International Workshop on Next GenerationNucleon Decay and Neutrino Detectors (NNN17)

Warwick Univ., October 26th, 2017

The PTOLEMY experiment
Towards Cosmological Relic Neutrino detection

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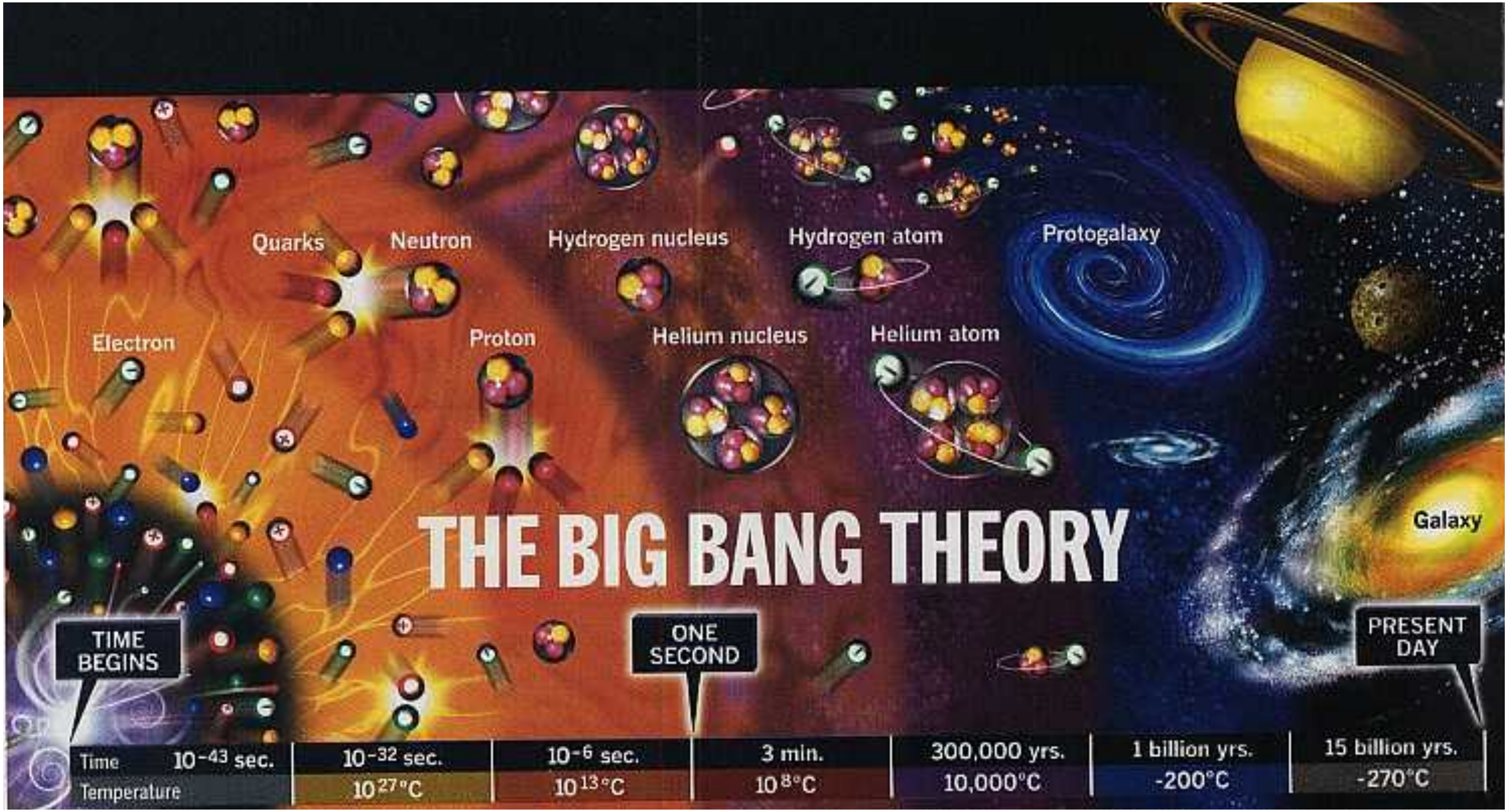
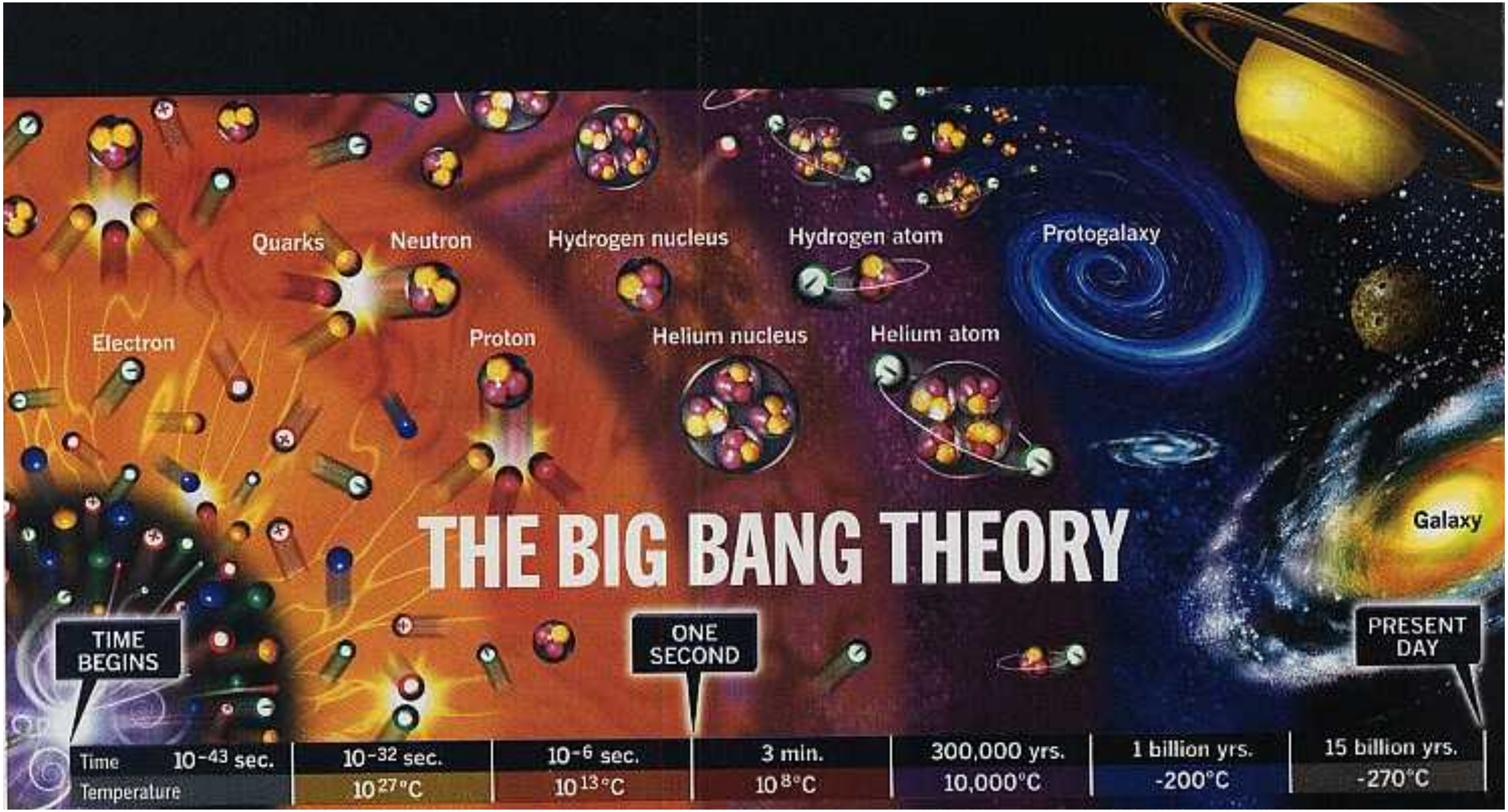
(Italy)



Neutral atoms (CMB)



Neutrinos decouple
(CνB)

Neutral atoms
(CMB)

Cosmological Relic 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 $\quad f_\nu(p,T) = \dfrac{1}{e^{p/T_\nu}+1} \qquad p_\nu \approx 10^{-4}\ \mathrm{eV}$

Number density today

$$n_\nu = \int \frac{d^3p}{(2\pi)^3} f_\nu(p,T_\nu) = \frac{3}{11} n_\gamma = \frac{6\zeta(3)}{11\pi^2} T_{CMB}^3 \cong \left(56\ \mathrm{cm}^{-3}\right)\times 6$$

Energy density today $\quad \Omega_\nu h^2 = \dfrac{\sum_i m_i}{94.1\ \mathrm{eV}}$

Since the energy of relic neutrino is so small collective interactions (“coherent”, order G_F or G_F^2) are a natural choice (however, the effect is not measurable !)

but…..

is direct detection possible ?

