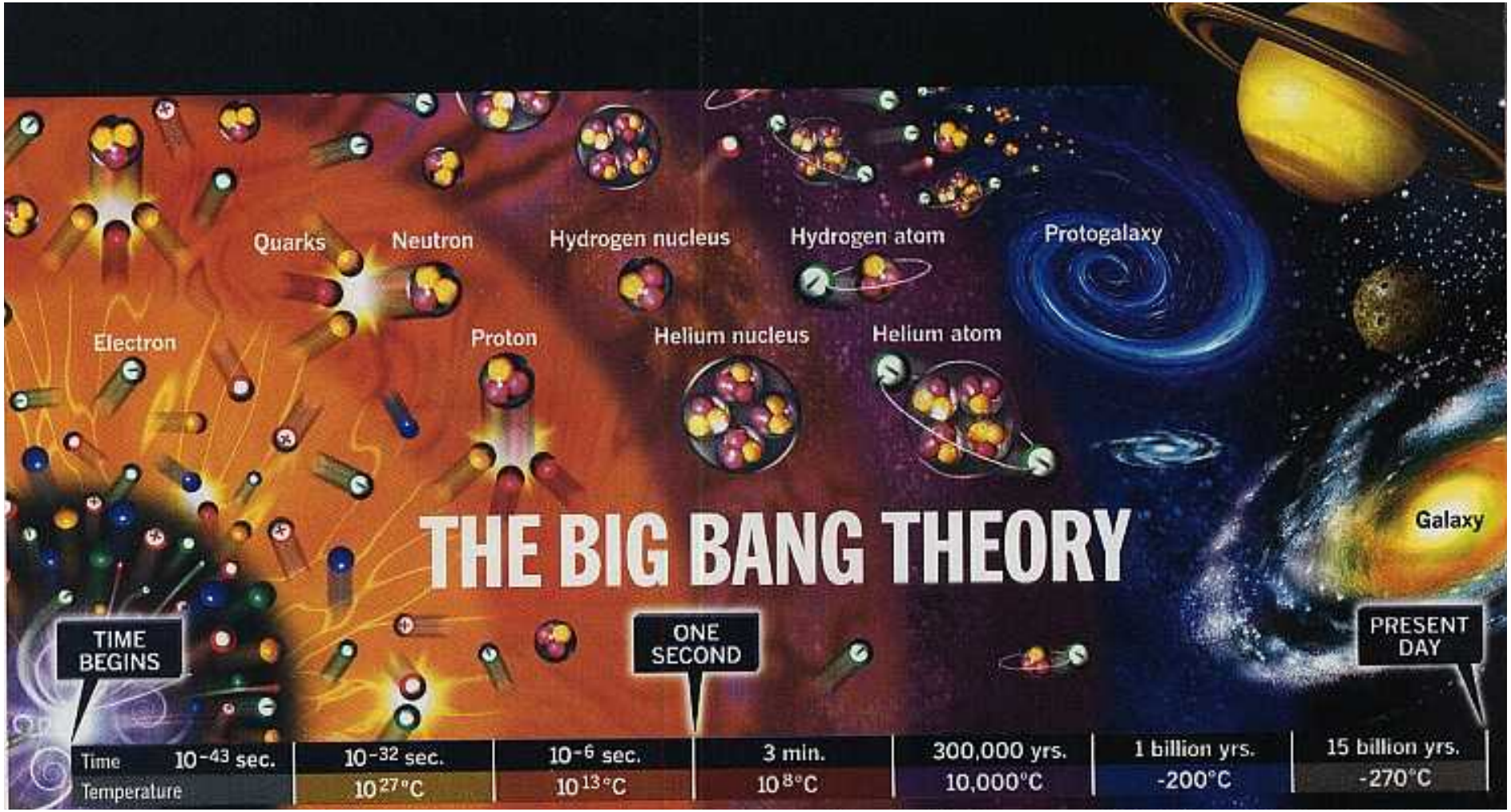
ICHEP 2018 Seoul, July 6th, 2018

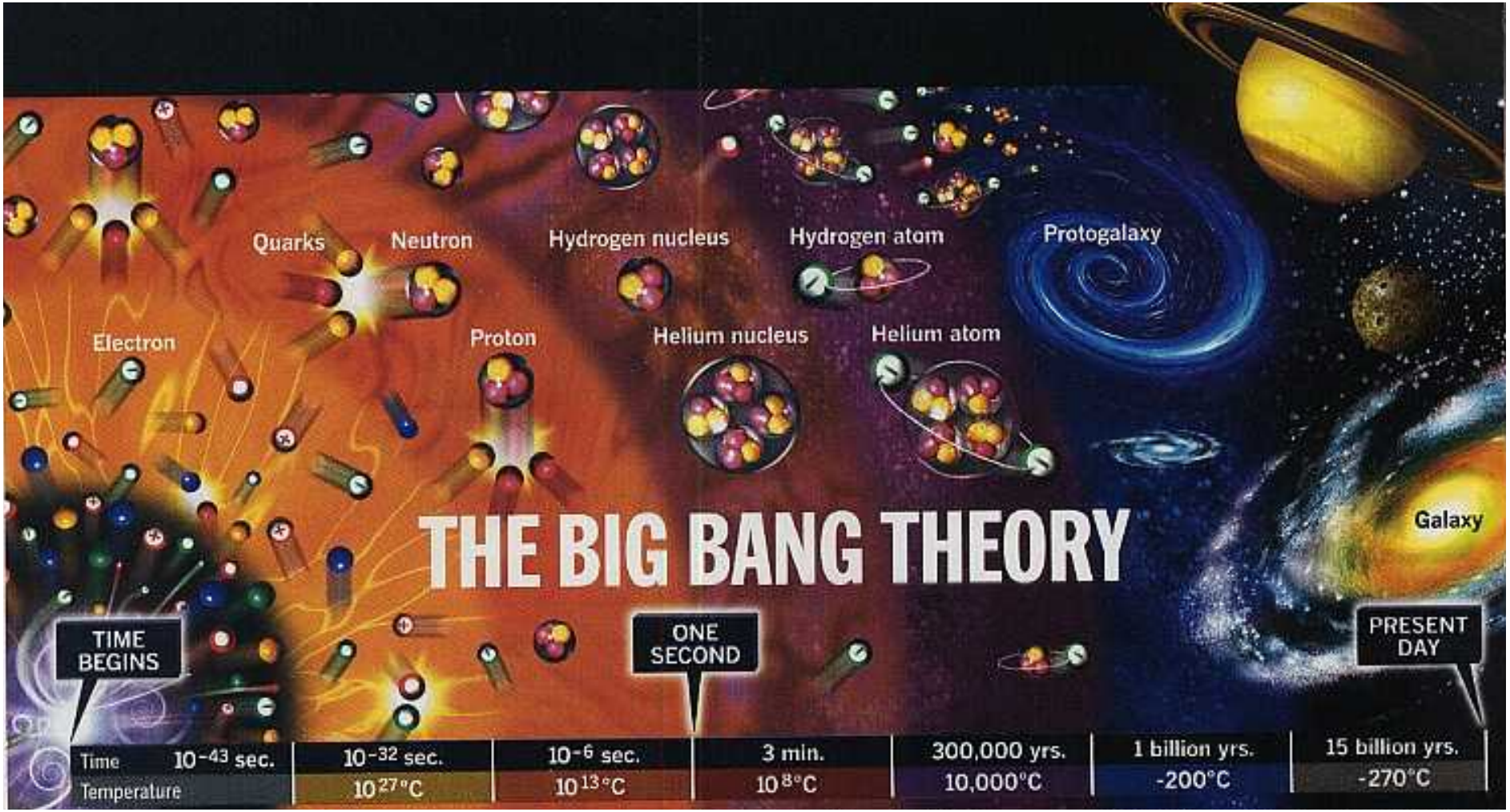
The PTOLEMY experiment
Towards Cosmological Relic Neutrino detection and directional Dark Matter search

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

on behalf of the PTOLEMY Collaboration



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

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 $$\Omega_\nu h^2 = \frac{\sum_i m_i}{94.1\ \mathrm{eV}}$$

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 <u>direct</u> 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…..

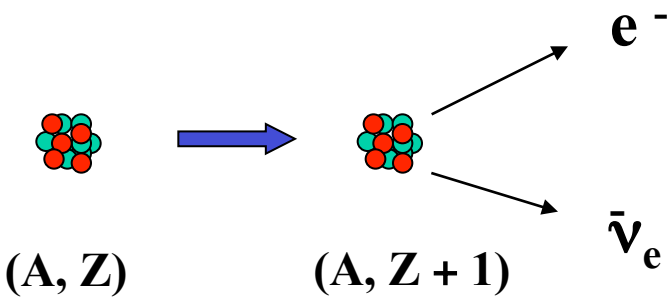
is <u>direct</u> detection possible ?

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

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

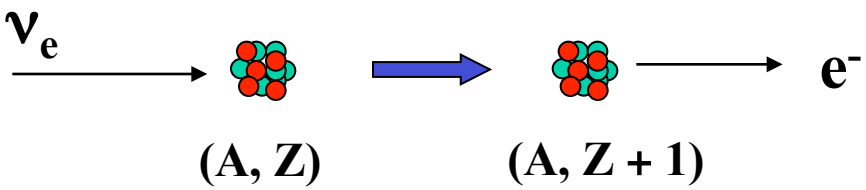
Known

Nuclear Beta decay



Possible

Neutrino Capture on a Beta Decaying Nucleus (NCB)



This process has no energy threshold !
Cross section is non vanishing !
Fixed initial energy and 2 body decay !

