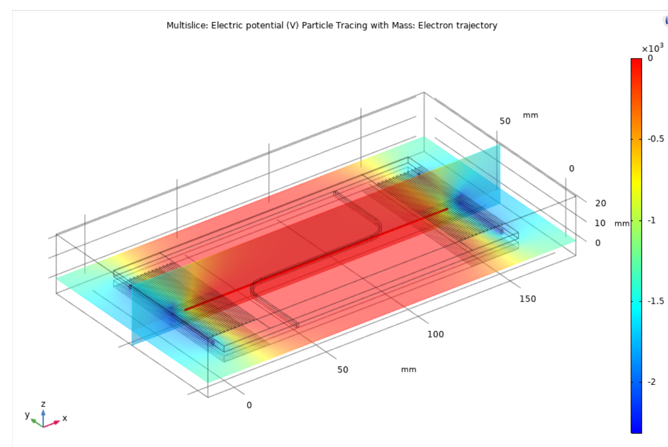
In case of candidate event set the EM filter voltages accordingly (see next slides)

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

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

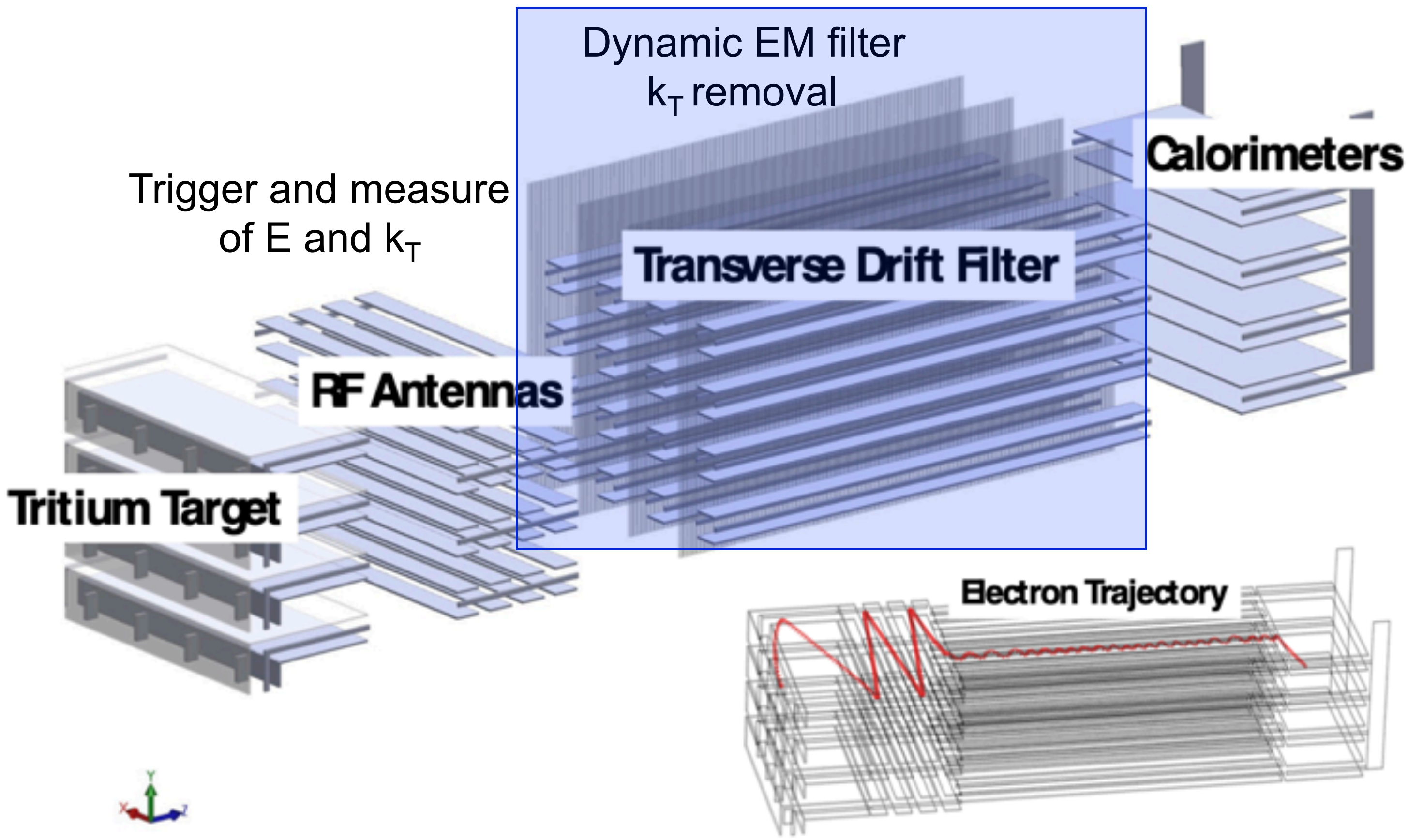


First detection of single electron cyclotron radiation
Phys.Rev.Lett. 114(2015)162501



COMSOL simulation of PTOLEMY RF test module (Princeton, NIKHEF, INFN)

PTOLEMY prototype layout



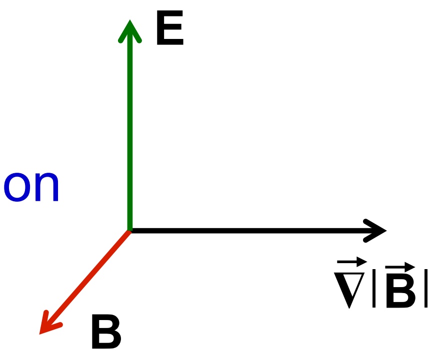
New concept EM filter

