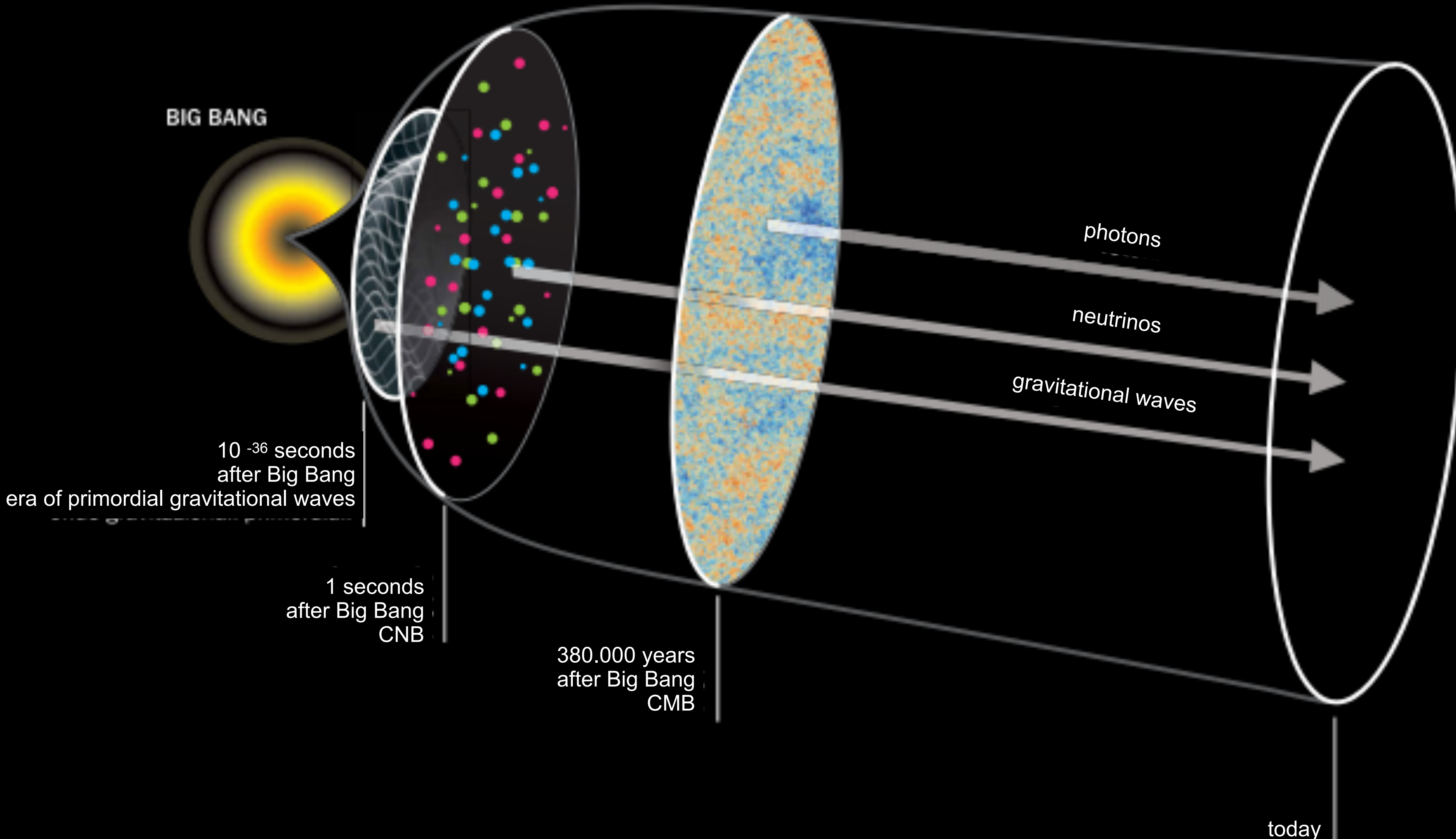
The PTOLEMY project: from an idea to a real experiment for detecting Cosmological Relic Neutrinos