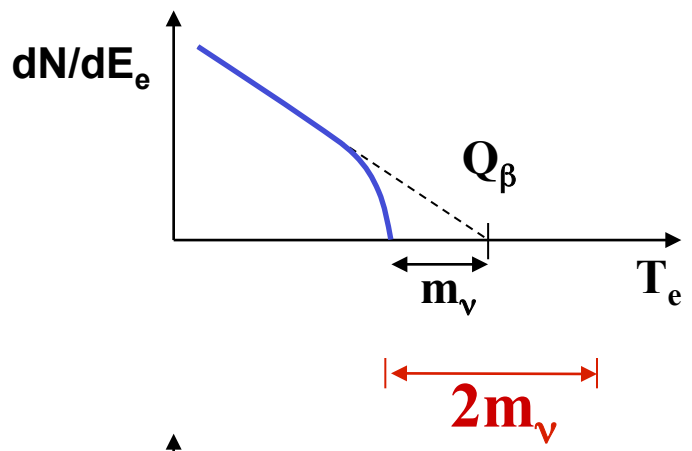
The effect of $m_\nu \neq 0$

Neutrino masses of the order of 1 eV are compatible with the present picture of our Universe

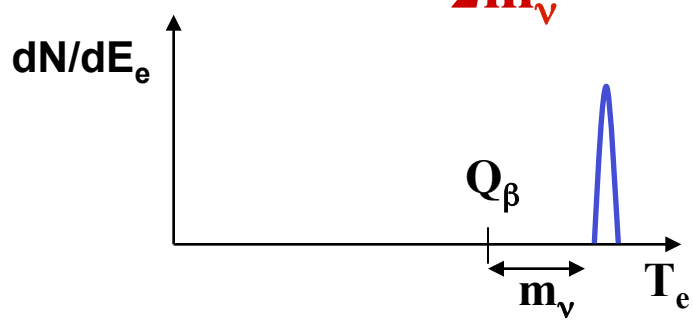
exploiting $m_\nu \neq 0$

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”

CνB detection using Tritium

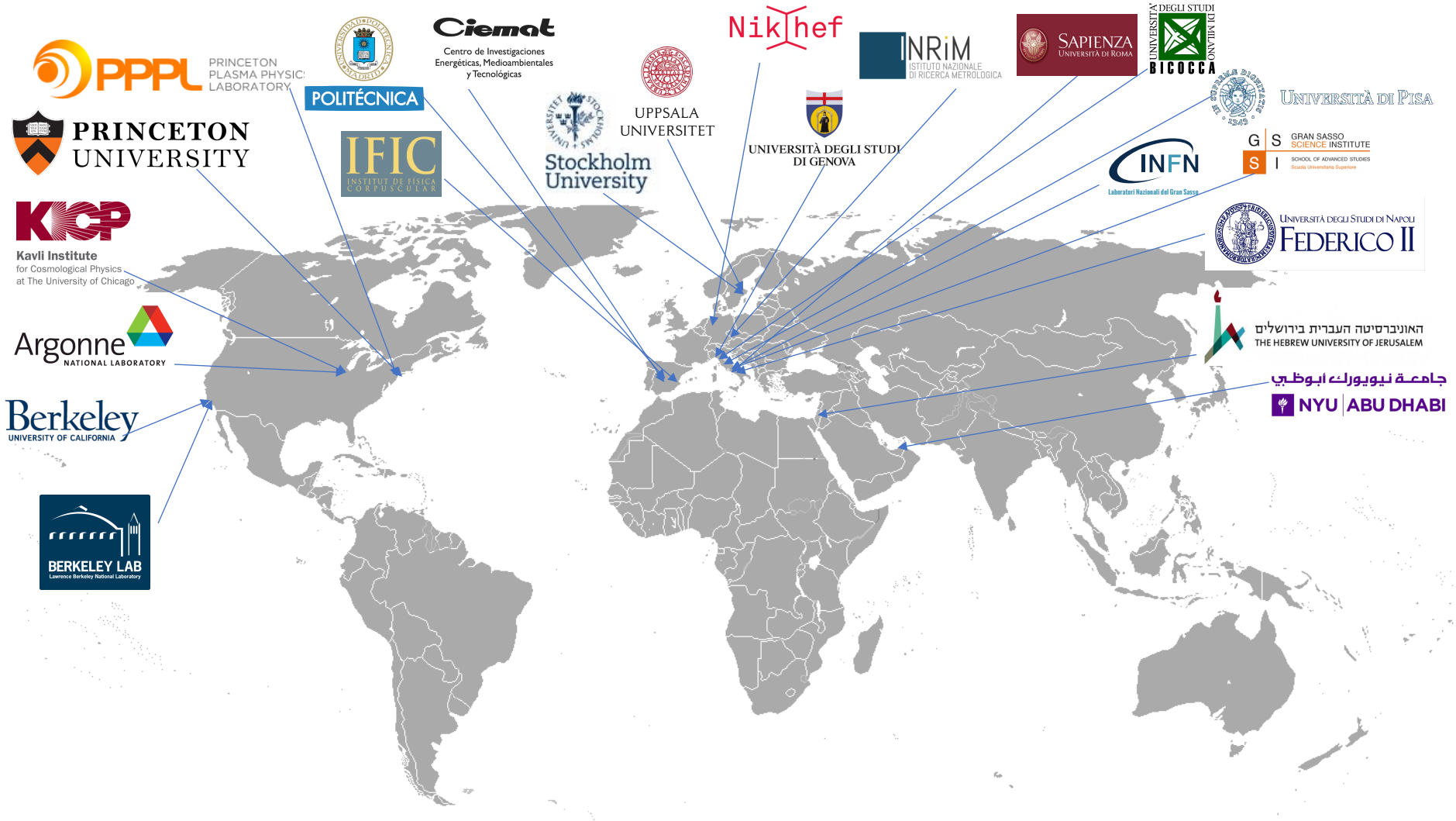
Signal to background ratio depends crucially on the energy resolution (Δ) at the beta decay endpoint

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

The PTOLEMY Collaboration



Letter of Intent to the Laboratori Nazionali del GranSasso (Italy)

PTOLEMY: A Proposal for Thermal Relic Detection of Massive Neutrinos and Directional Detection of MeV Dark Matter

E. Baracchini[3], M.G. Betti[11], M. Biasotti[5], F. Calle-Gomez[15], G. Cavoto[10,11], C. Chang[22,23], A.G. Cocco[7], A.P. Colijn[13], J. Conrad[18], N. D'Ambrosio[2], M. Faverzani[6], A. Ferella[18], P. Fernandez de Salas[16], E. Ferri[6], P. Garcia[14], G. Garcia Gomez-Tejedor[15], S. Gariazzo[17], F. Gatti[5], C. Gentile[25], A. Giachero[6], J. Godmundsson[18], Y. Hochberg[1], Y. Kahn[26], M. Lisanti[26], C. Mancini-Terracciano[10], G. Mangano[7], L.E. Marcucci[9], C. Mariani[11], G. Mazzitelli[4], M. Messina[20], A. Molinero-Vela[14], E. Monticone[12], A. Nucciotti[6], F. Pandolfi[10], S. Pastor-Carpi[17], C. Pérez de los Heros[19], O. Pisanti[7,8], A. Polosa[10,11], A. Puiu[6], M. Rajteri[12], R. Santorelli[14], K. Schaeffner[3], C.G. Tully[26], Y. Raitses[25], N. Rossi[10], F. Zhao[26], K.M. Zurek[21,22]

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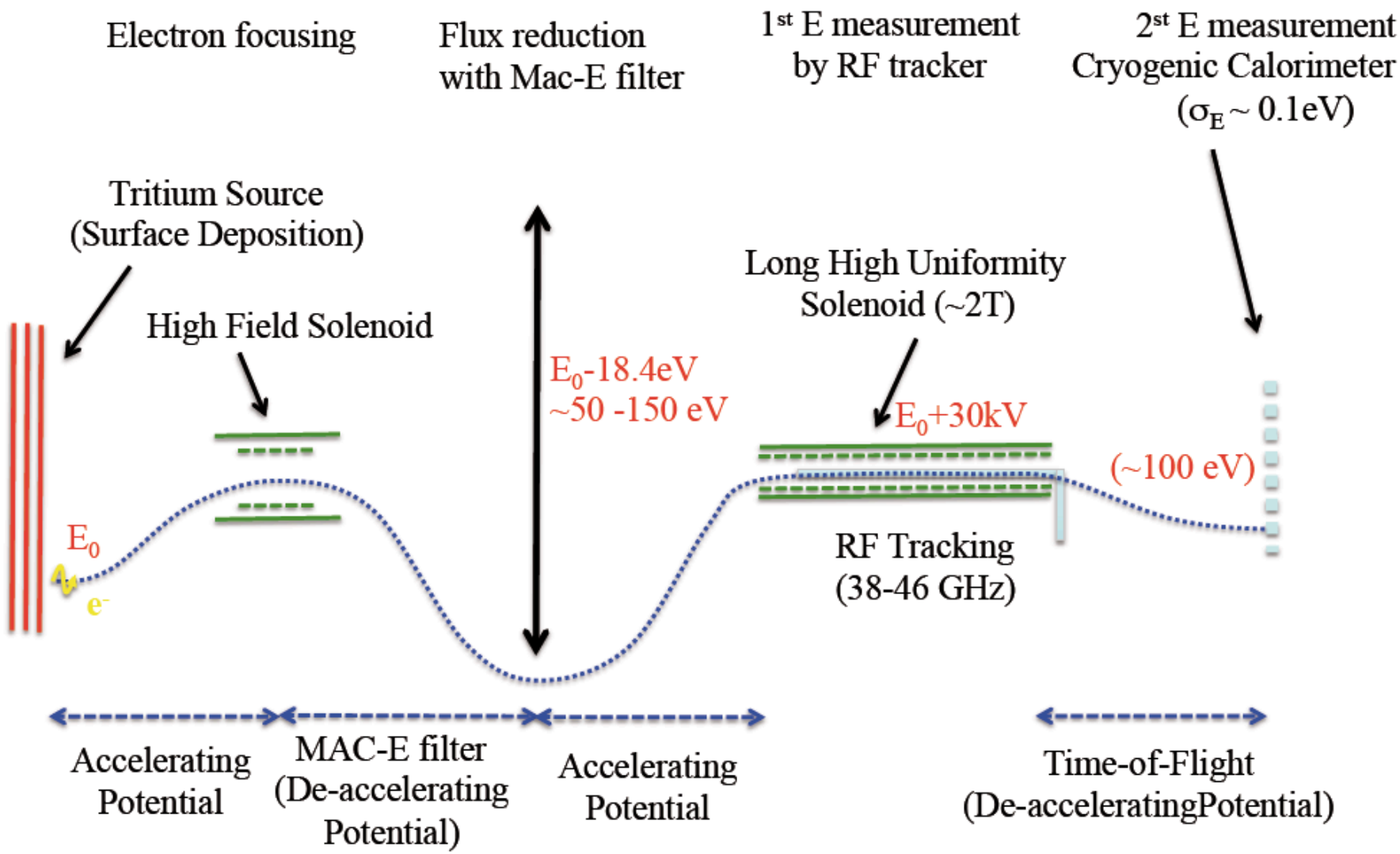
Submitted: March 19th, 2018