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

$\vec{\mathbf{E}} \times \vec{\mathbf{B}}$ **drift** $\qquad$ ∇**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

$$E_x = 0 \ ,$$

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

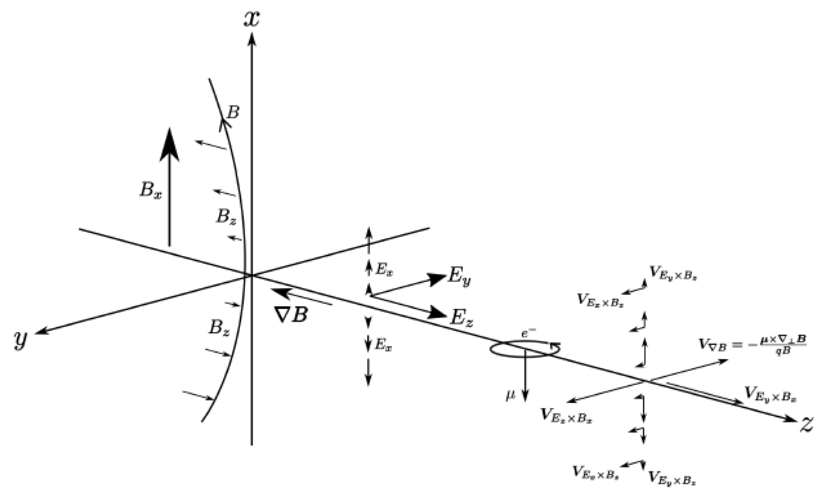
$$E_z = -E_0 \sin\left(\frac{y}{\lambda}\right) e^{-z/\lambda} \ ,$$

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

$$B_y = 0 \ ,$$

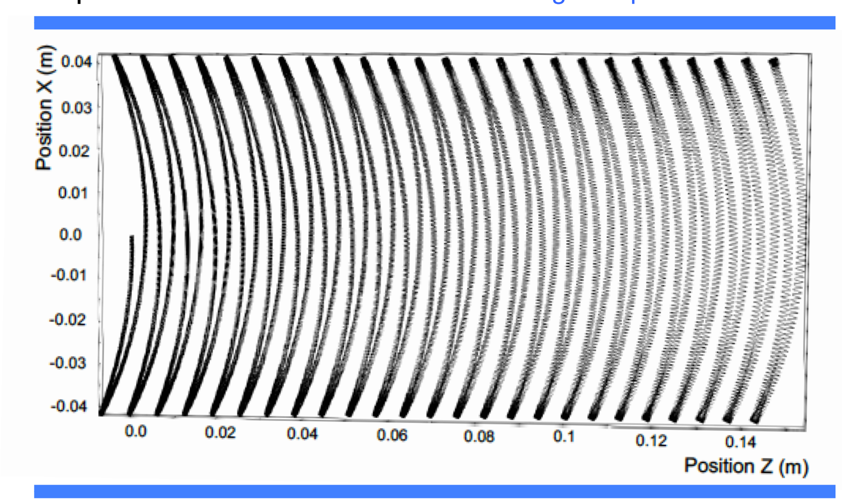
$$B_z = -B_0 \sin\left(\frac{x}{\lambda}\right) e^{-z/\lambda}$$