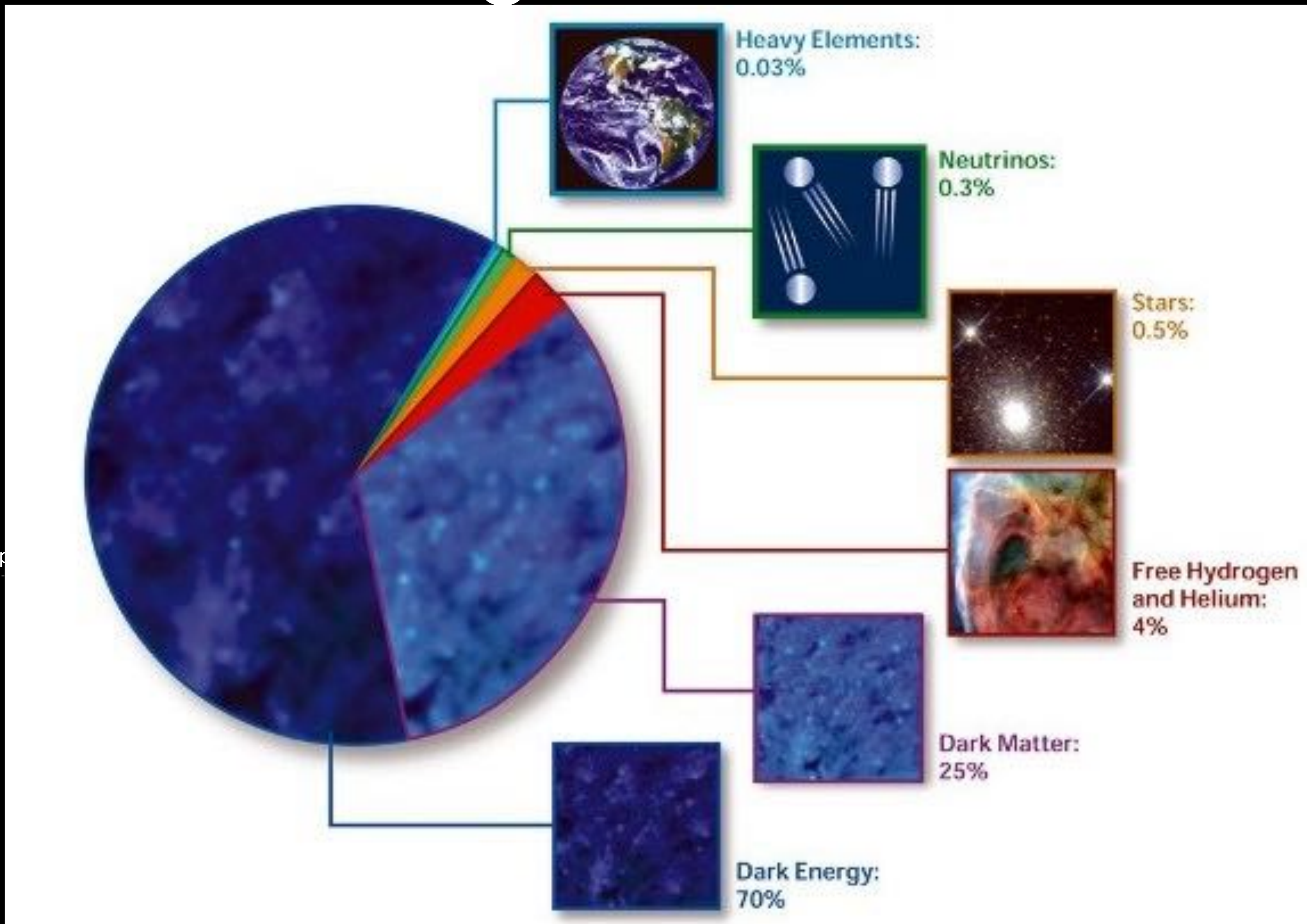
23 May 2018

Dr. Marcello Messina
New York University Abu Dhabi
جامعة نيويورك ابوظبي
NYU ABU DHABI