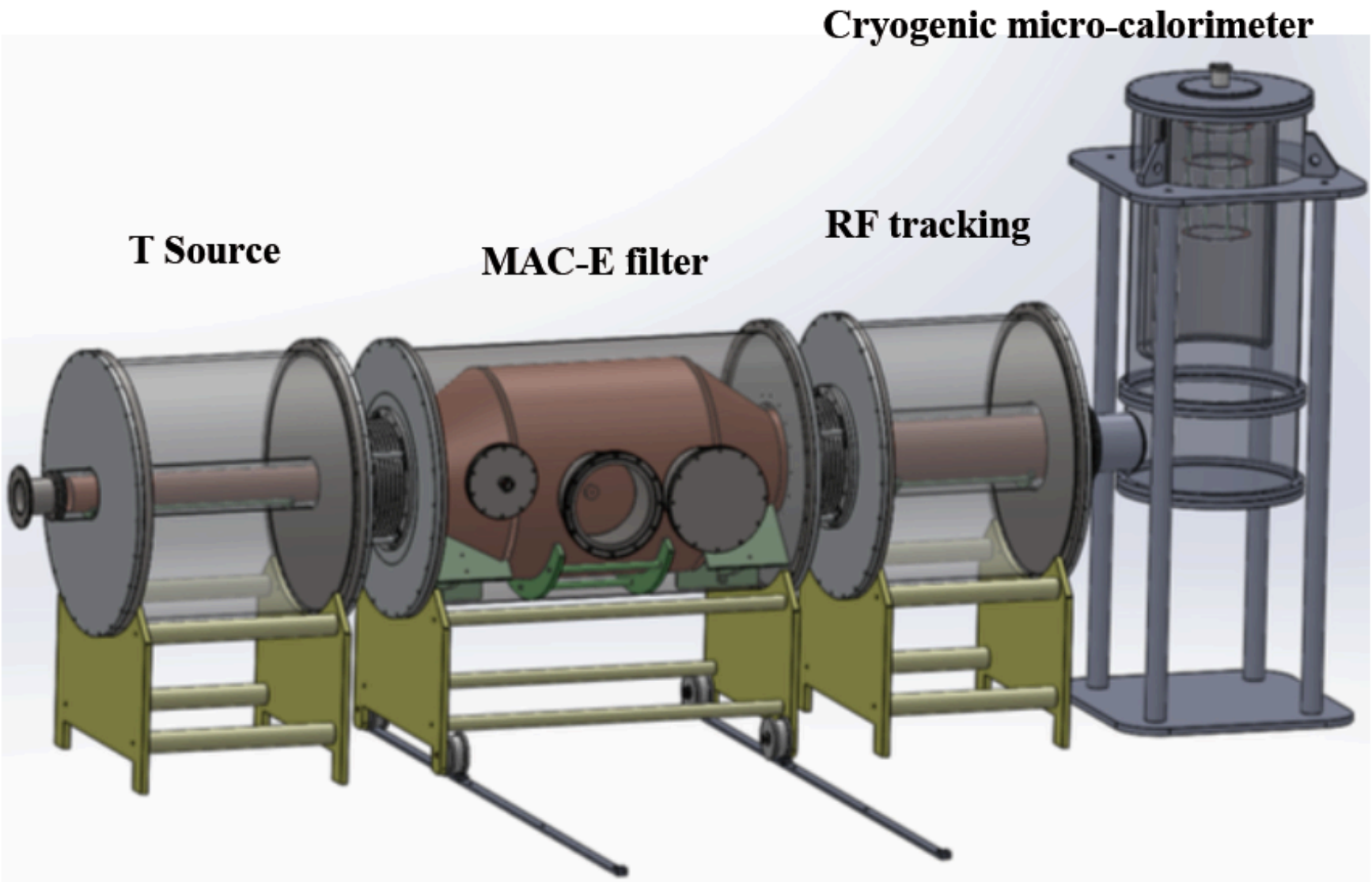
GS Scientific Committee green light: May 31st

The PTOLEMY prototype



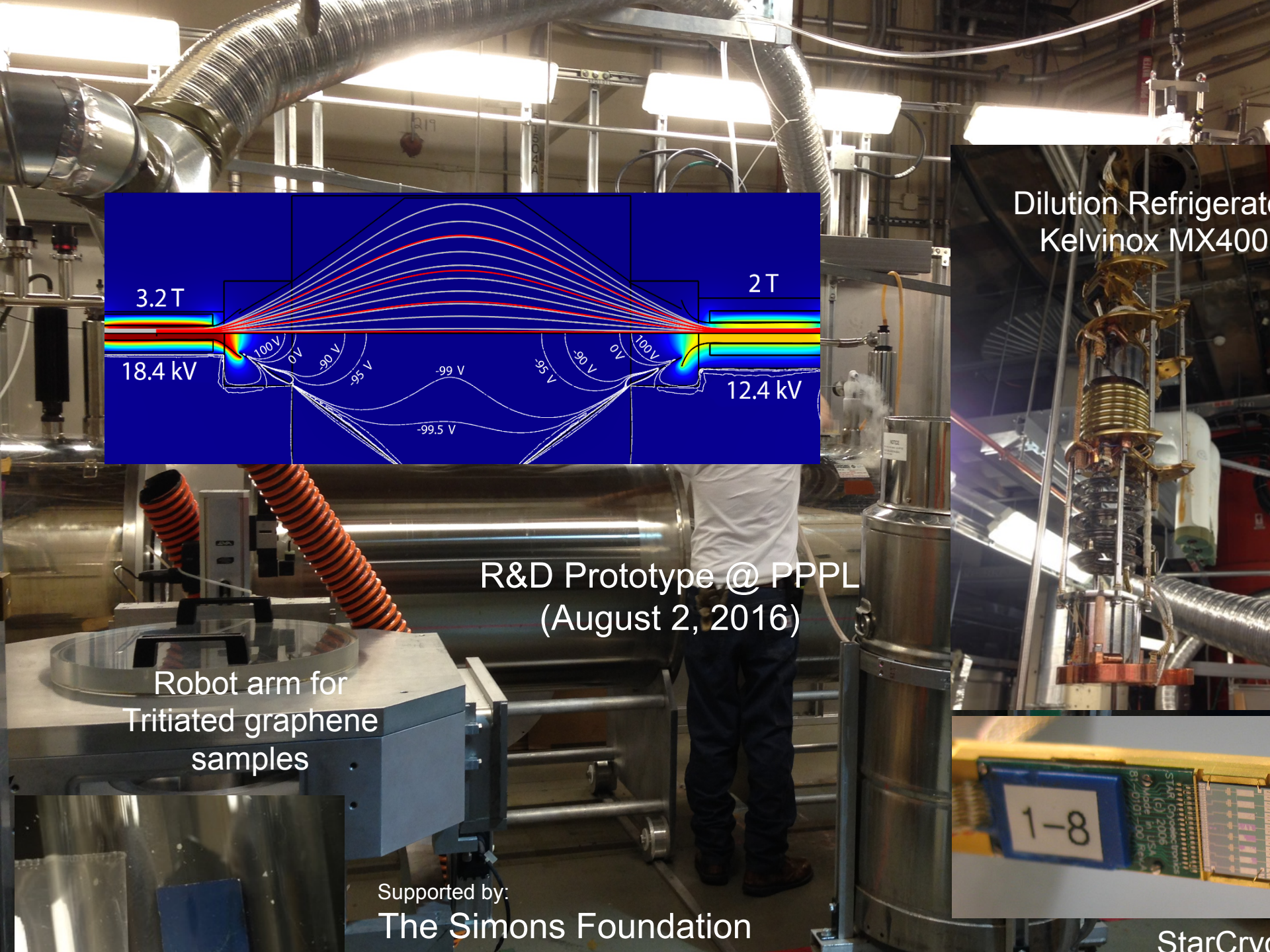
T source + MAC-E filter + RF tagging + sub-eV resolution μ-cal

The PTOLEMY prototype
@ Princeton



R&D Prototype @ PPPL
(August 2, 2016)

Supported by:
The Simons Foundation
The John Templeton Foundation


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

The PTOLEMY prototype

PTOLEMY roadmap

Phase I

Proof-of-principle @ LNGS:

TES, Graphene, background level (3 to 5 years)

Phase II

Technical design for a scalable detector

Phase III

Full detector construction and search for relic neutrino

(7 events/100 g Tritium expected)

Three major challenges
towards the full scale PTOLEMY detector

- Reduce target induced E_e smearing (molecular effects)

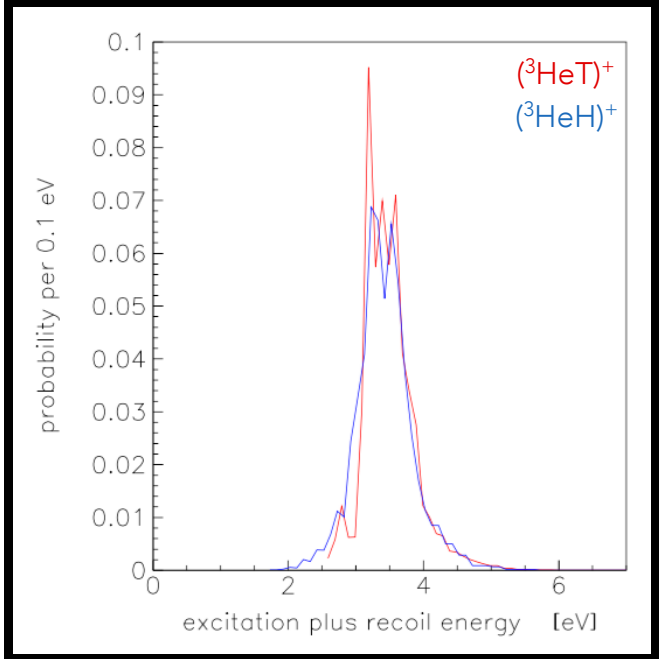
- Compress a 70m spectrometer length (KATRIN) down to cm scale and replicate it 10^4-10^6 times (lower precision since final measurement made by the microcalorimeter)