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

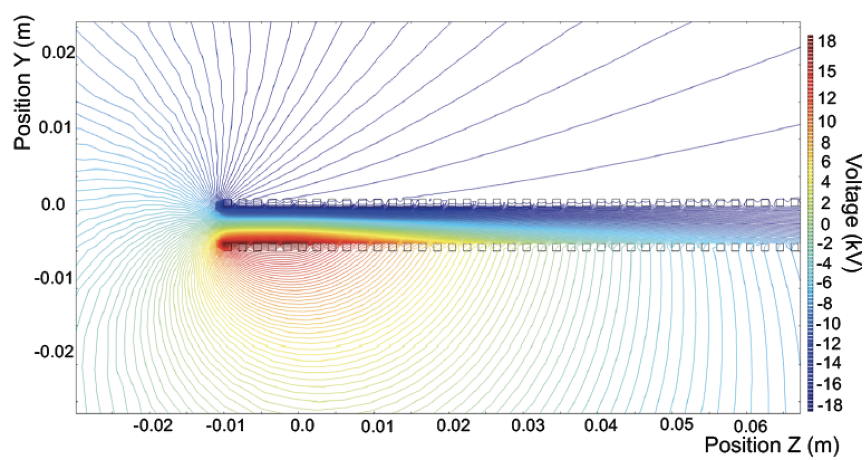


Top view

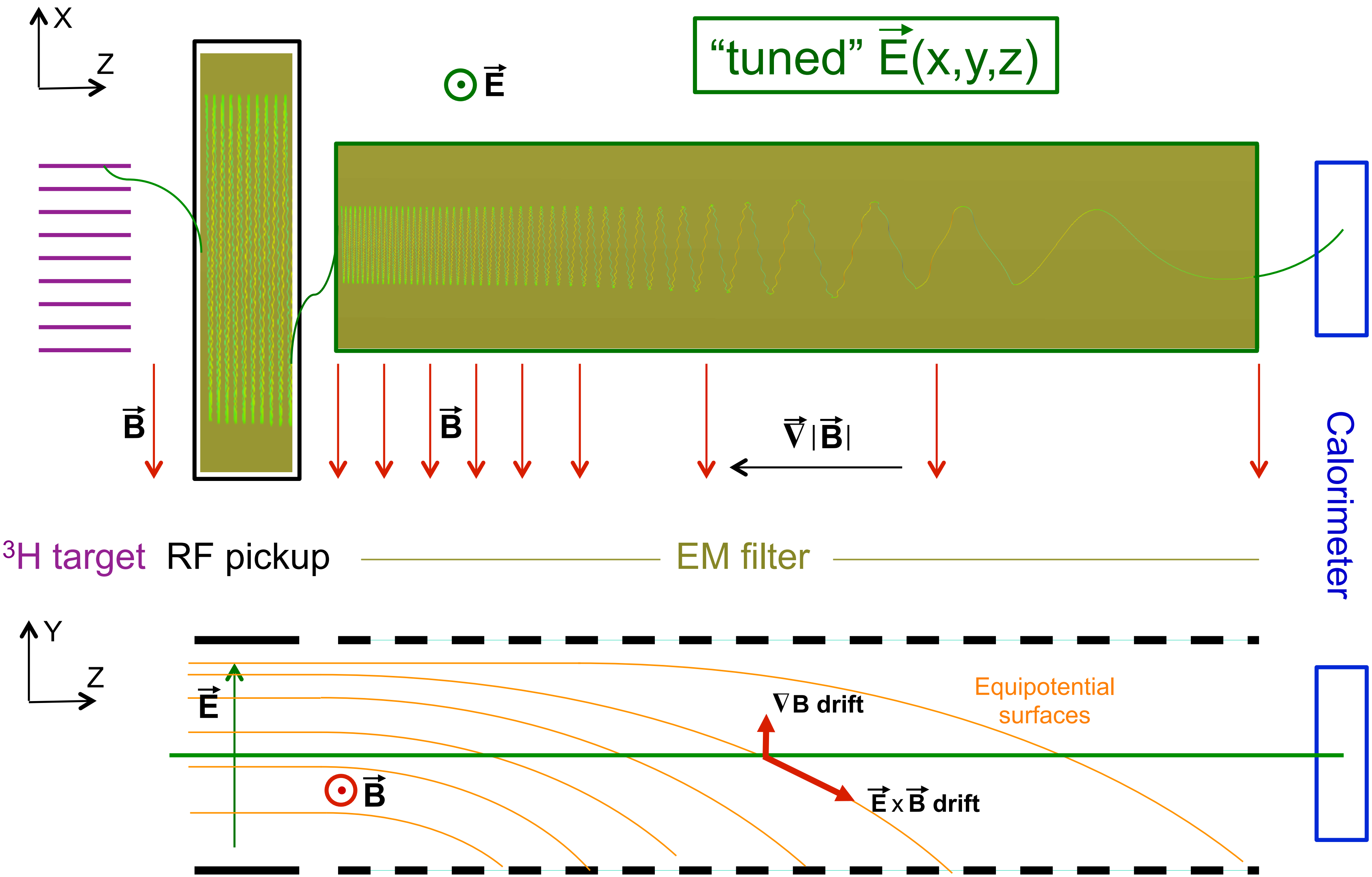
negative potential walls



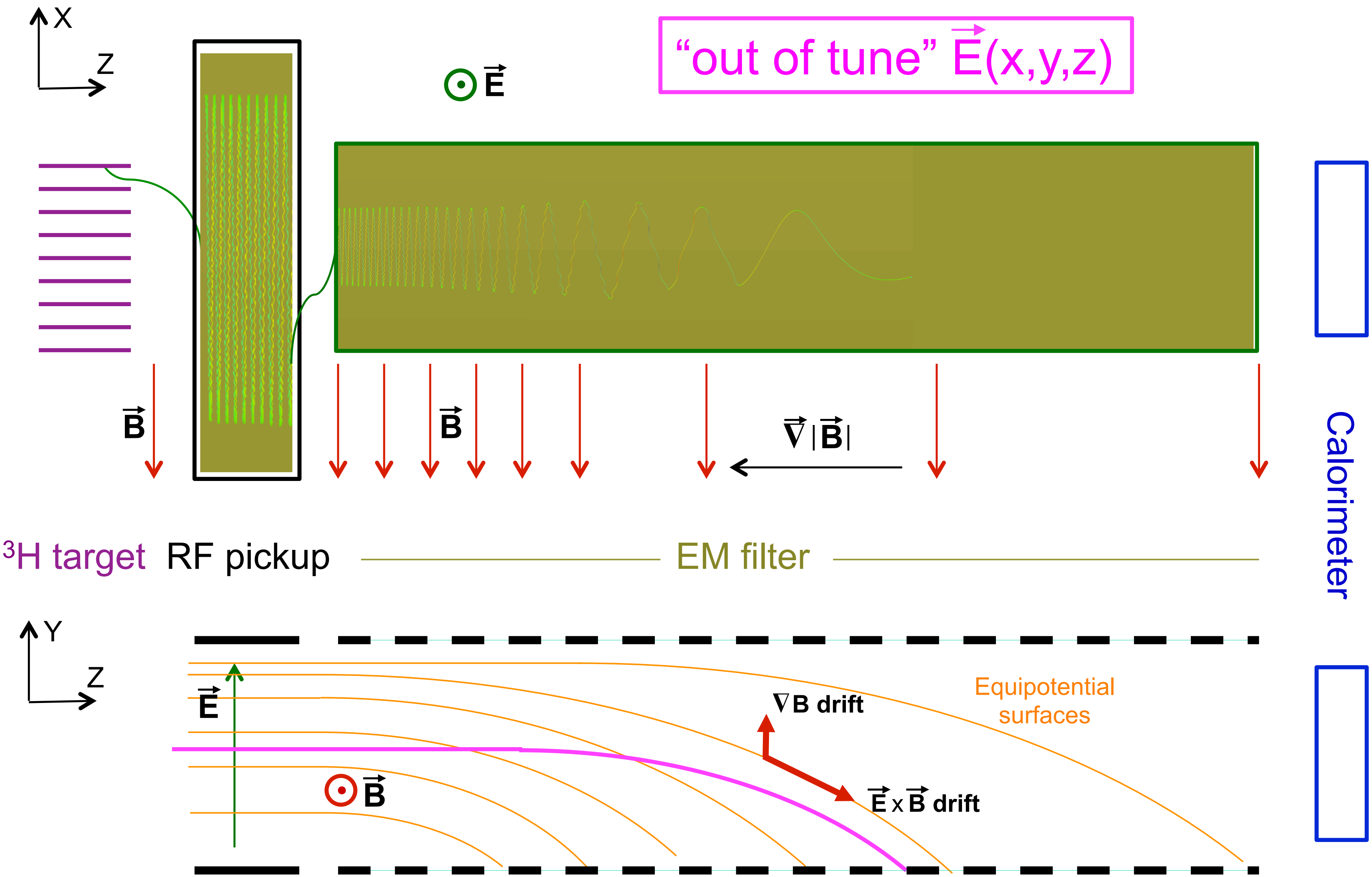
Side view



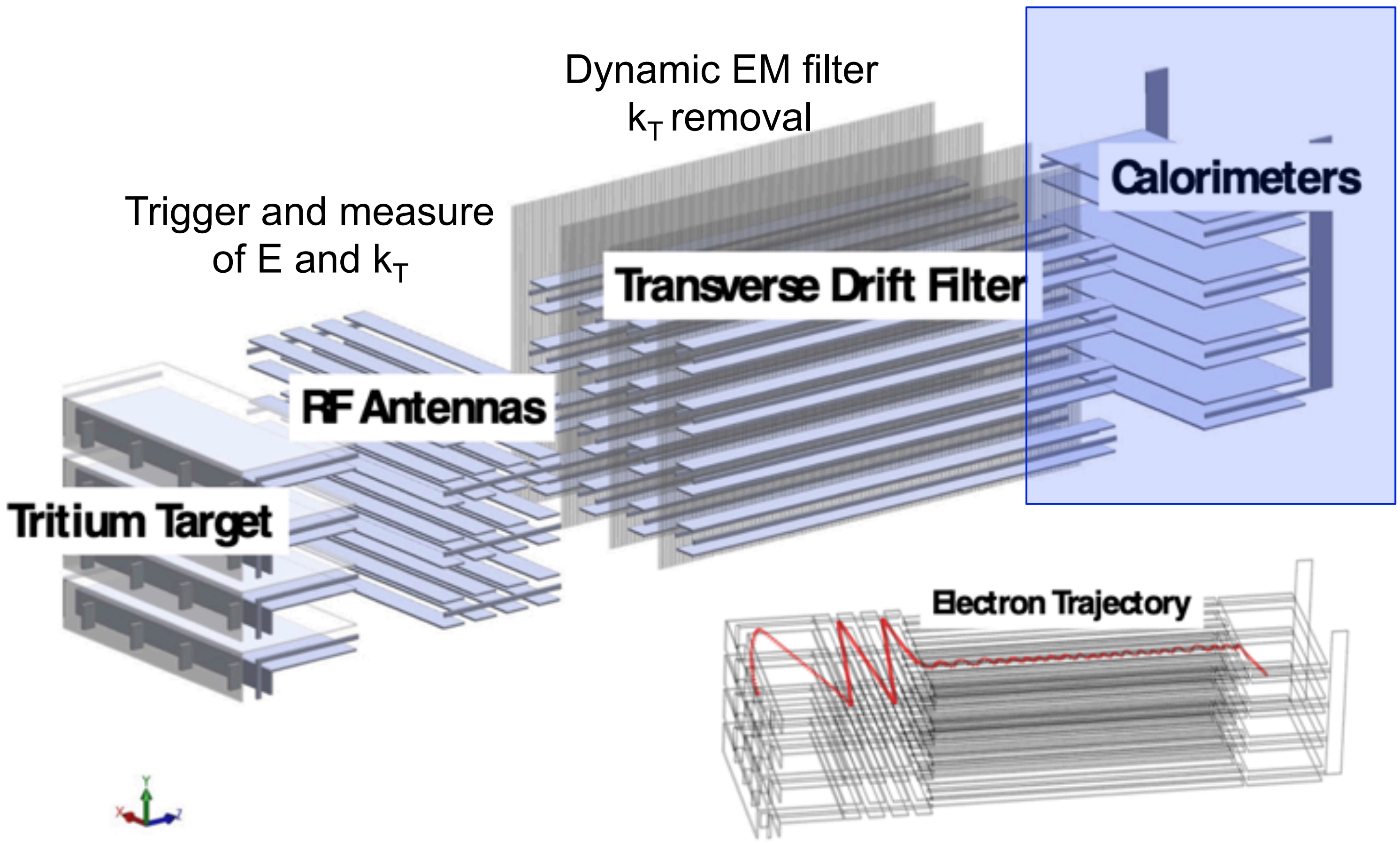
New concept EM filter
Dynamic tuning