Since the energy of relic neutrino is so small collective interactions (“coherent”, order G_F or G_F^2) are a natural choice (however, the effect is not measurable !)

but…..

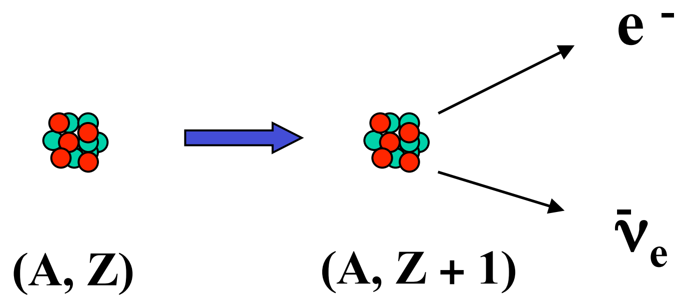
is direct detection possible ?

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

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

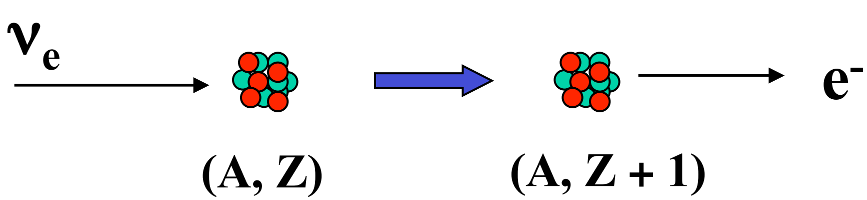
Known

Nuclear Beta decay



Possible

Neutrino Capture on a Beta Decaying Nucleus (NCB)



This process has no energy threshold !
Cross section is non vanishing !

NCB Cross Section Evaluation

The case of Tritium

Using the expression $$\sigma_{\mathrm{NCB}} v_\nu = \frac{G_\beta^2}{\pi} p_e E_e F(Z, E_e) C(E_e, p_\nu)_\nu$$

we obtain $$\sigma_{\mathrm{NCB}}(^3\mathrm{H}) \frac{v_\nu}{c} = (\ 7.7 \pm 0.2\ ) \times 10^{-45}\ \mathrm{cm}^2$$

where the error is due to Fermi and Gamow-Teller matrix element uncertainties

---

Using shape factors ratio $$\sigma_{\mathrm{NCB}} v_\nu = 2\pi^2 \ln 2 \frac{p_e E_e F(Z, E_e)}{f t_{1/2}}$$

$$\sigma_{\mathrm{NCB}}(^3\mathrm{H}) \frac{v_\nu}{c} = (\ 7.84 \pm 0.03\ ) \times 10^{-45}\ \mathrm{cm}^2$$

where the error is due only to uncertainties on Q_β and $t_{1/2}$

Relic Neutrino Detection

using $\beta^{\pm}$ decaying nuclei

In the case of Tritium we estimate that 7.5 neutrino capture events per year are obtained using a total mass of 100 g

In case of CνB gravitational clustering we expect a significant signal enhancement

m_ν (eV)	FD (events yr^{-1})	NFW (events yr^{-1})	MW (events yr^{-1})
0.6	7.5	90	150
0.3	7.5	23	33
0.15	7.5	10	12

FD = Fermi-Dirac NFW= Navarro,Frenk and White
MW=Milky Way (Ringwald, Wong)

Relic Neutrino Detection

signal to background ratio

The ratio between capture (λ_ν) and beta decay rate (λ_β) is obtained using the same nuclear shape factor parametrization

$$\frac{\lambda_\nu}{\lambda_\beta} = \frac{2\pi^2 n_\nu}{\mathcal{A}}$$

In the case of Tritium (and using n_ν=50) we found that

$$\lambda_\nu(^3\mathrm{H}) = 0.66 \cdot 10^{-23} \lambda_\beta(^3\mathrm{H})$$

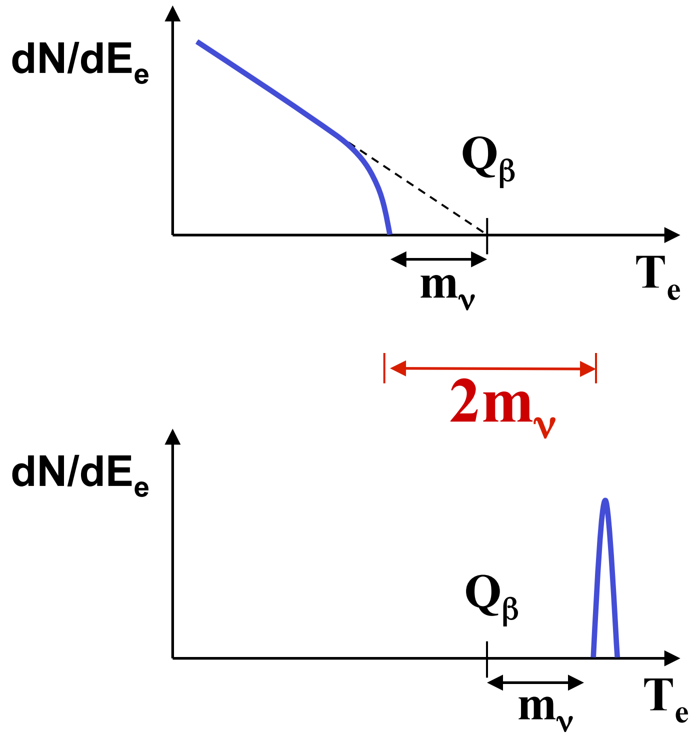
The effect of $m_\nu \neq 0$

Neutrino masses of the order of 1 eV are compatible with the present picture of our Universe exploiting $m_\nu \neq 0$

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

Nuclear Beta decay

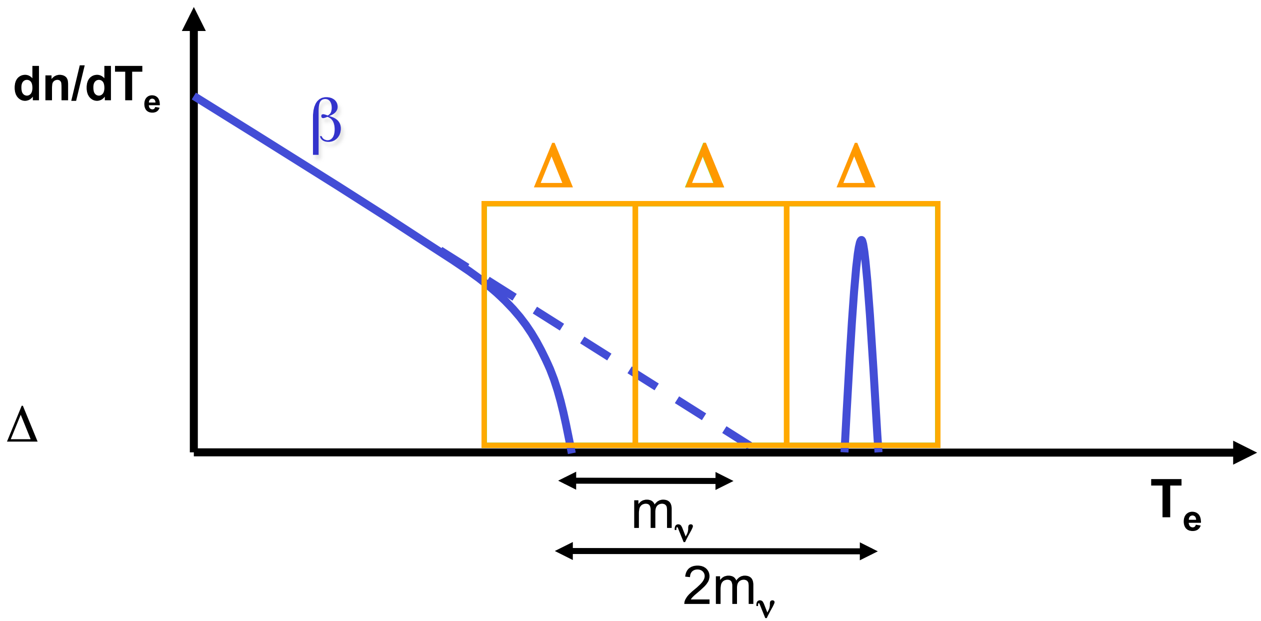
Neutrino Capture on a Beta Decaying Nucleus



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”

Relic Neutrino Detection

signal to background ratio



Observing the last energy bins of width Δ

$$\frac{S}{B} = \frac{9}{2}\zeta(3)\left(\frac{T_\nu}{\Delta}\right)^3 \frac{1}{(1+2m_\nu/\Delta)^{3/2}}\left[\frac{1}{\sqrt{2\pi}}\int_{\frac{2m_\nu}{\Delta}-\frac{1}{2}}^{\frac{2m_\nu}{\Delta}+\frac{1}{2}} e^{-x^2/2}dx\right]^{-1}$$

where the last term is the probability for a beta decay electron at the endpoint to be measured beyond the $2m_\nu$ gap