- Measure the energy spectrum directly with σ_E ~ O(0.05 eV)

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 (2D structure)

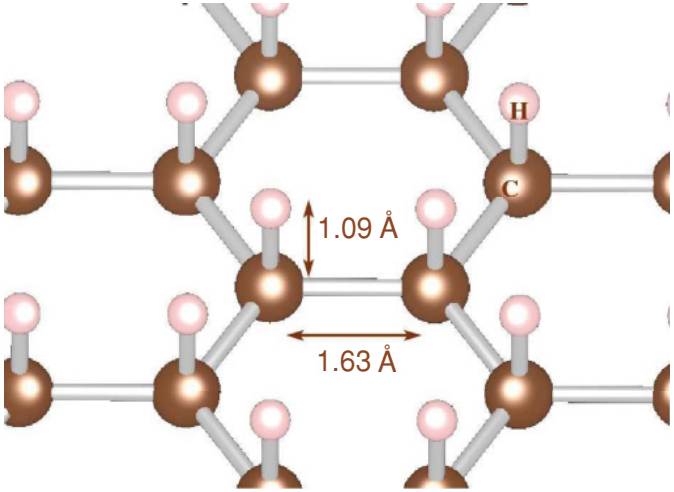
Single-sided (loaded on substrate) and planar (uniform bond length)

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

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

Semiconductor (Voltage Reference)

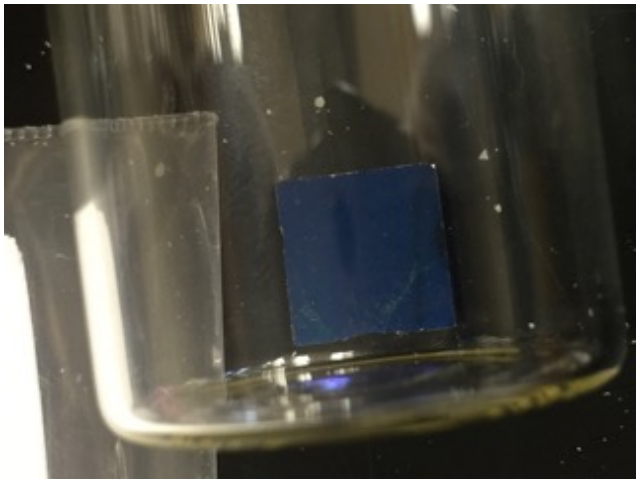
Polarized tritium (directionality?)

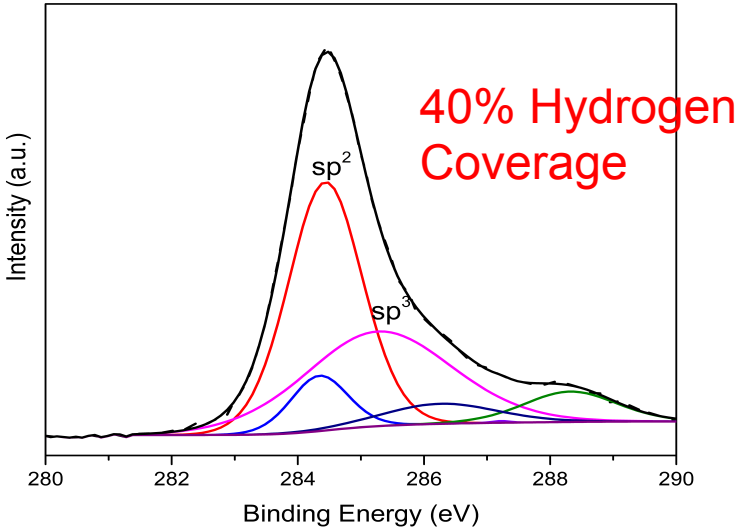


Tritiated graphene target

Samples produced at
Savannah River National Laboratory

Ready to be tested…





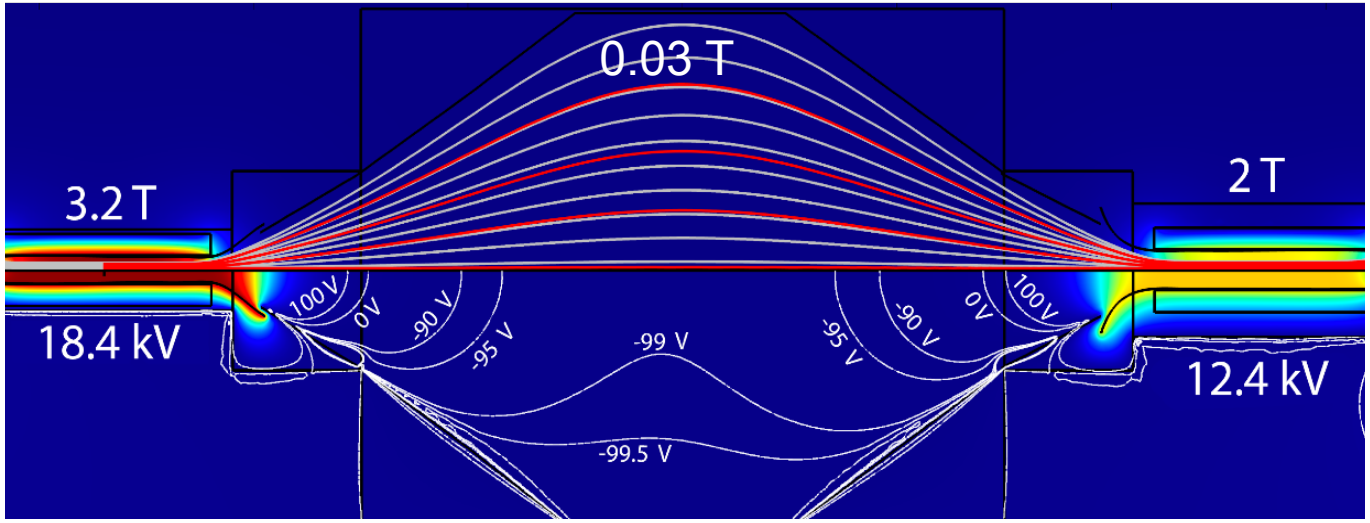
Cold Plasma Loading (PPPL)
XPS (X-Ray Photoelectron Spectroscopy)
sp2 is from non hydrogenated C atoms
sp3 is hydrogenated C atoms.
The area ratio is used to calculate H coverage

MAC-E filter

Low magnetic gradient adiabatically transforms cyclotron trajectories into longitudinal motion

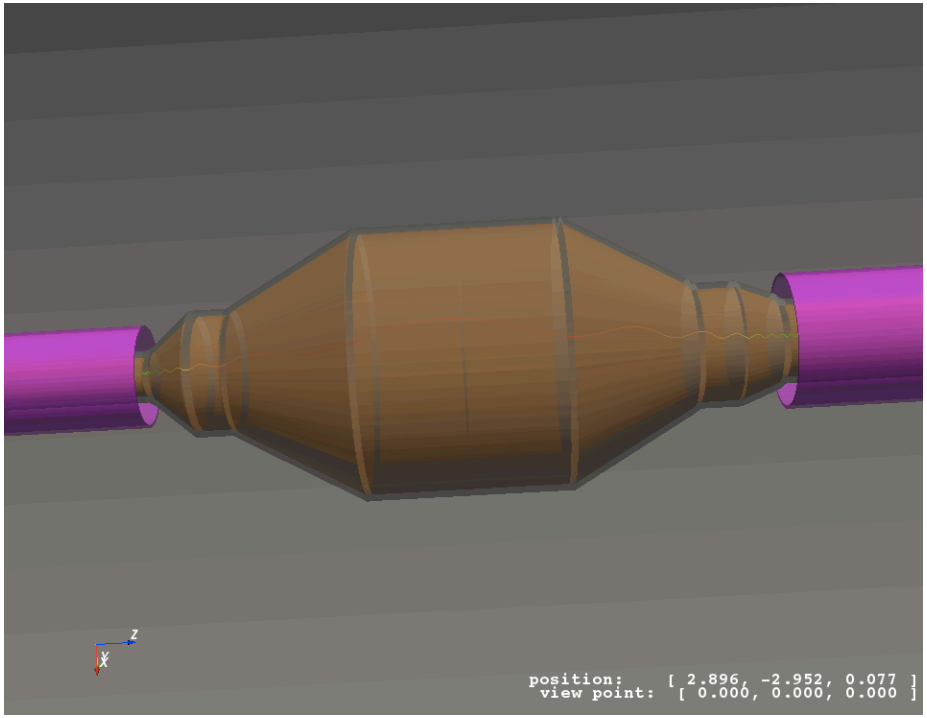
$$\mu = \frac{E_\perp}{B} \qquad \frac{\Delta E}{E} = \frac{B_{\min}}{B_{\max}}$$

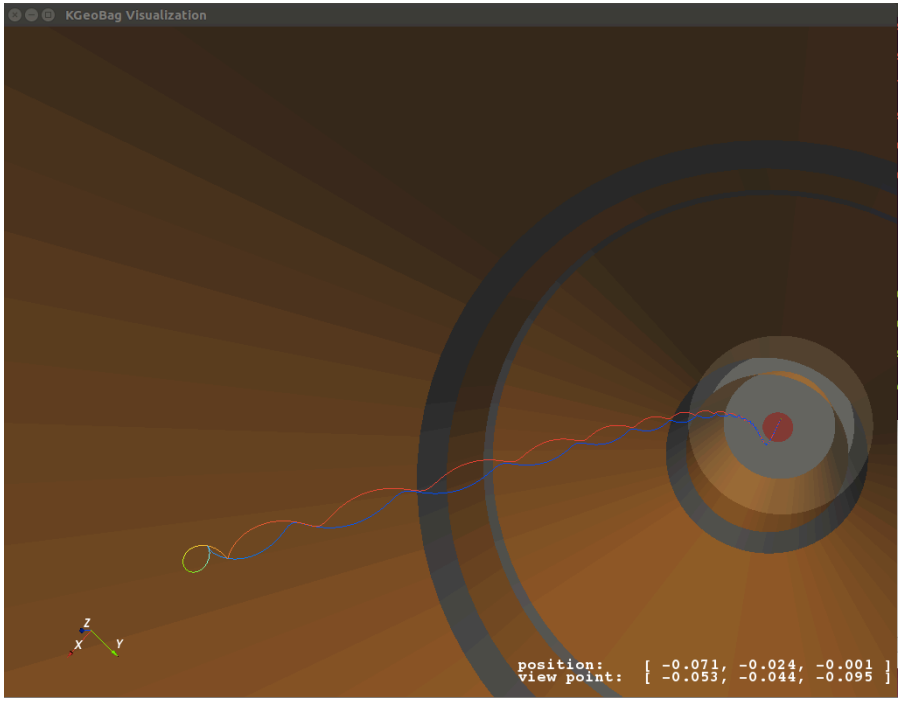
Electric field sets the energy cutoff



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)