New concept EM filter
Dynamic tuning

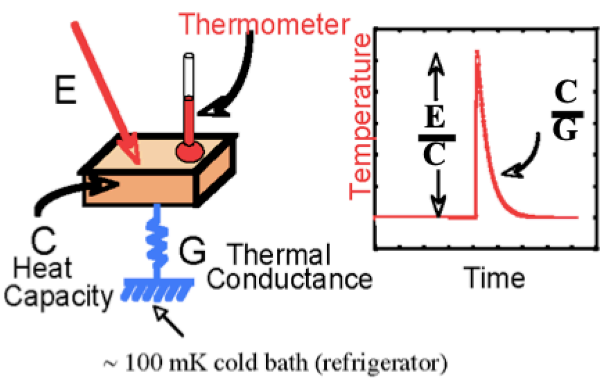


PTOLEMY prototype layout



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

Cryogenic Transition Edge Sensors (TES)

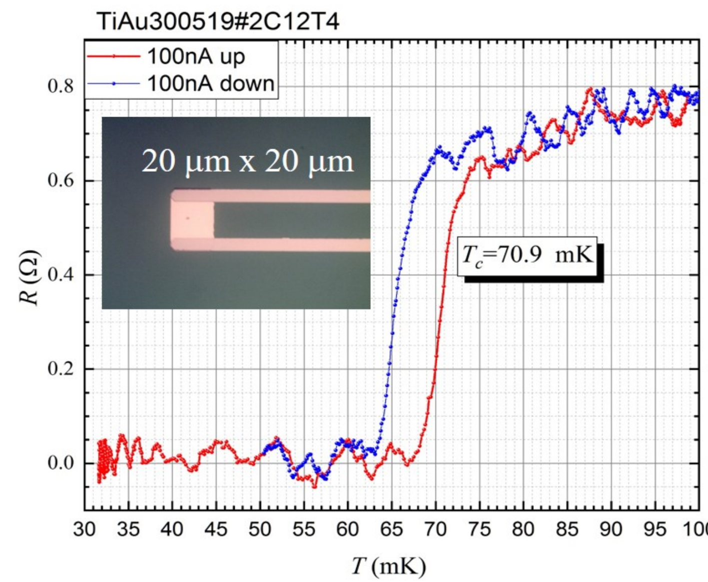


10÷100eV electron can be stopped with very small C (10^4 smaller than for X-ray)

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

ΔE=0.11 eV for 0.8 eV IR photon already achieved @ 106 mK (10x10 μm²) at INRiM

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



3 Resistive transition for a TiAu bilayer TES with 12 nm of Ti and 27 nm of Au. In the inset, a picture of the sample with an area of 400 μm²

Major technological challenges
towards the full scale PTOLEMY detector

- Assemble a 100 g (35×10^{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 σ_E better than O(0.05 eV)
  - TES array with SQUID multiplexing read-out

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 !