Looking Back in Time



Looking Back in Time



era of p

Cosmological Relic Neutrinos

What we know that Cosmological Neutrino Background (CNB)

$$\sim 1\sec > BigBang$$

Date of birth

$$\bar{n}_{\nu_i 0} = \bar{n}_{\bar{\nu}_i 0} = \frac{3}{22}\bar{n}_{\gamma 0} = 56cm^{-3}$$

density per flavor

$$T_{\nu,0} = \left(\frac{4}{11}\right)^{1/3} T_{\gamma 0} = 1.95K$$

temperature

$$\bar{p}_{\nu_i 0} = \bar{p}_{\bar{\nu}_i 0} = 3T_{\nu,0} = 5\times 10^{-4}eV$$

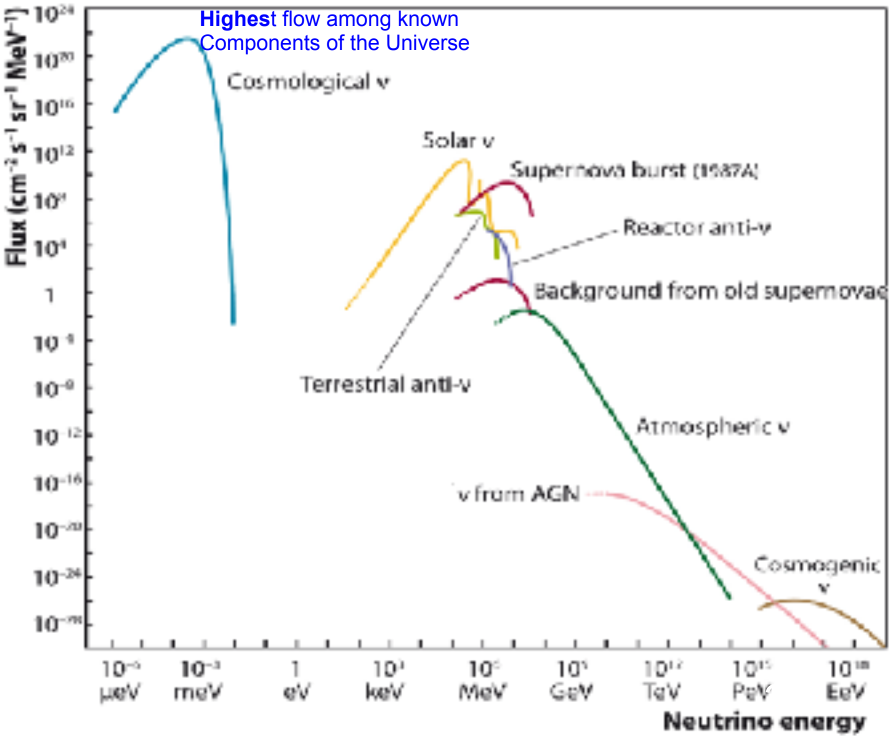
mean kinetic energy

$$D = \frac{1}{\bar{p}_{\nu_i}} = \frac{0.12cm}{\left\langle p/T_{\nu,0\bar{p}_{\nu_i 0}}\right\rangle}$$