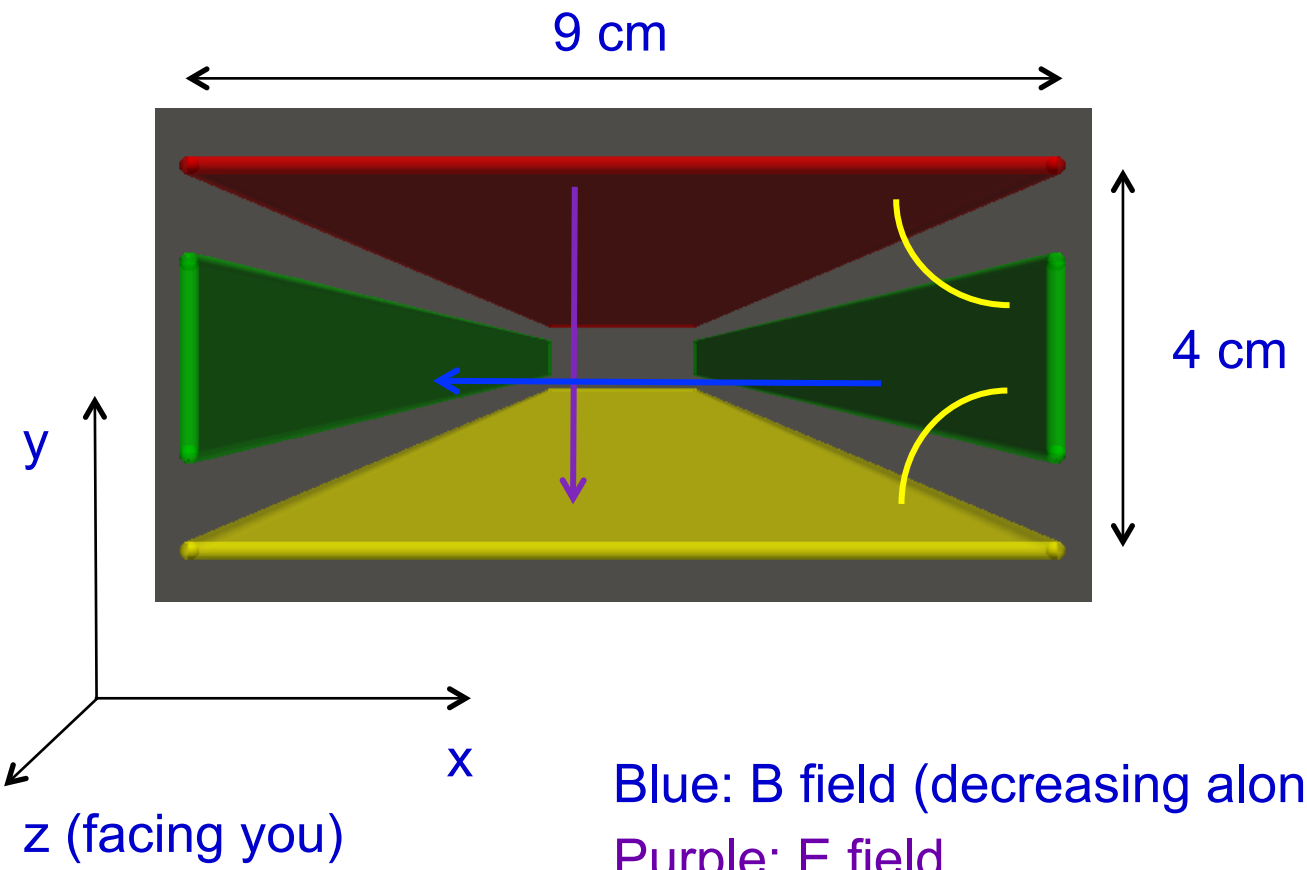
PTOLEMY prototype
MAC-E filter performances analysis





Kassiopeia package
(KATRIN Collaboration)

New E×B filtering design



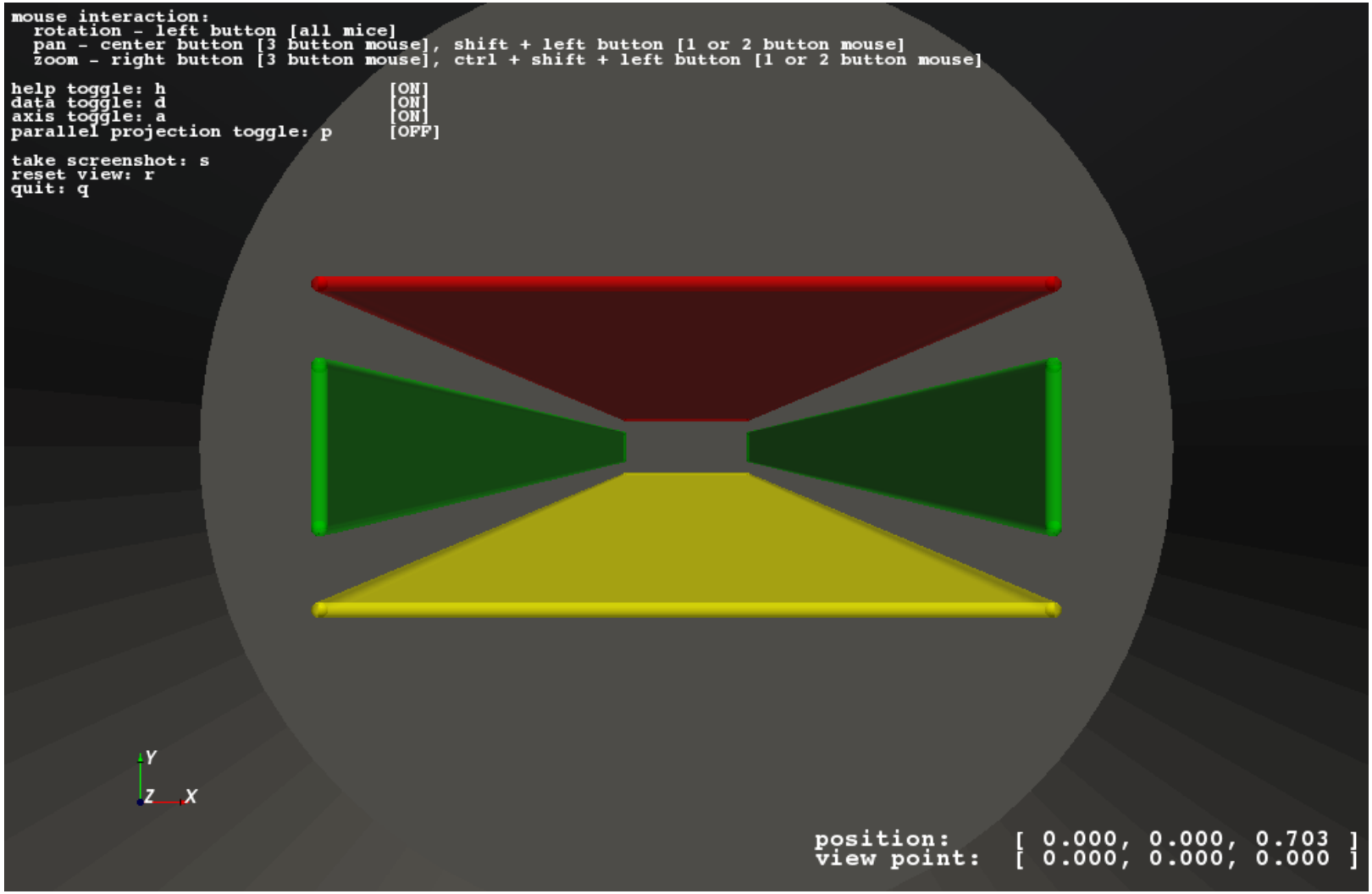
Blue: B field (decreasing along -z)