It works for $\Delta < m_\nu$

CνB detection using Tritium

Signal to background ratio depends crucially on the energy resolution (Δ) at the beta decay endpoint (It works 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 it would take one and a half year to observe a 5σ effect

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

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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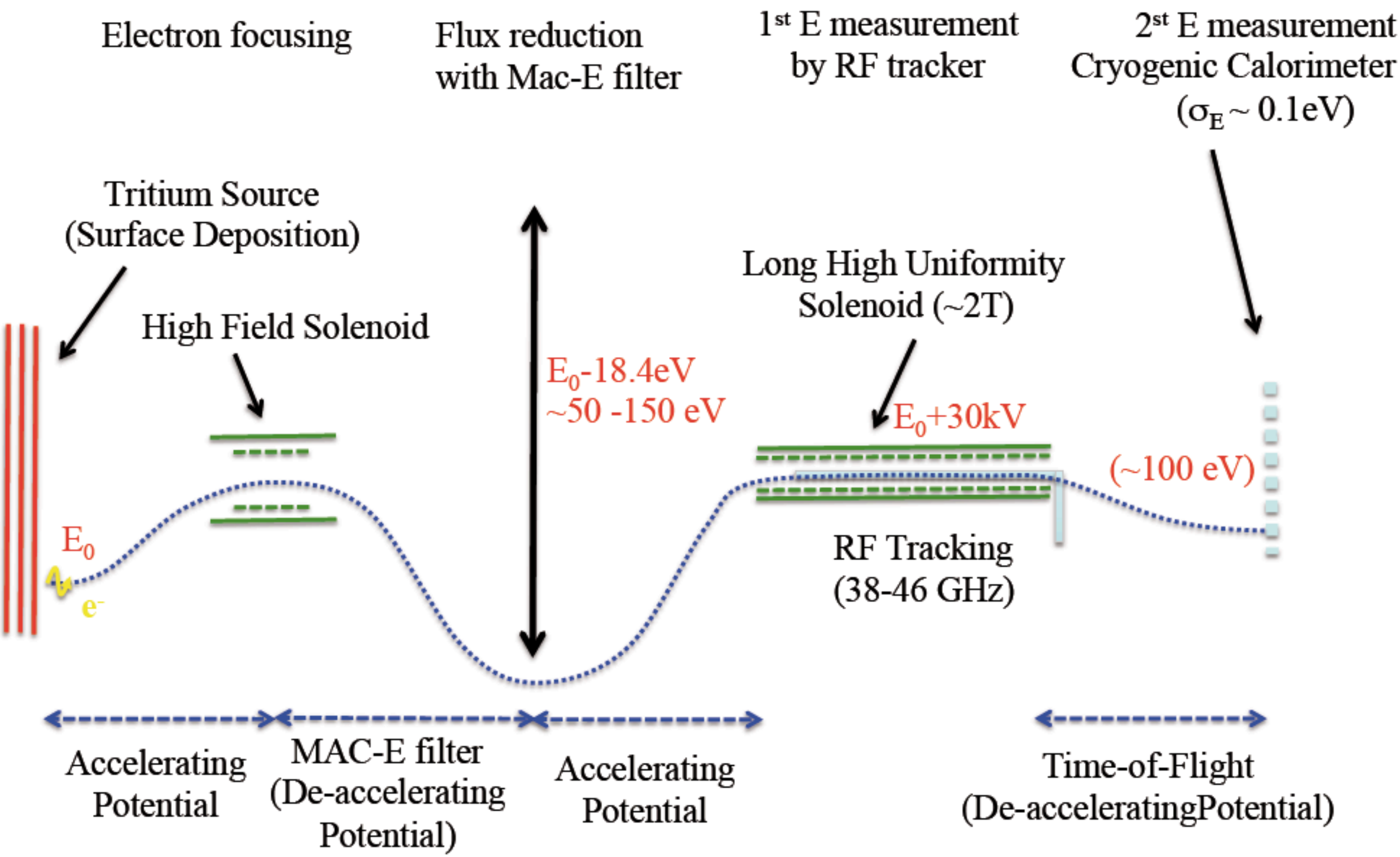
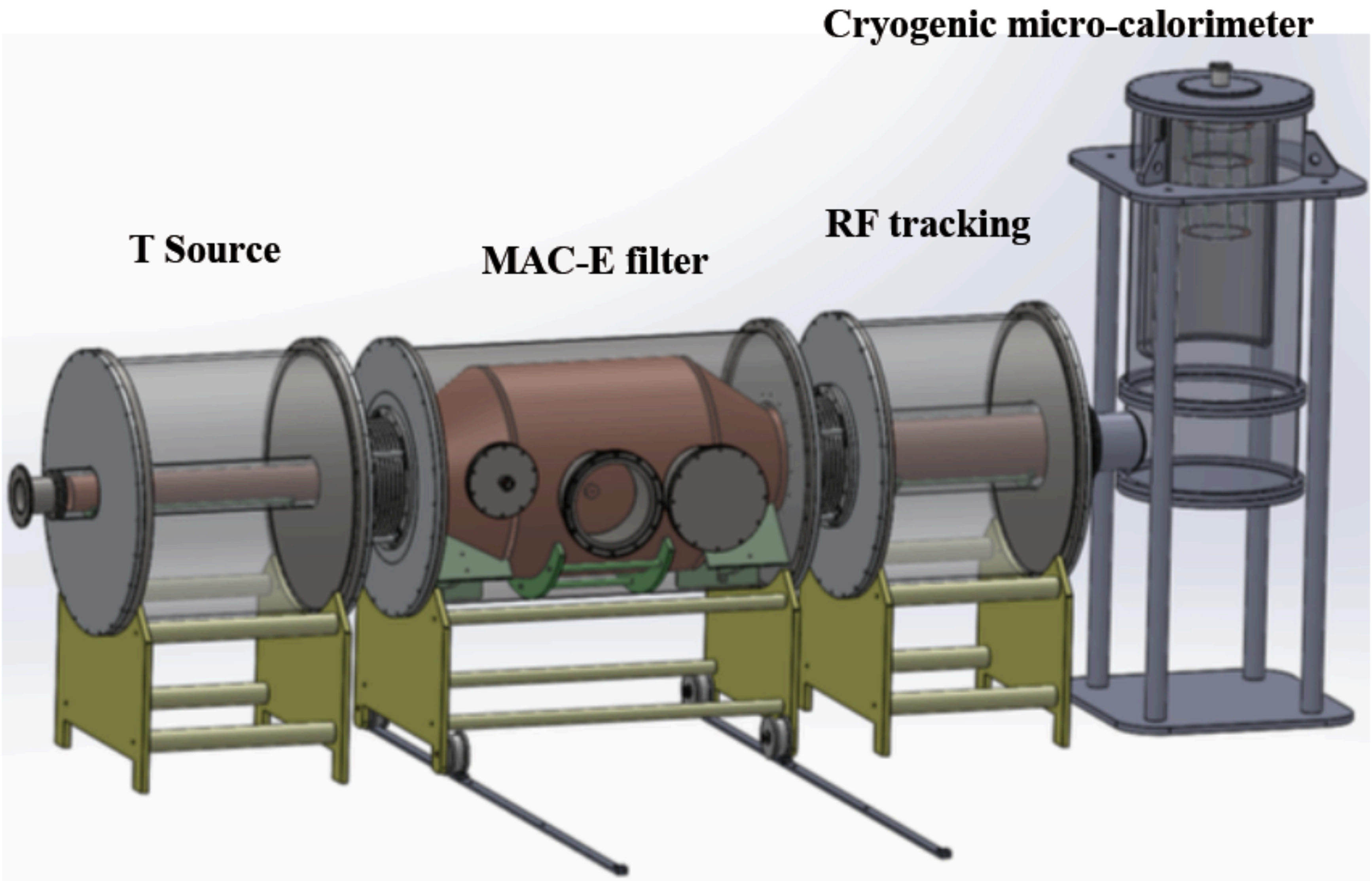
[6]Department of Physics, Columbia University