Wave function extension

$$f_0 = 1/\left(1+\exp\left(p/T_{\nu,0}\right)\right)$$

p distribution without late-time small scale clustering and $\mu/T_\nu<0.1$

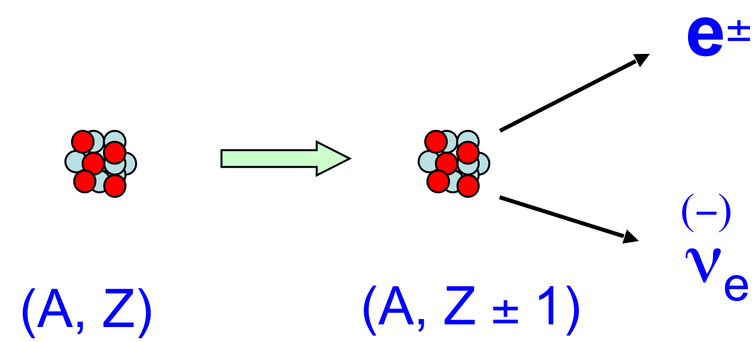


An unstable nucleus is an optimal target for very low energy neutrino detection

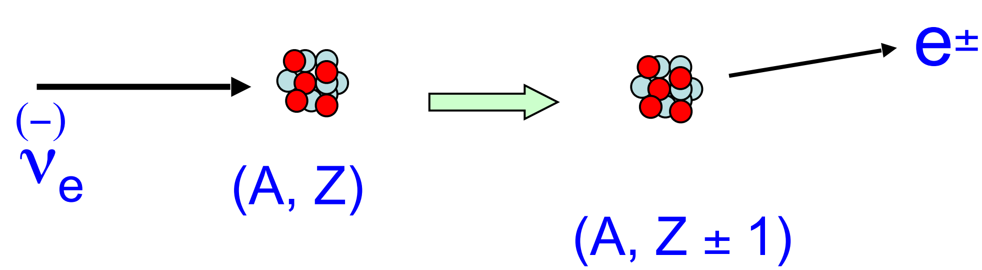
W. Weinberg, Phys. Rev. 128 1962

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

β decay



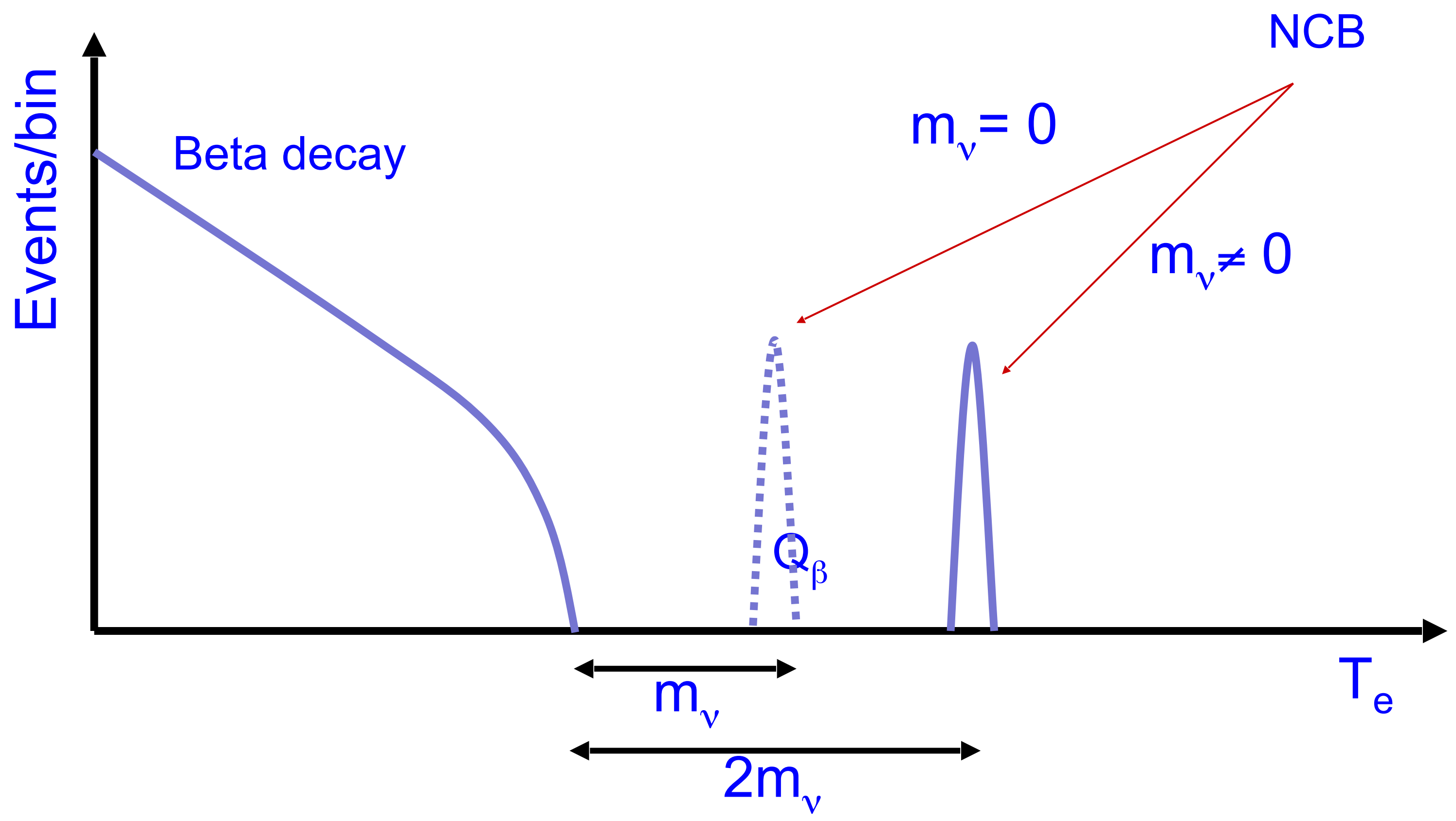
Neutrino Capture on a Beta decaying nucleus (NCB)