Purple: E field

Yellow: E•B bottle

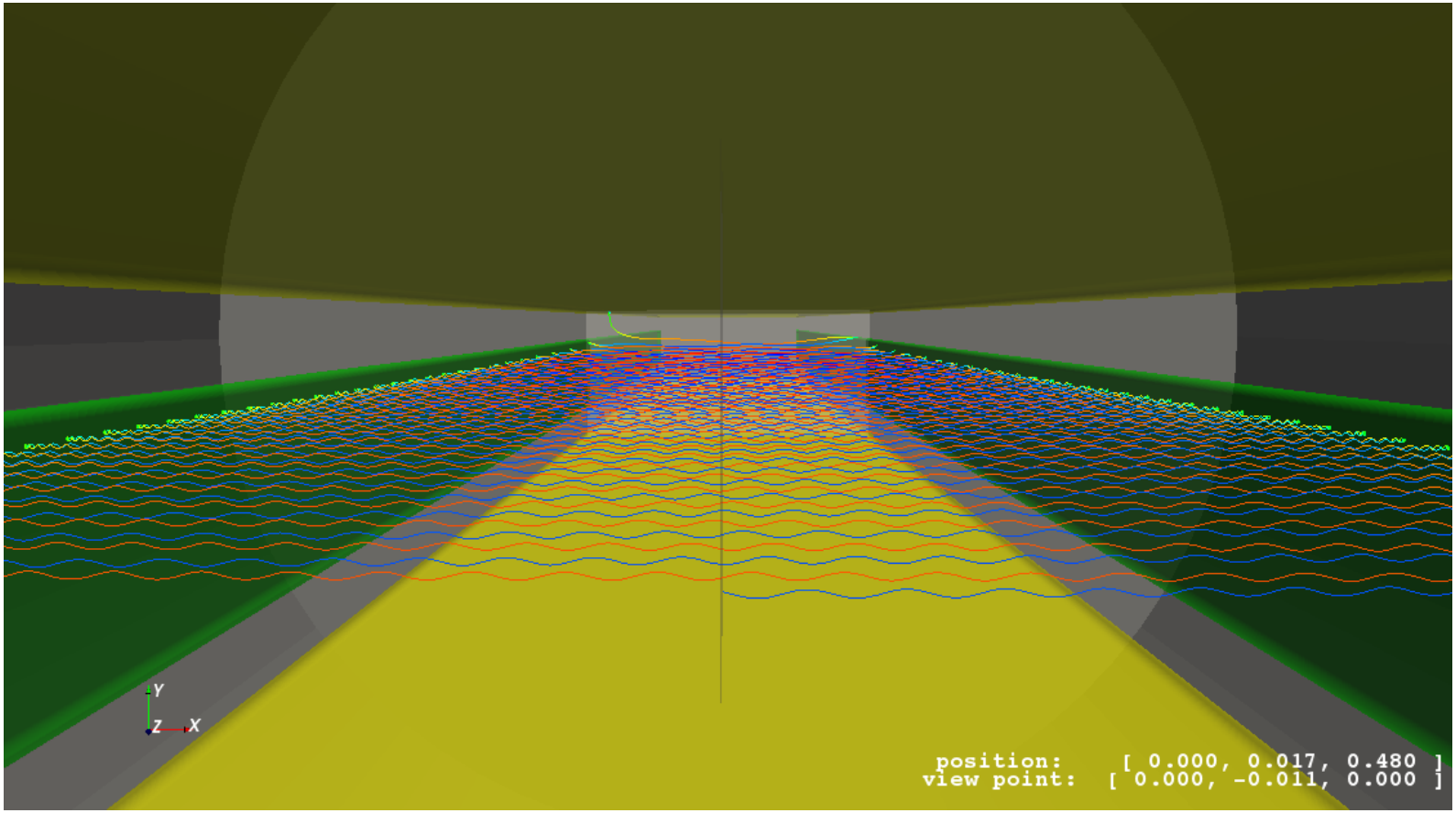
New E×B filtering design

(Kassiopeia simulation package)



New E×B filtering design

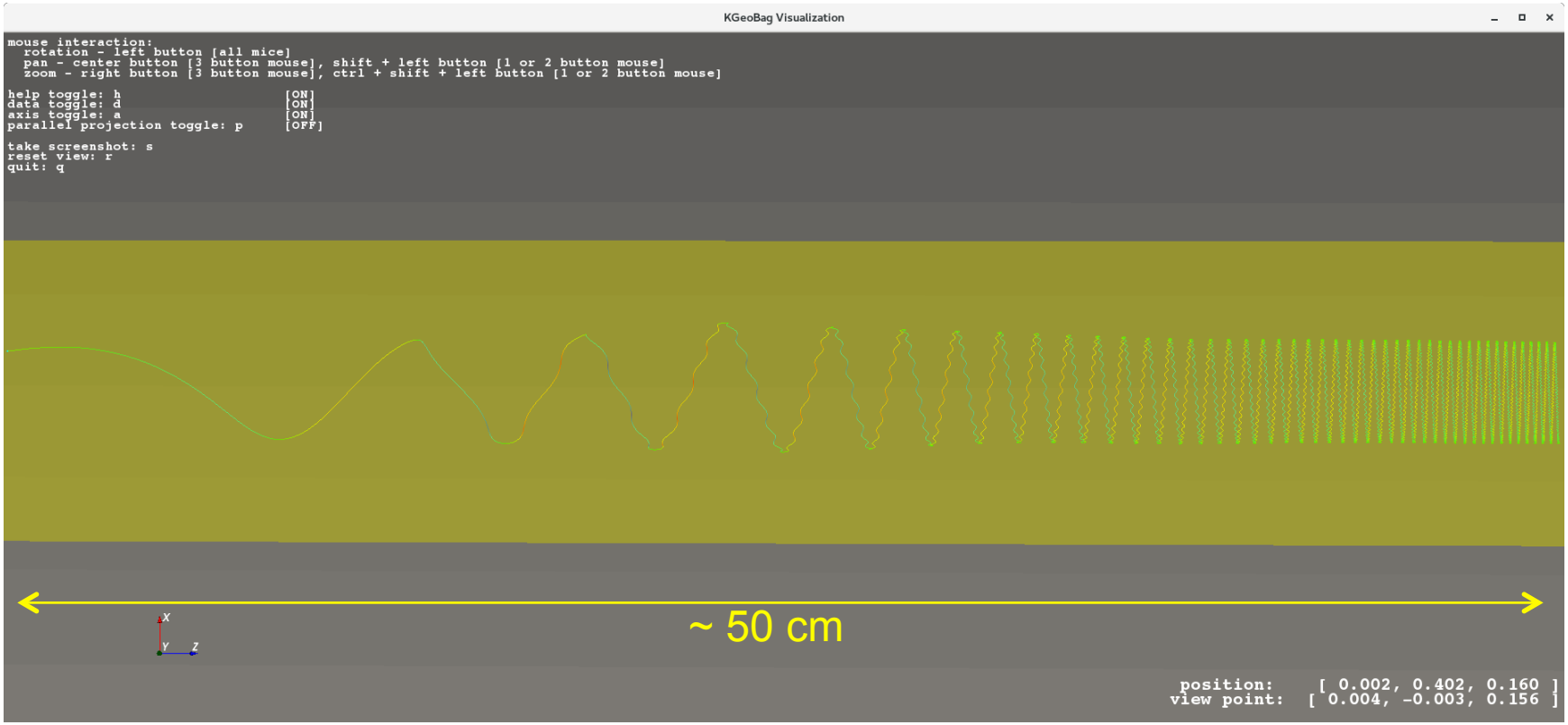
(Kassiopeia simulation package)



electron left-right bouncing while ExB drifting

New E×B filtering design

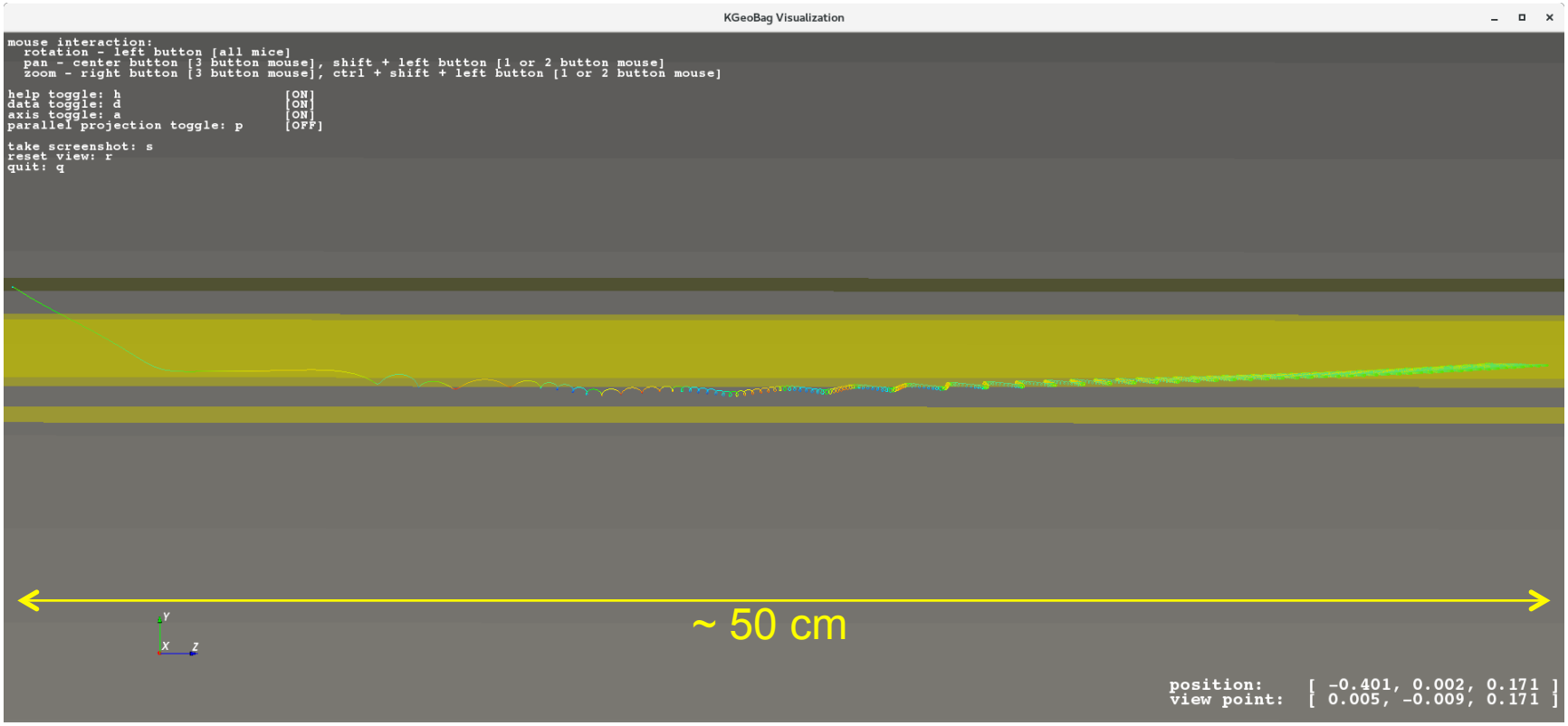
(Top view)



Example of 15 keV electron loosing transverse energy as the B field intensity decrease (drift is from the right to the left)

New E×B filtering design

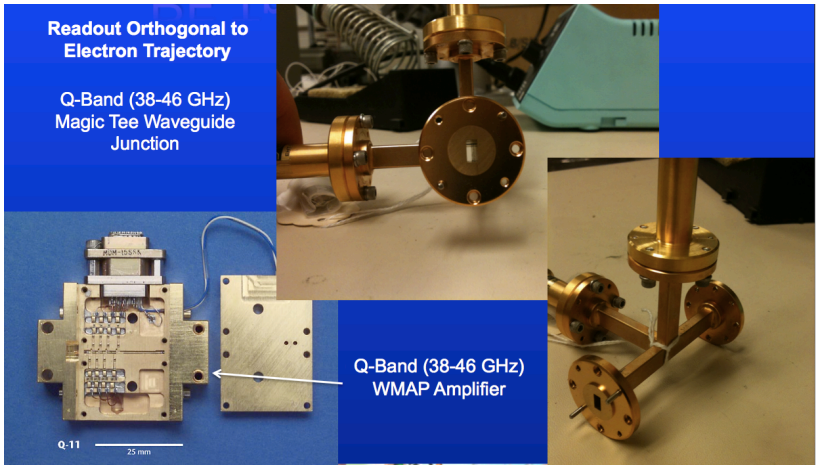
(side view)