Thank you

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 CνB 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 CνB unless:

1) use CνB as a target for accelerated fully ionized beam

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

For allowed transitions and using n_ν= 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)

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

2) there exist a nucleus for which

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

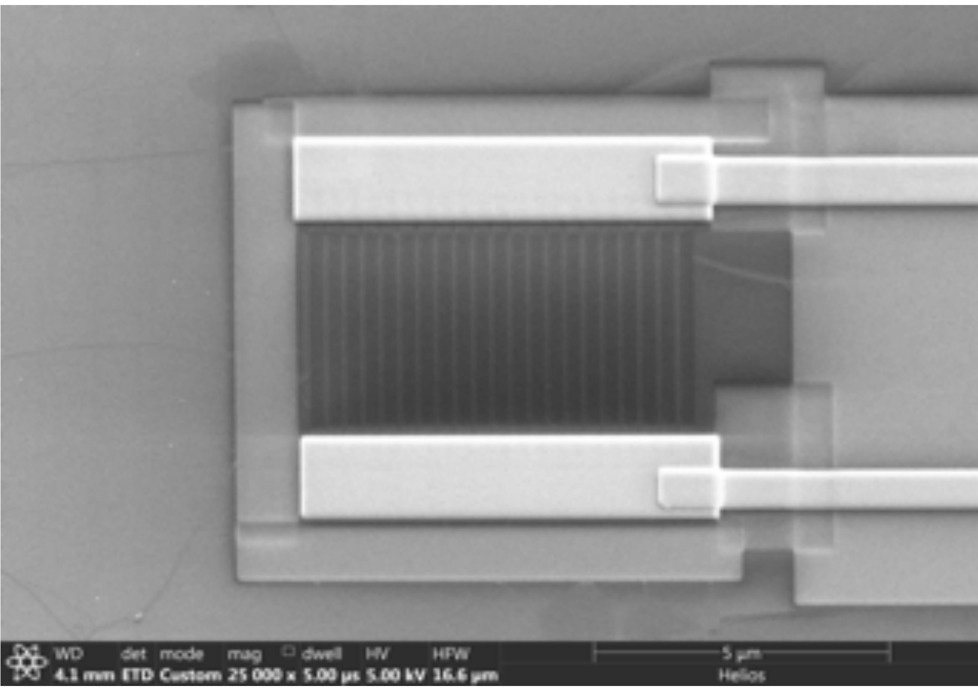
In this case:

- the reaction has no energy threshold on the incoming antineutrino
- unique signature since β^+ 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

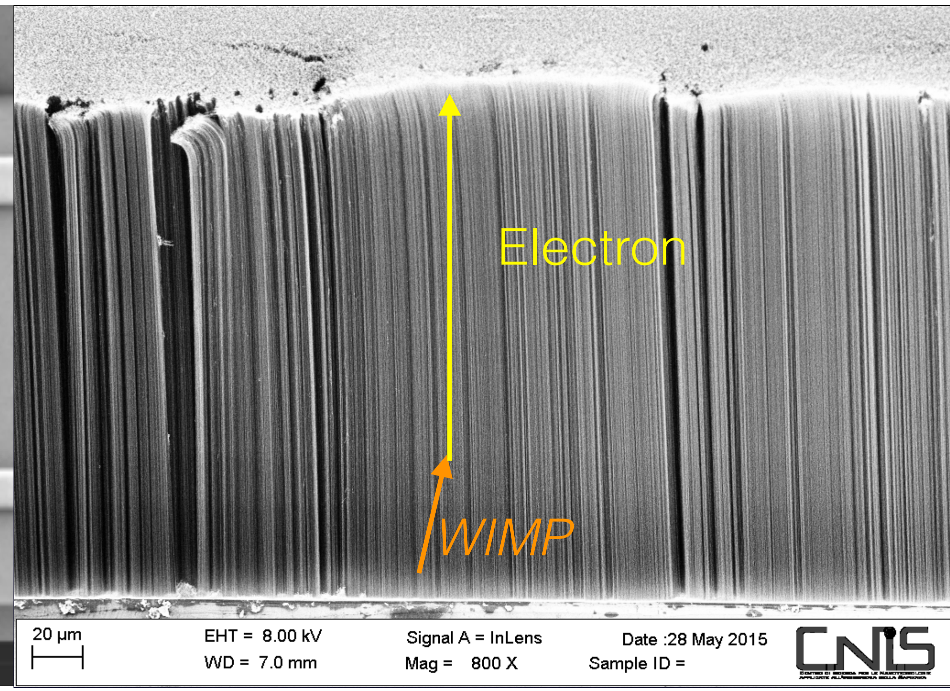
Graphene Targets for directional DM detection
Two Concepts