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

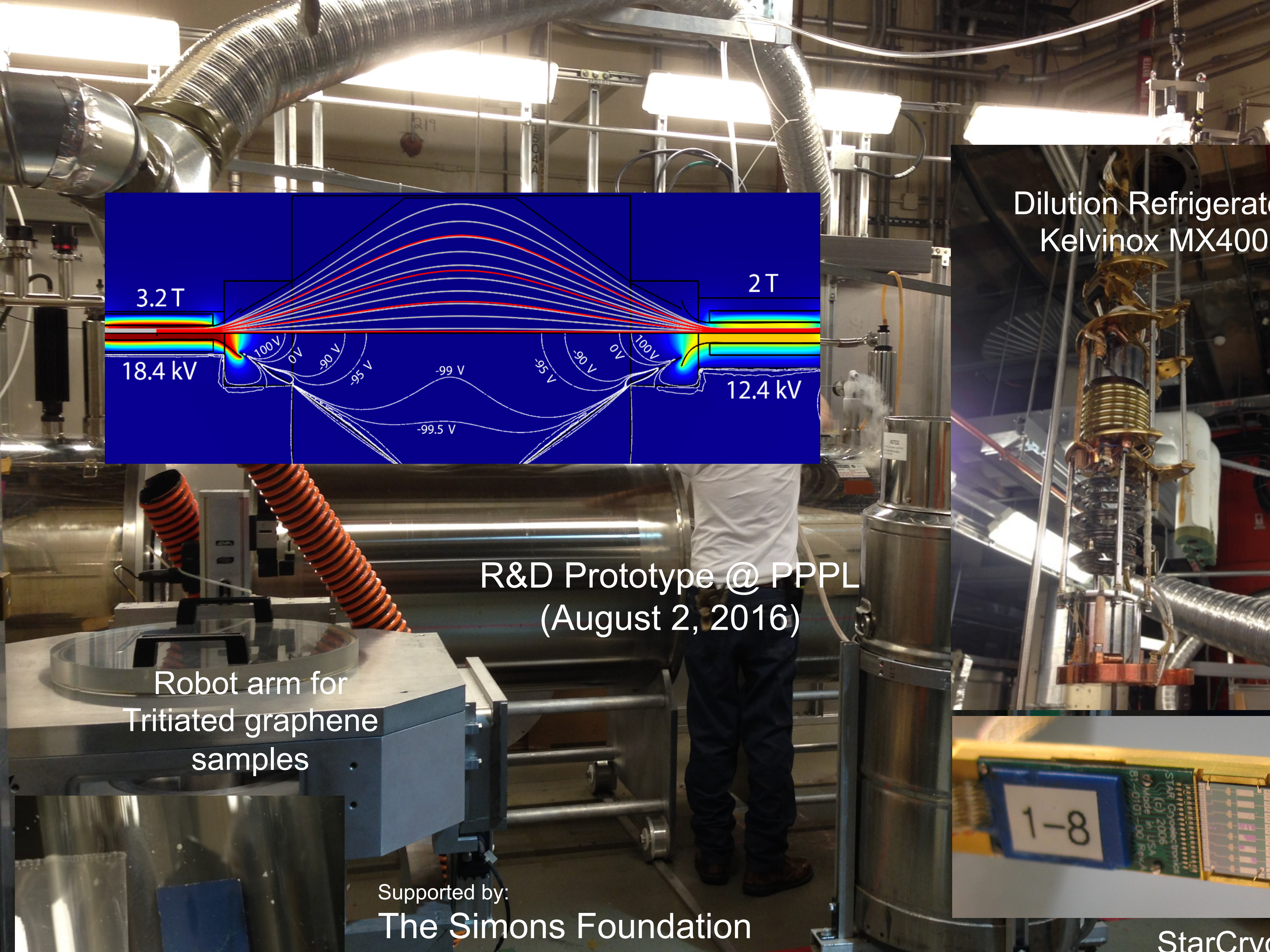
100 g T source + MAC-E filter + RF tagging + sub-eV resolution μ-cal



The PTOLEMY prototype
@ Princeton




R&D Prototype @ PPPL
(August 2, 2016)
Supported by:
The Simons Foundation
The John Templeton Foundation


3.2 T
18.4 kV
2 T
12.4 kV
100V
0V
-90 V
-95 V
-99 V
-99.5 V
-95 V
-90 V
0V
100V
Dilution Refrigerat
Kelvinox MX400
R&D Prototype @ PPPL
(August 2, 2016)
Robot arm for
Tritiated graphene
samples
1–8
Supported by:
The Simons Foundation

The PTOLEMY prototype

Three major challenges
towards the full scale PTOLEMY detector

- Reduce target induced E_e smearing (molecular effects)

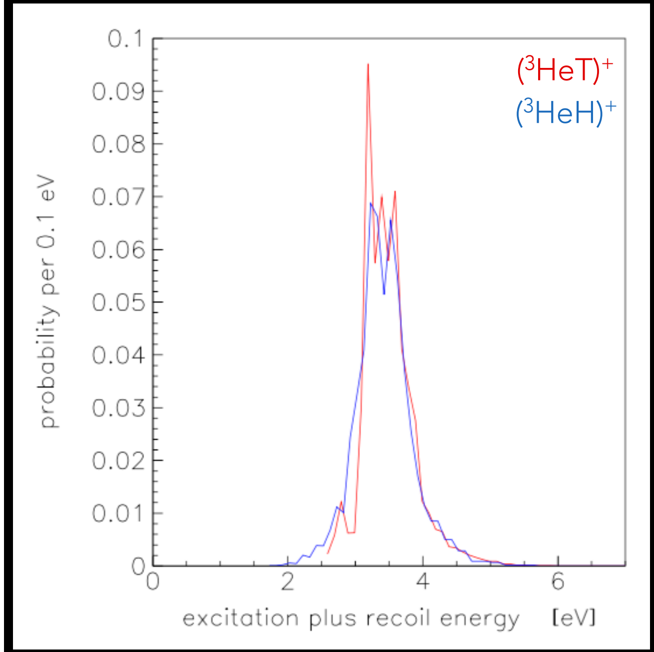
- Compress a 70m spectrometer length (KATRIN) down to cm scale and replicate it 10^4-10^6 times (lower precision since final measurement made by the microcalorimeter)

- Measure the energy spectrum directly with σ_E ~ O(0.1 eV) or better

Tritium target

Characteristics:

- High density and packing factor
- Weakly bound to substrate
- Low interaction probability
- Electron focusing to the (E,B) 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

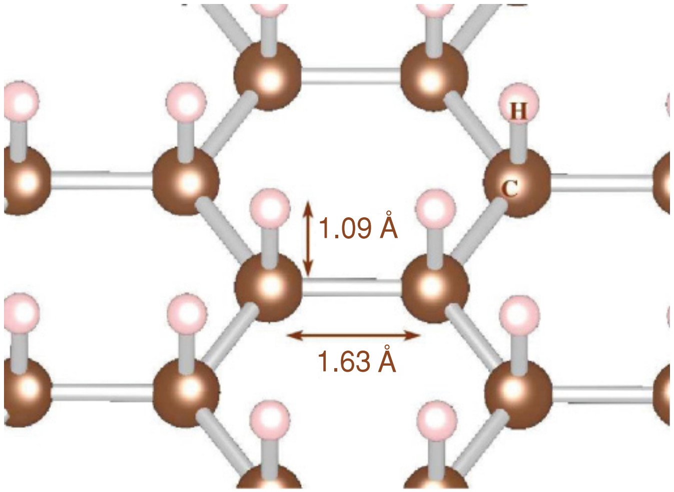
Single-sided (loaded on substrate) and planar (uniform bond length)

Binding Energy < 3 eV

Source strength with surface densities of ~1 Ci/cm^2 (100 μg/cm^2)

Semiconductor (Voltage Reference)

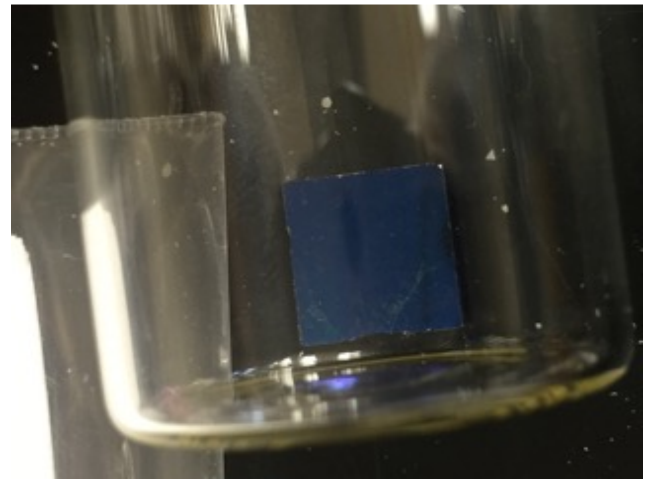
Polarized tritium (directionality?)