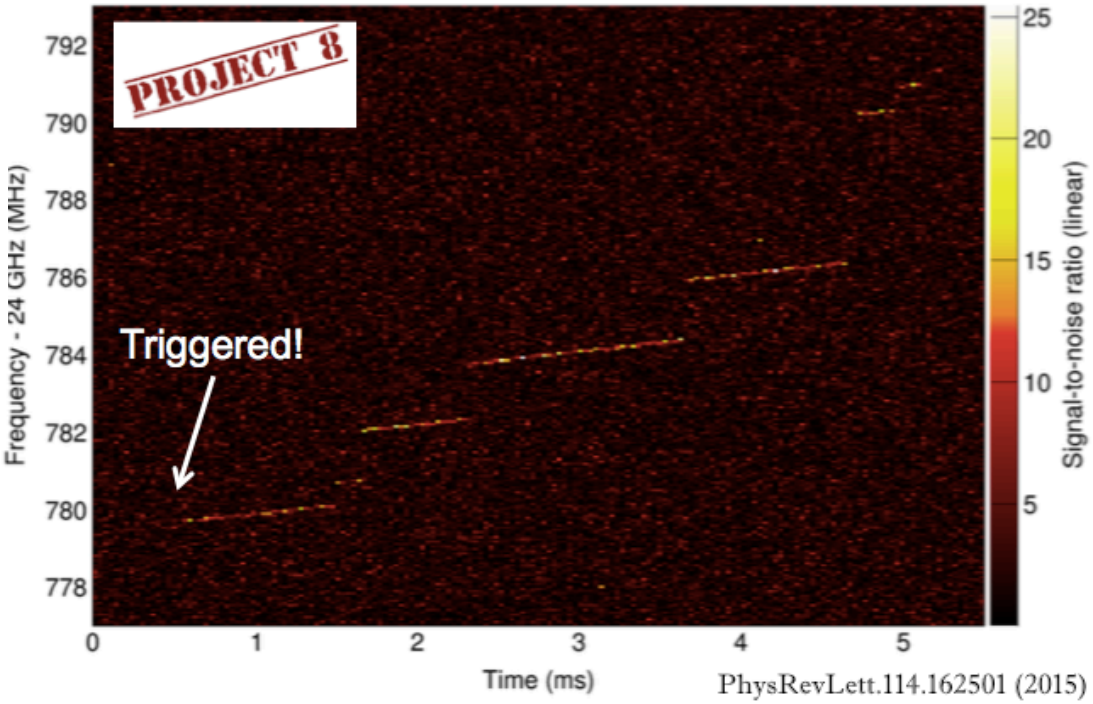


Example of 15 keV electron loosing transverse energy as the B field intensity decrease (drift is from the right to the left)

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.



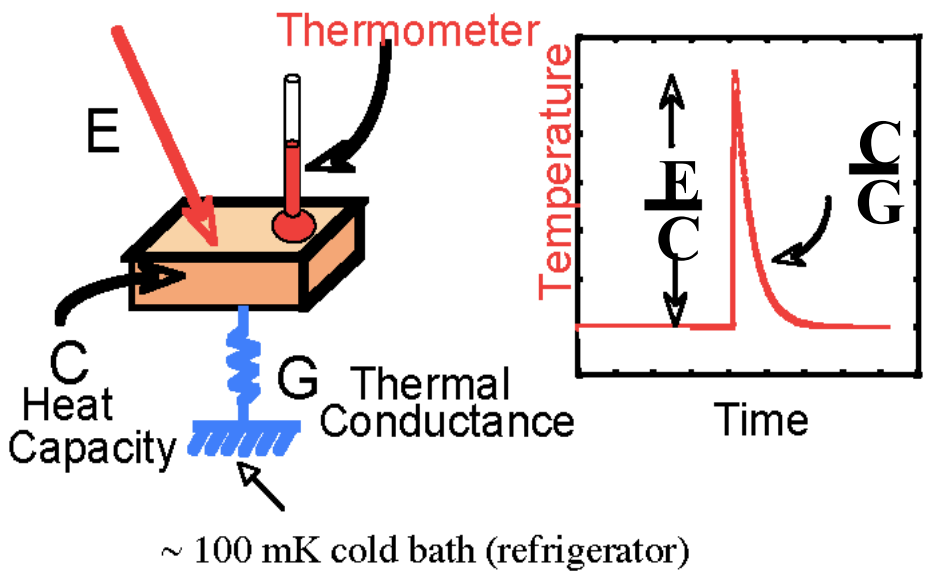


First detection of single electron cyclotron radiation

Phys.Rev.Lett. 114(2015)162501

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

Cryogenic Transition Edge Sensors (TES)

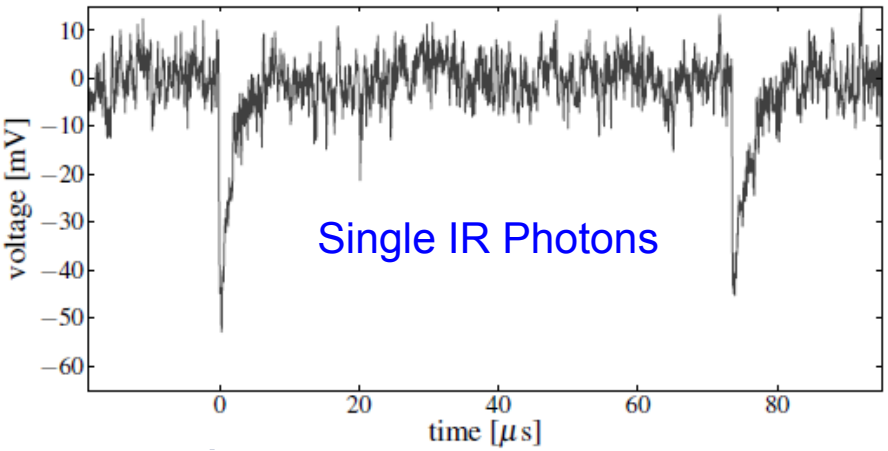


10÷100eV electron can be stopped with very small C (10^{-4} smaller than for X-ray)

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

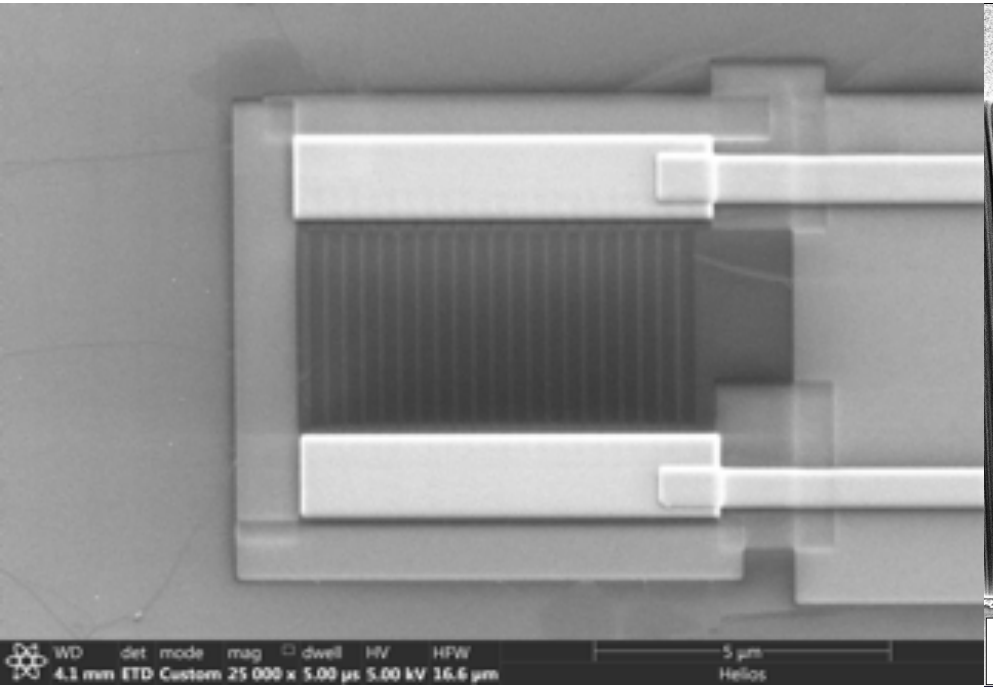
- Reduce target induced E_e smearing (molecular effects)
  New source (Tritiated-Graphene or Cryogenic Au(111))

- 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

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

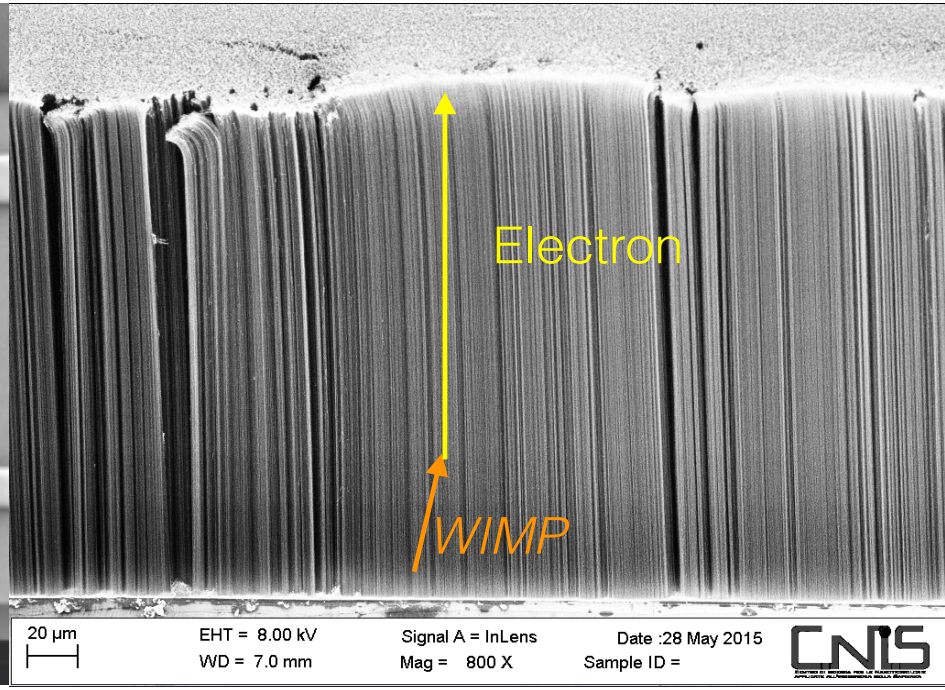
Graphene Targets for directional DM detection
Two Concepts