PTOLEMY-G^3



Self-instrumented with G-FETs

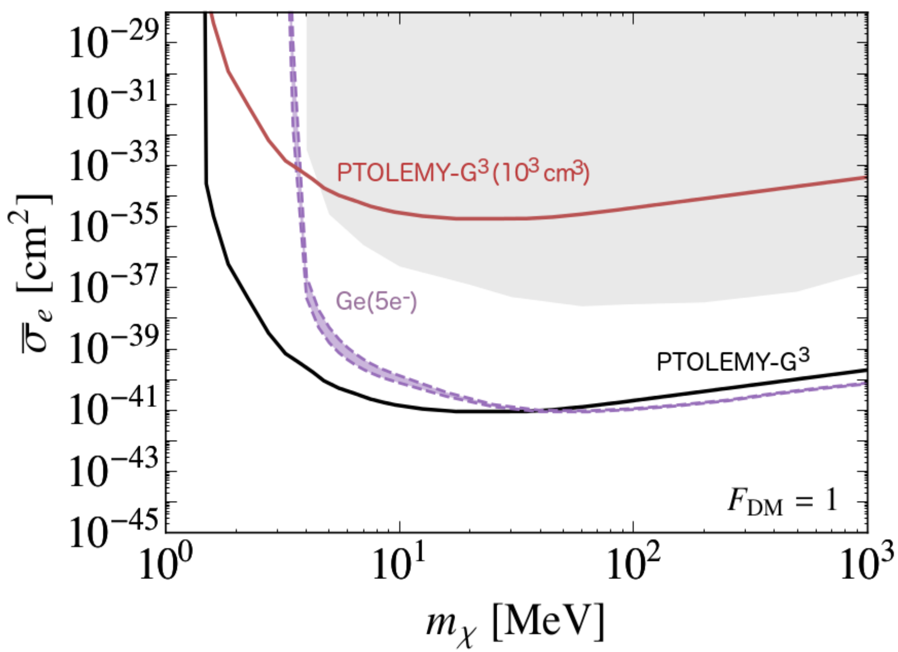
PTOLEMY-CNT



Anisotropy of aligned CNTs

Direction Detection of MeV Dark Matter

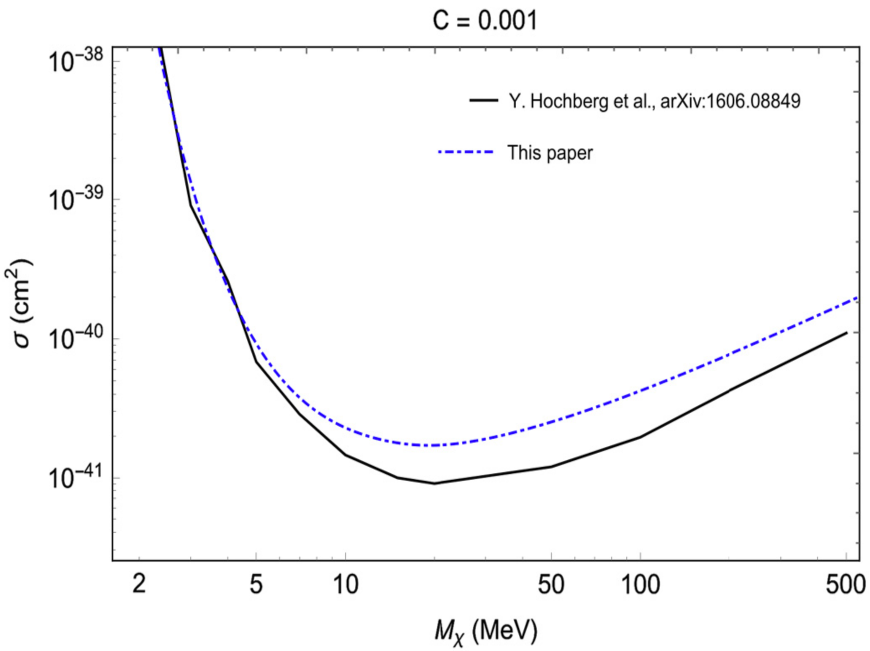
PTOLEMY-G^3



Self-instrumented with G-FETs

Physics Letters B772 (2017) 239

PTOLEMY-CNT



Anisotropy of aligned CNTs

Physics Letters B776 (2018) 338