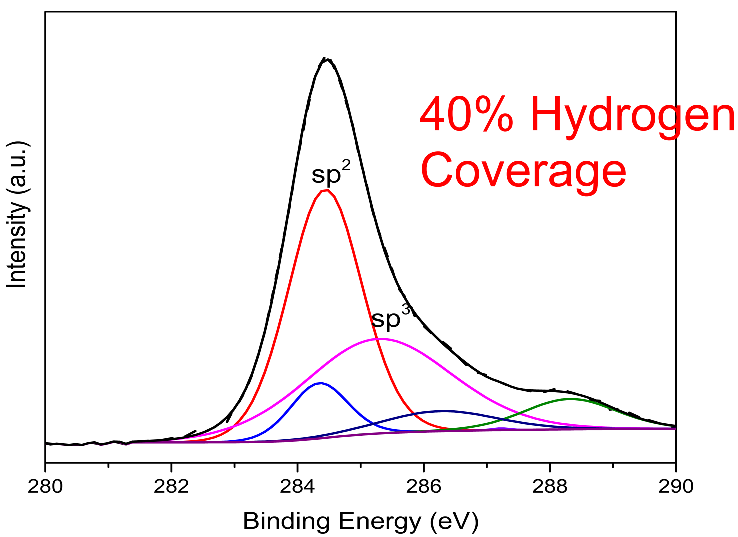


Tritiated graphene target

Samples produced at
Savannah River National Laboratory

Ready to be tested…





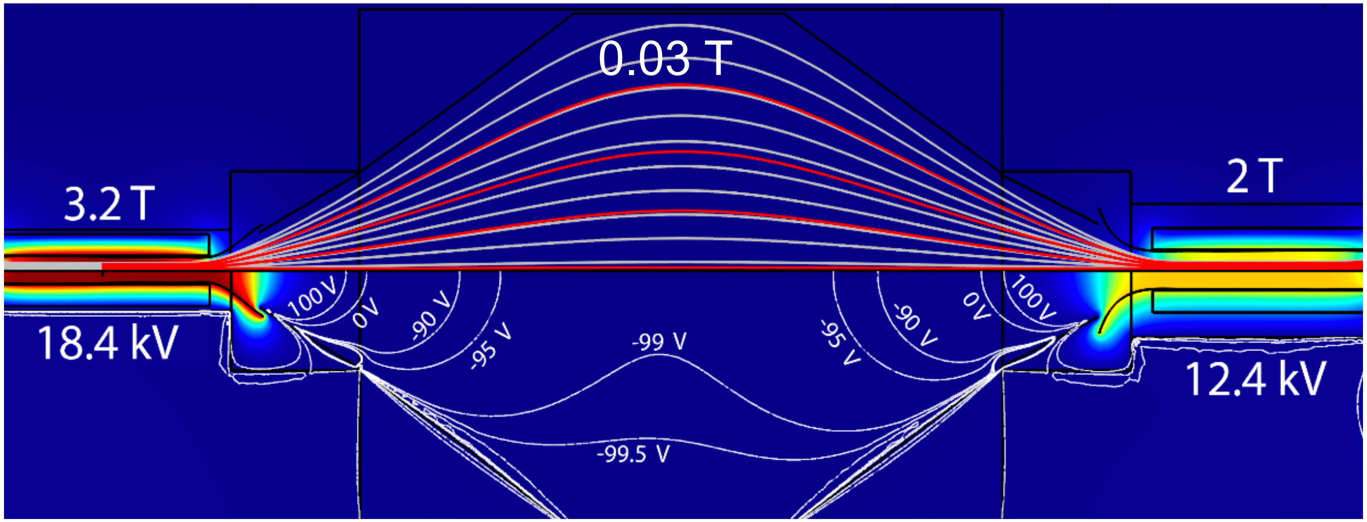
Cold Plasma Loading (PPPL)
XPS (X-Ray Photoelectron Spectroscopy)
Analysis: sp2 is from unhydrogenated C atoms. sp3 is hydrogenated C atoms. The area ratio of sp2 and sp3 is used to calculate H coverage

MAC-E filter

Low magnetic gradient adiabatically transforms cyclotron trajectories into longitudinal motion

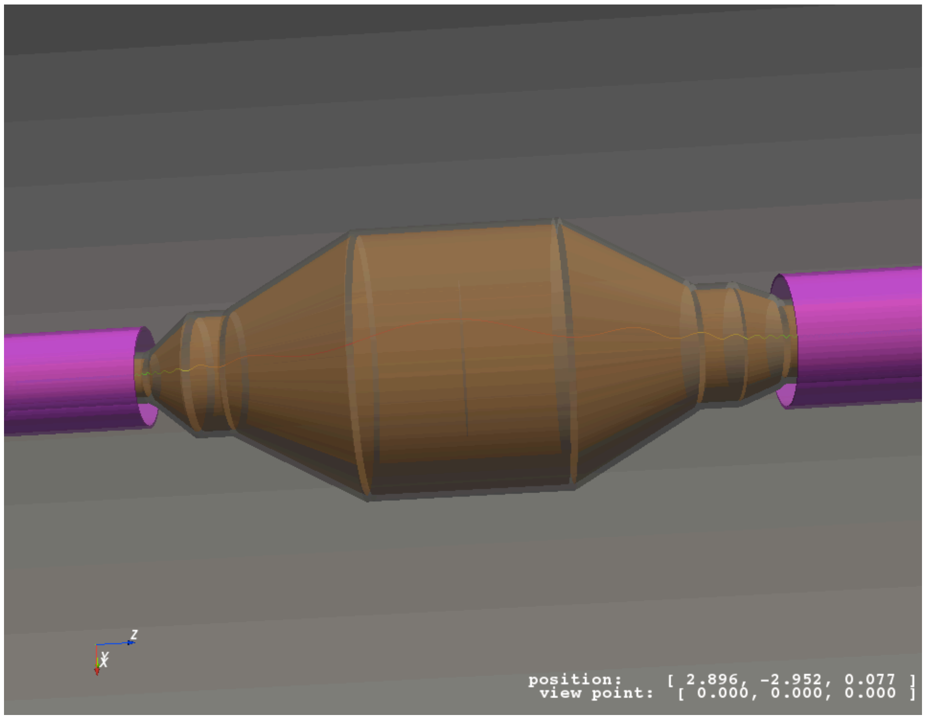
$$\mu = \frac{E_{\perp}}{B} \qquad \frac{\Delta E}{E} = \frac{B_{\min}}{B_{\max}}$$

Electric field sets the energy cutoff

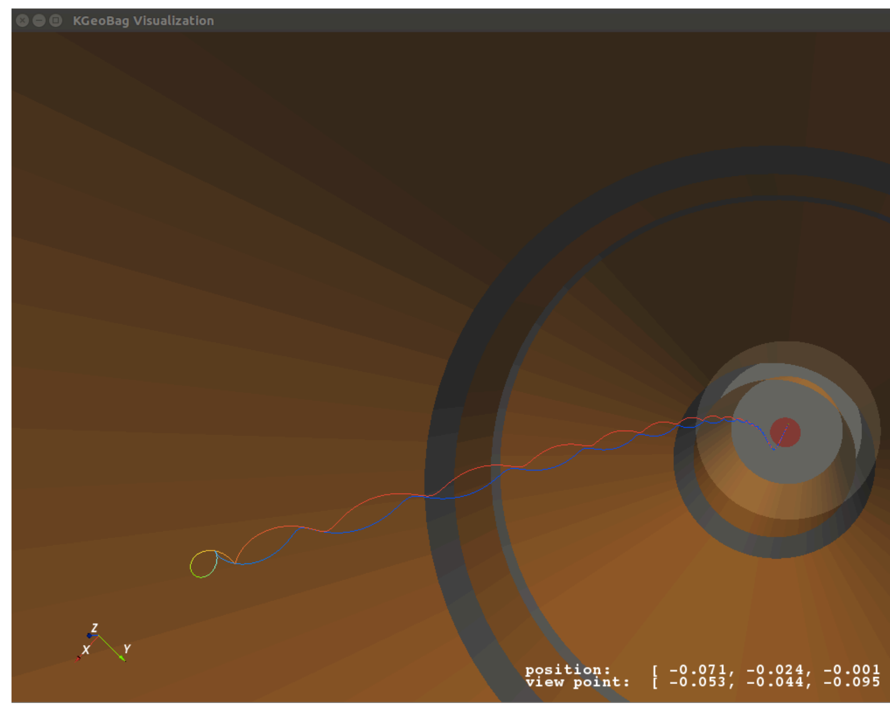


If the threshold is set at ~1eV the event rate reduction is ~ $(\Delta E/Q)^3 = 1.55\ 10^{-13}$
(for comparison, the activity of 1 g of T is of $3.6\ 10^{+14}$ Hz)

PTOLEMY prototype
MAC-E filter performances analysis



Kassiopeia package
(KATRIN Collaboration)