PTOLEMY-G^3



Self-instrumented with G-FETs

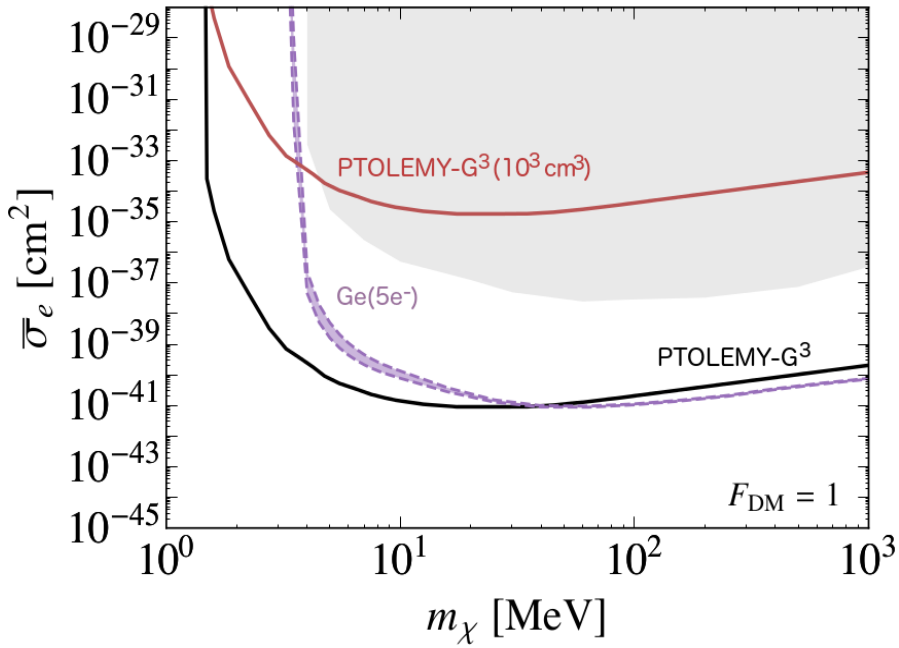
PTOLEMY-CNT



Anisotropy of aligned CNTs

Direction Detection of MeV Dark Matter

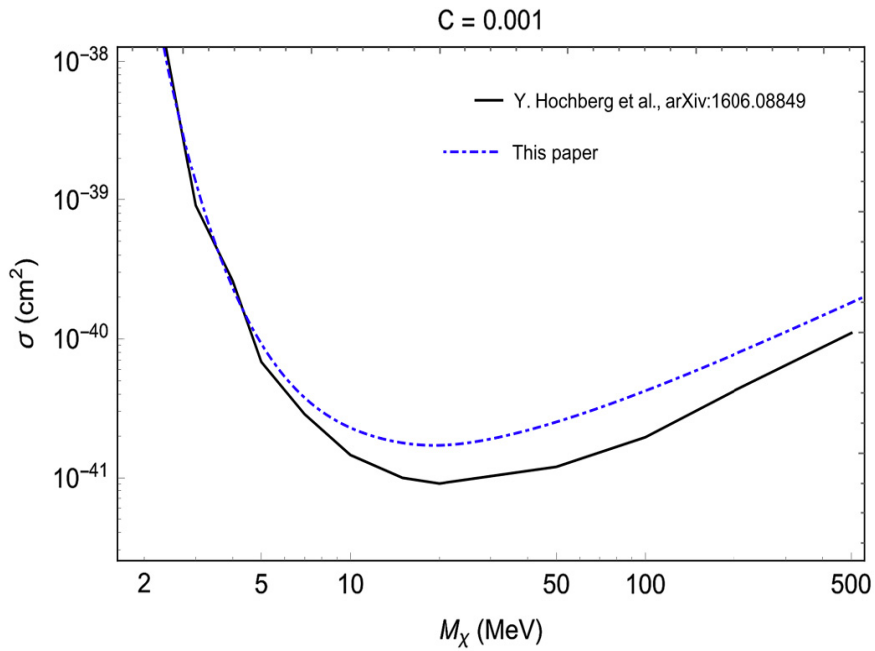
PTOLEMY-G^3



Self-instrumented with G-FETs

Physics Letters B772 (2017) 239

PTOLEMY-CNT



Anisotropy of aligned CNTs

Physics Letters B776 (2018) 338

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 Collaboration will start prototype installation and commissioning at LNGS after the summer

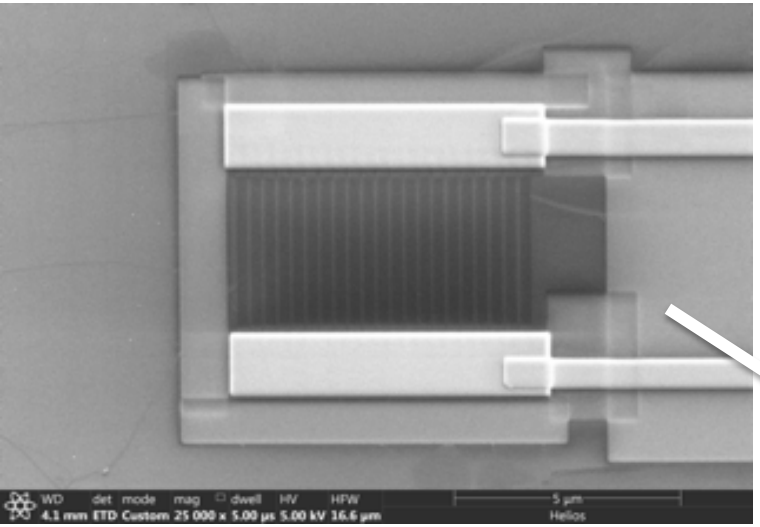
Many (interesting) activities are ongoing and many (smart) ideas still needed !

(enthusiastic collaborators are welcome !)

Yesterday news: Simons Foundation Grant for three more years

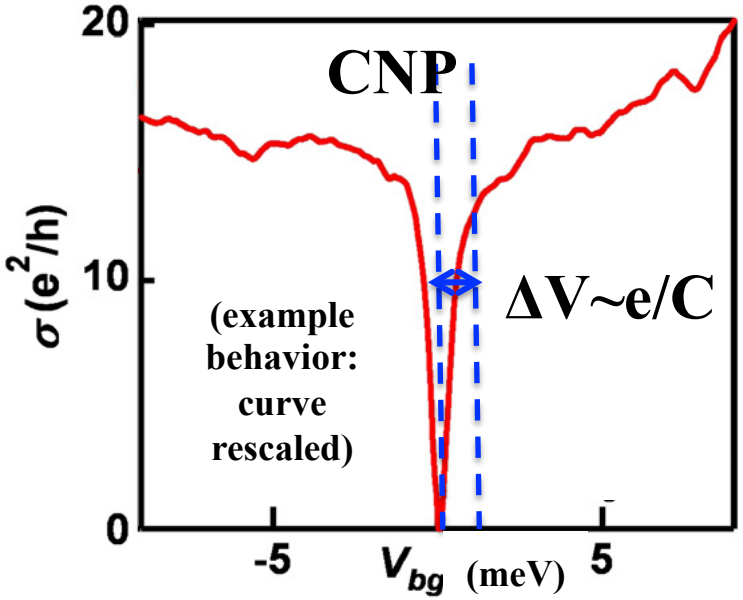
Thank you

G-FET

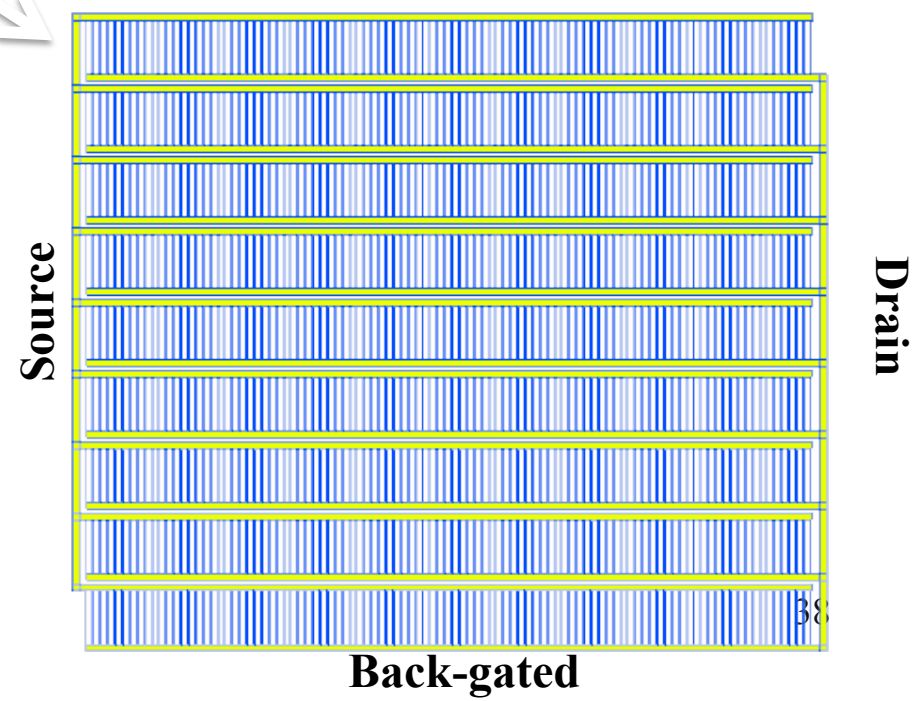


Principles of Operation:

- 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