This process has no energy threshold !

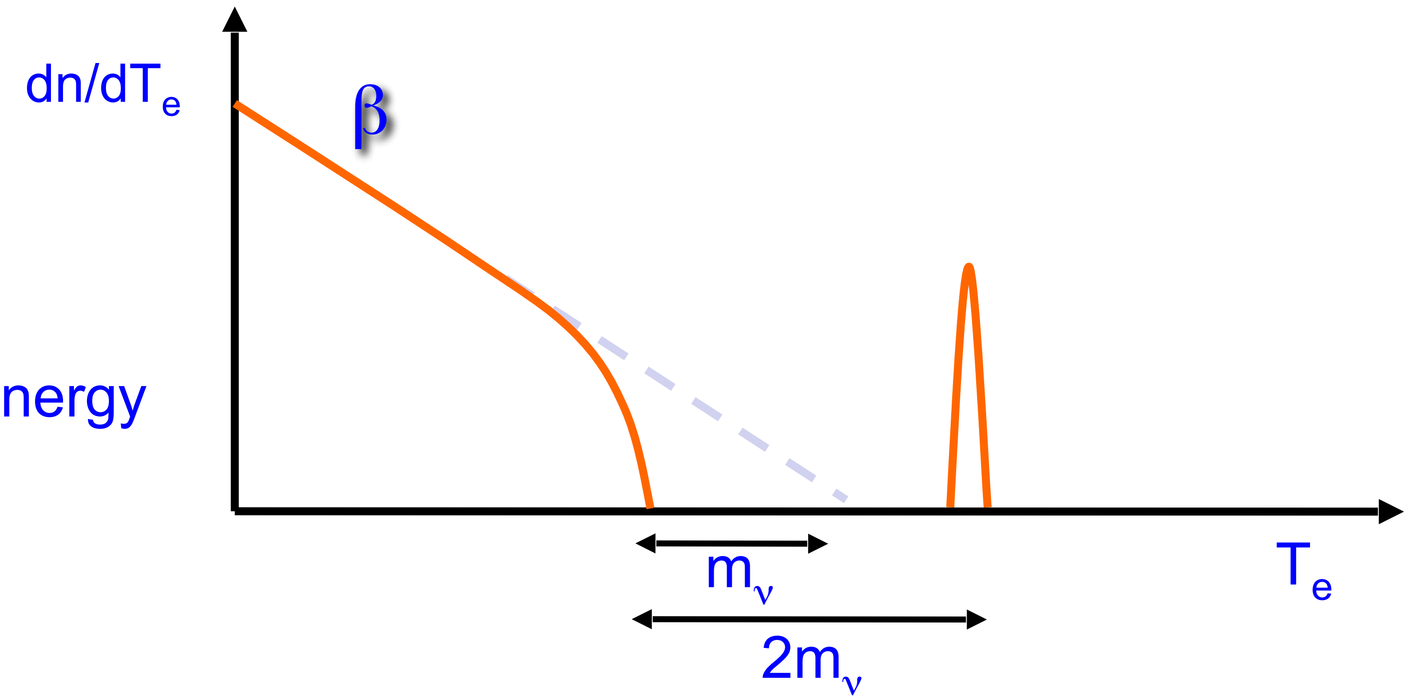
NCB signature

Neutrino masses ~ 0.5 eV are compatible with the present picture of our Universe.