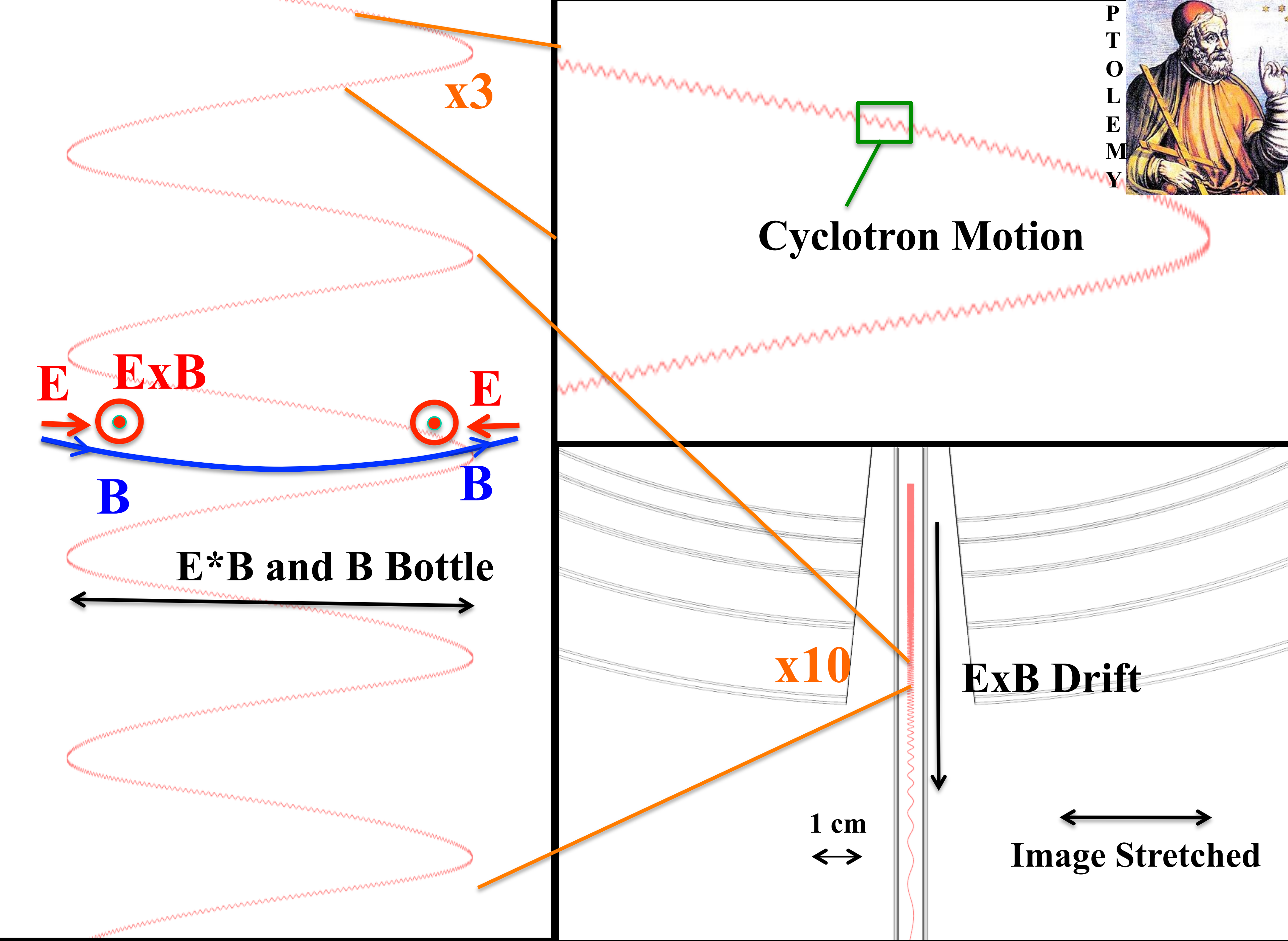


New ExB filtering design

In traditional MAC-E filters, as B drops along the longitudinal kinetic energy (KE) of the electron, transverse KE → longitudinal and E*B term trades total KE with potential energy – electrons below filter cut-off bounce (reverse longitudinal momentum) due to E*B

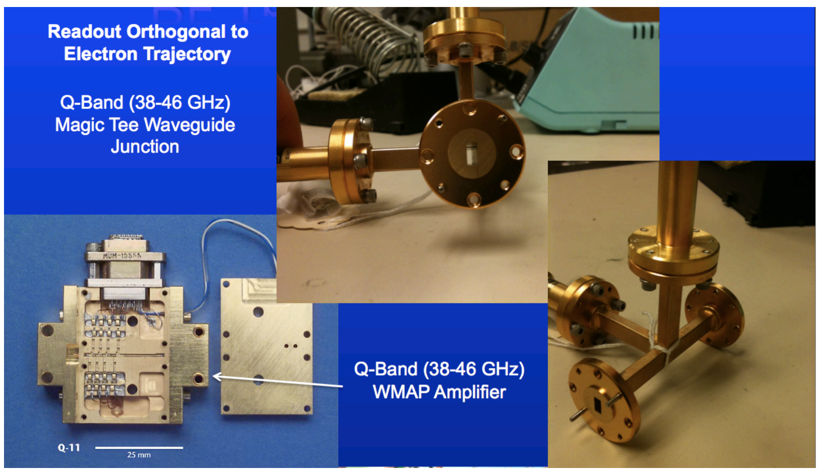
PTOLEMY: electrons enter at a fixed reference voltage into one end of an E*B bottle, as they bounce back and forth, they trade KE for potential energy as they slowly ExB drift vertically in the voltage potential and also drift into lower B field from transverse ExB drift where they exchange transverse KE → longitudinal

Simulation studies shows promising results


x3
PTOLEMY
Cyclotron Motion
E
ExB
E
B
B
E*B and B Bottle
x10
ExB Drift
1 cm
Image Stretched

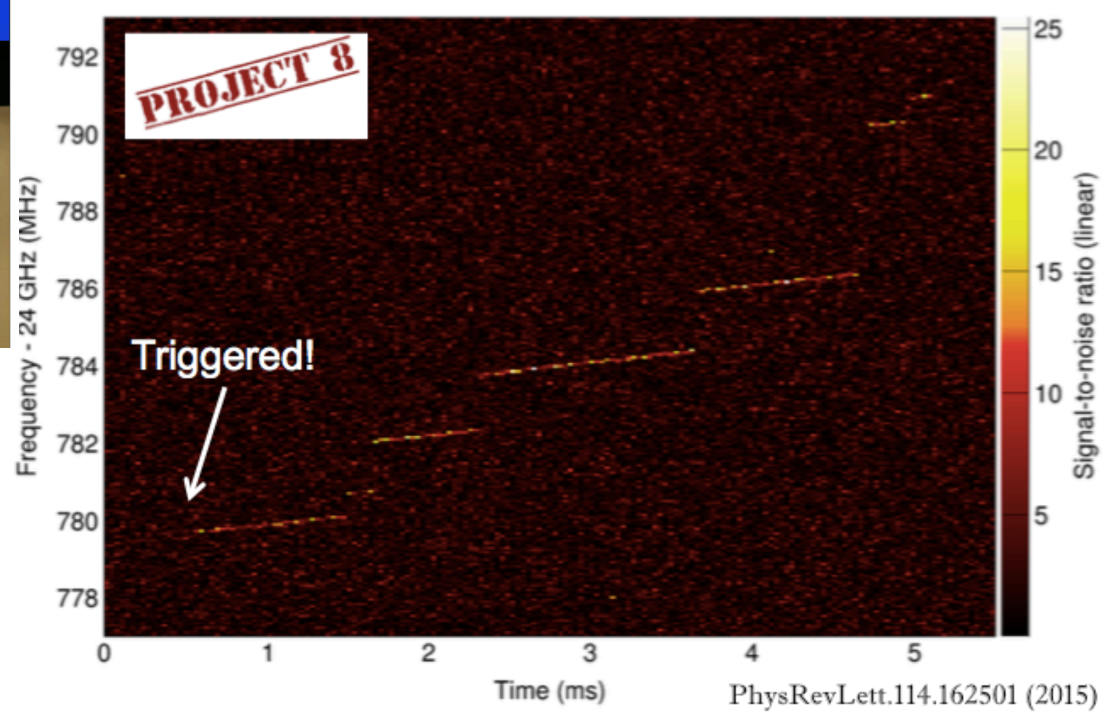
RF tracking and time-of-flight

Thread electron trajectories (magnetic field lines) through an array of Project-8 type antennas with wide bandwidth (few x10^{-5}) to identify cyclotron RF signal in transit times of order 0.2 msec.



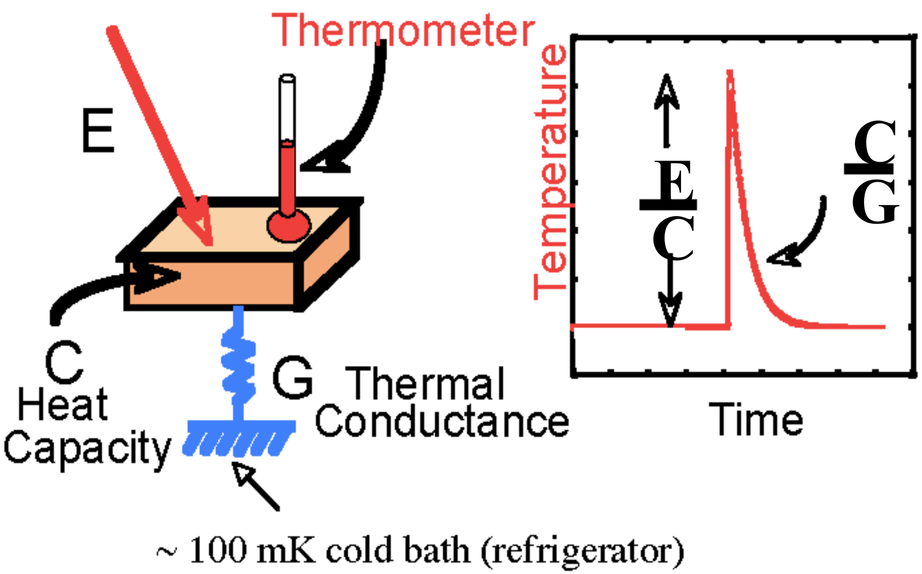
First detection of single electron cyclotron radiation

Phys.Rev.Lett. 114(2015)162501



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

Cryogenic Transition Edge Sensors (TES)

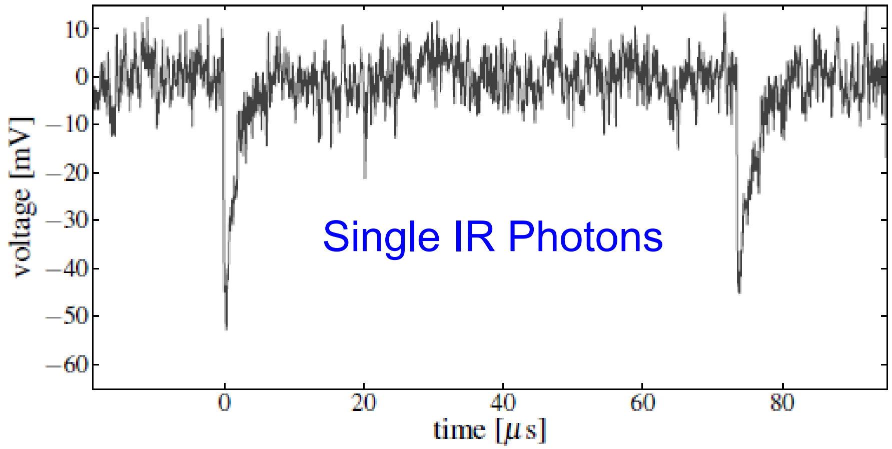


10÷100eV electron can be stopped with very small C (10^{-4} smaller than for X-ray)

Fast time response
Bandwidths of ~1 MHz to record ~10 kHz of electrons hitting the individual sensors

Microcal Energy Resolution

- TES microcalorimeters resolution of 0.15eV@100eV (~100mK) are no longer the focus
- Most TES work is headed toward optical with extremely low heat capacitance (small absorber thickness)



Example:

IR TES cameras
~0.3 eV resolution achieved
at 0.8 eV for single IR photons

- Recent developments shows resolutions of 0.05 eV @ 300 mK !!!

(Monticone and co-workers – INRIM)

This was “unrealistic” 10 years ago !!

Three major challenges

- Reduce target induced E_e smearing (molecular effects)
  New source (Tritiated-Graphene or Cryogenic Au(111))

- Compress a 70m spectrometer length (KATRIN) down to cm scale and replicate it 10^4-10^6 times (lower precision since final measurement made by the microcalorimeter)
  - New ExB filter concept
  - RF tag/triggering (Project 8 development)
  - Graphene-FET (G-FET) as a potential trigger system

  Phys. Lett. B 772(2017)239

- Measure the energy spectrum directly with $\sigma_E \sim O(0.1\ \mathrm{eV})$ or better
  High-resolution electron microcalorimeter

PTOLEMY prototype programme

Re-commission Kelvinox MX400 dilution refrigerator

Installation of StarCryo calorimeter

Re-commission magnets

Install central vacuum tank and HV system for MAC-E filter

Install graphene target test sample

Data-taking tests with full setup scheduled by the end of the year

The prototype will be moved to Laboratori Nazionali del GranSasso (ITALY) in 2018 to perform tests in a background free underground environment

PTOLEMY programme

A lot of R&D to be done and and a lot smart ideas still needed but…

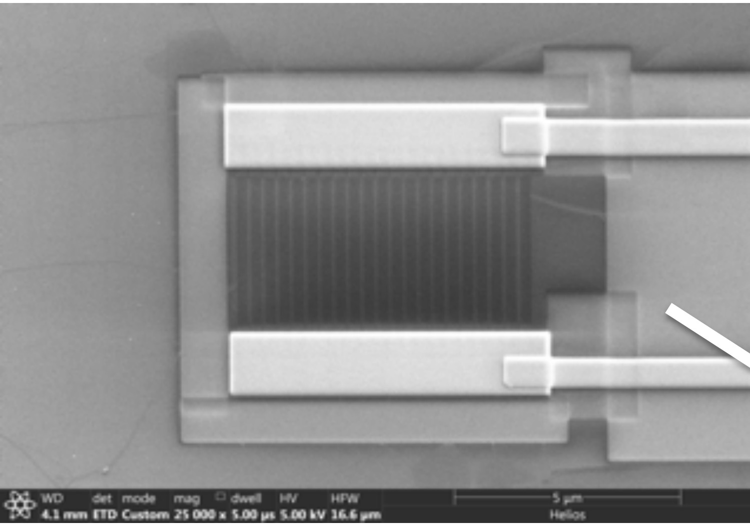
...what was “impossible” a few years ago is now merely “challenging”

The PTOLEMY “kick-off” meeting will take place in LNGS (Italy) on 11-12 December in order to start focusing on the full scale project

(enthusiastic collaborators are welcome !)

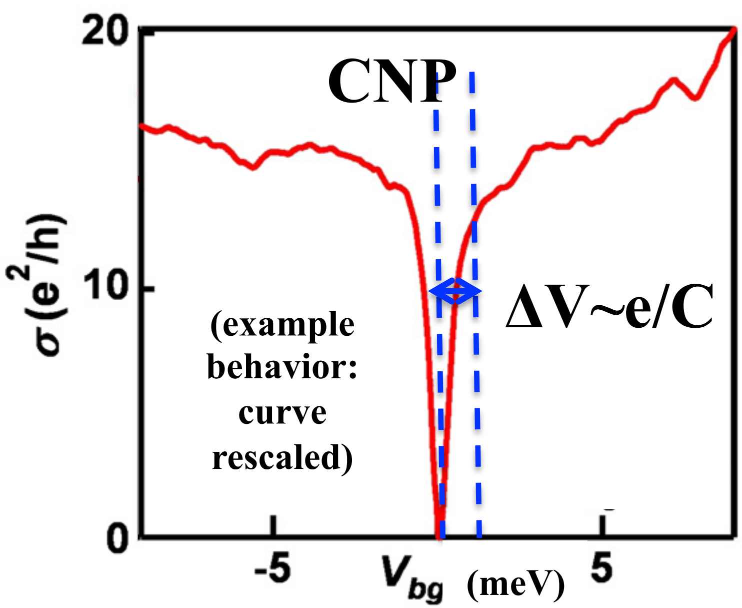
Thank you

G-FET

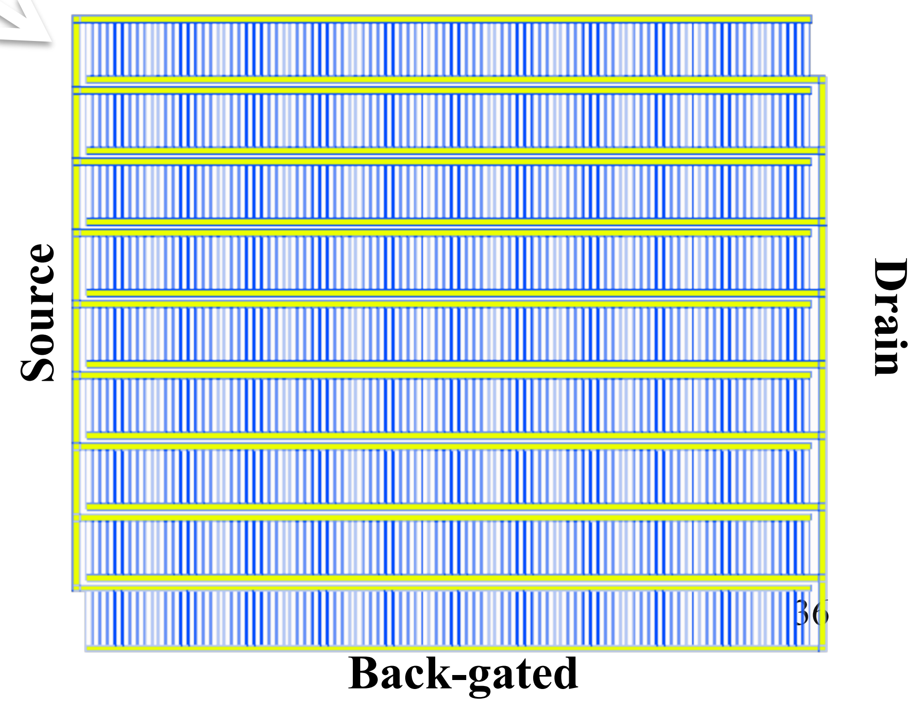


Principles of Operation:

- Tunable meV band gap set by nanoribbon width (E_{gap} ~ 0.8eV/width[nm])
- Large jump in conductivity (~10^{10} charge carriers) relative to charge neutrality point under the field-effect from a single electron scatter



Scalability to Interdigitated Capacitor



PTOLEMY-G^3

- Directional Detection of Dark Matter with 2D target
  - Hochberg, et. al, 2017 Phys.Lett.B 772(2017)239

    http://arxiv.org/abs/1606.08849
- Graphene field-effect transistors (G-FETs) arranged into a fiducialized volume of stacked planar arrays – Graphene cube (G^3)
  - Unprecedented sensitivity to electron recoil, at the level of single charge detection
- G-FETs provide tunable meV band gaps and provide high-granularity particle tracking when configured into arrays
  - A narrow, vacuum-separated front-gate of the G-FET imposes a kinematic discrimination on the maximum electron recoil energy, and the FET-to-FET hopping trajectory of an ejected electron indicates the scattering direction, shown to be correlated to the dark matter wind
- In this experiment we look for MeV dark matter scattering events that liberate an electron from the graphene target, in the absence of any other activity in the G^3

Detection: G_F

Stodolsky effect: energy split of electron spin states in the ν background

requires ν chemical potential (Dirac) or net helicity (Majorana)

requires breaking of isotropy (Earth velocity)

results depend on Dirac/Majorana,relativistic/non relativistic, clustered/unclustered

Duda et al '01

$$\Delta E \approx G_F g_A \vec{s} \cdot \vec{\beta}_{\oplus} (n_\nu - \overline{n}_\nu)$$

Torque on frozen magnetized macroscopic piece of material of dimension R

$$\mathbf{a} \approx 10^{-27} \left(\frac{100}{A}\right)\left(\frac{cm}{R}\right)\left(\frac{\beta_{\oplus}}{10^{-3}}\right)\left(\frac{n_\nu - \overline{n}_\nu}{100\, cm^{-3}}\right) cm\, s^{-2}$$

Presently Cavendish torsion balances: $\mathbf{a} \approx 10^{-12}\, cm\, s^{-2}$

Detection: G_F^2

ν-Nucleus collision: net momentum transfer due to Earth peculiar motion

$$\sigma_{\nu N} = G_F^2 E_\nu^2$$

$$a = n_\nu v_\nu \frac{N_A}{A} \sigma_{\nu N} \Delta p$$

$$\Delta p = \beta_\oplus E_\nu$$

$$\Delta p = \beta_\oplus m_\nu$$

$$\Delta p = \beta_\oplus T_\nu$$

$$\Rightarrow \quad \mathbf{a \approx (10^{-46} - 10^{-54}) \frac{A}{100} \, cm\, s^{-2}}$$

Coherence enhancement

$$\lambda_\nu \approx 1/T_\nu \quad - \quad 1/\mathrm{m}_\nu \approx mm \qquad N_c = \frac{N_A}{A} \rho \lambda_\nu^3$$

Zeldovich and Khlopov '81

Smith and Lewin '83

NCB Cross Section

a new parametrization

Beta decay rate $$\lambda_\beta = \frac{G_\beta^2}{2\pi^3} \int_{m_e}^{W_o} p_e E_e F(Z, E_e) C(E_e, p_\nu)_\beta E_\nu p_\nu \, dE_e$$

NCB $$\sigma_{\mathrm{NCB}} v_\nu = \frac{G_\beta^2}{\pi} p_e E_e F(Z, E_e) C(E_e, p_\nu)_\nu$$

The nuclear shape factors C_β and C_ν both depend on the same nuclear matrix elements

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

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

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)

Example: NCB Cross Section

on $\beta^{\pm}$ nuclei for different types of decay transitions

- Superallowed transitions $$\sigma_{\mathrm{NCB}} v_\nu = 2\pi^2 \ln 2 \frac{p_e E_e F(Z, E_e)}{f t_{1/2}}$$

- This is a very good approximation also for allowed transitions since $$\frac{C(E_e, p_\nu)_\beta}{C(E_e, p_\nu)_\nu} \simeq 1$$

- *i-th* unique forbidden

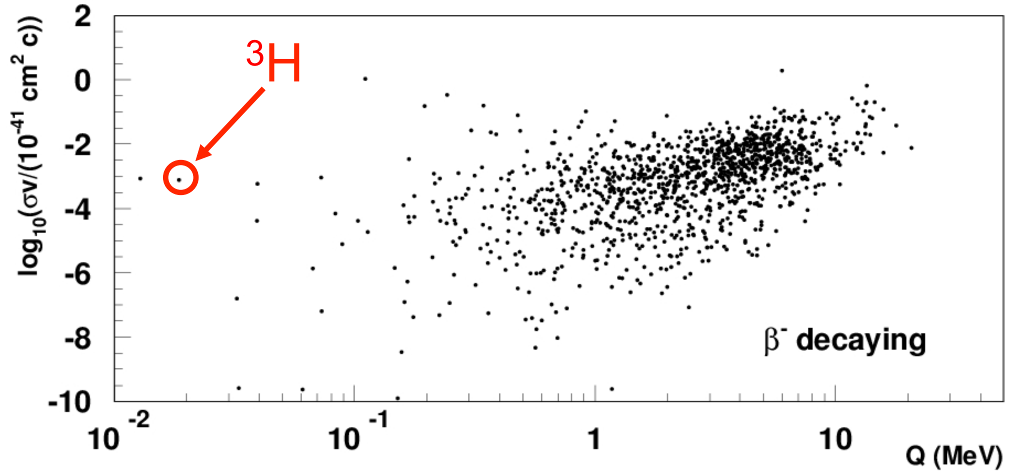
$$C(E_e, p_\nu)^i_\beta = \left[\frac{R^i}{(2i+1)!!}\right]^2 \left| {}^A F^{(0)}_{(i+1)\, i\, 1} \right|^2 u_i(p_e, p_\nu)$$

$$\mathcal{A}_i = \int_{m_e}^{W_o} \frac{u_i(p'_e, p'_\nu) p'_e E'_e F(Z, E'_e)}{u_i(p_e, p_\nu) p_e E_e F(Z, E_e)} E'_\nu p'_\nu \mathrm{d}E'_e$$

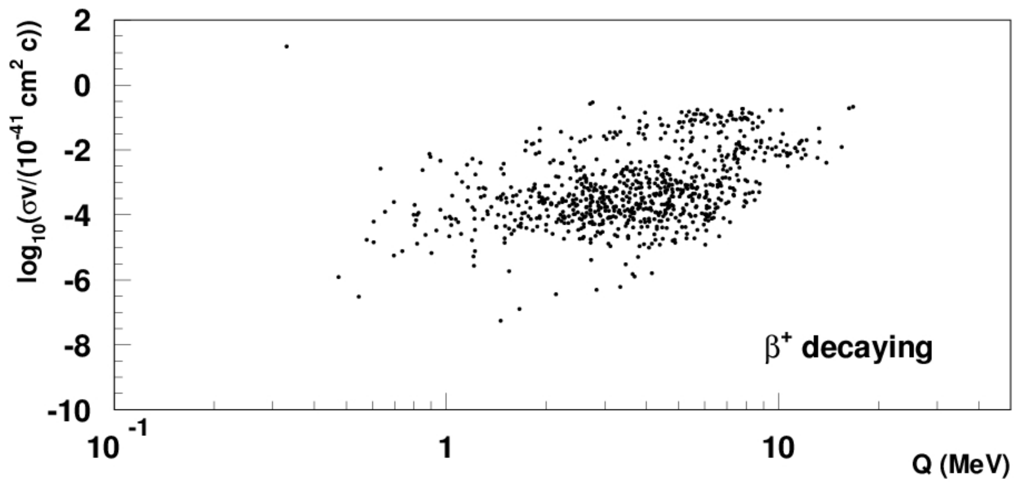
NCB Cross Section Evaluation

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