The events induced by Neutrino Capture have a unique signature: there is a gap of $2m_\nu$ between the NCB electron energy and the energy of beta decay electrons at the endpoint.

Signal to background ratio



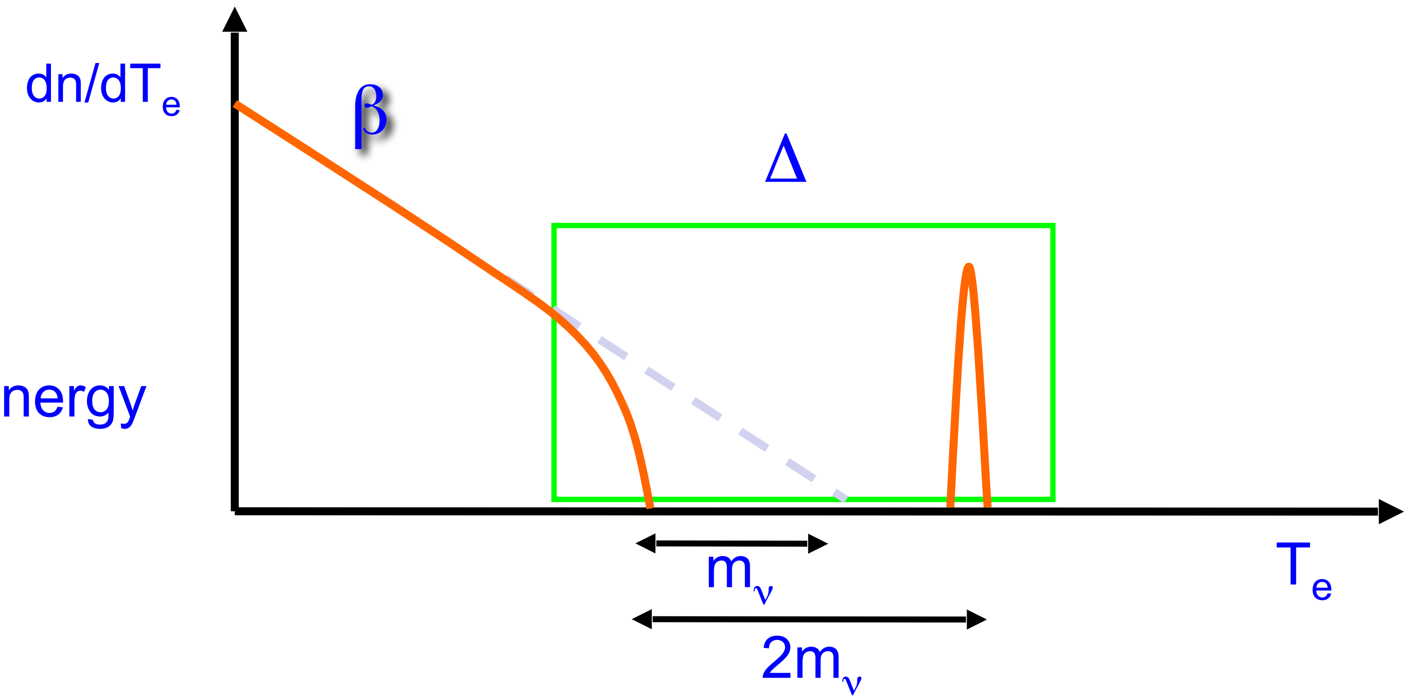
Observing the last energy bins of width Δ

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

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 $\Delta < m_\nu$

Signal to background ratio



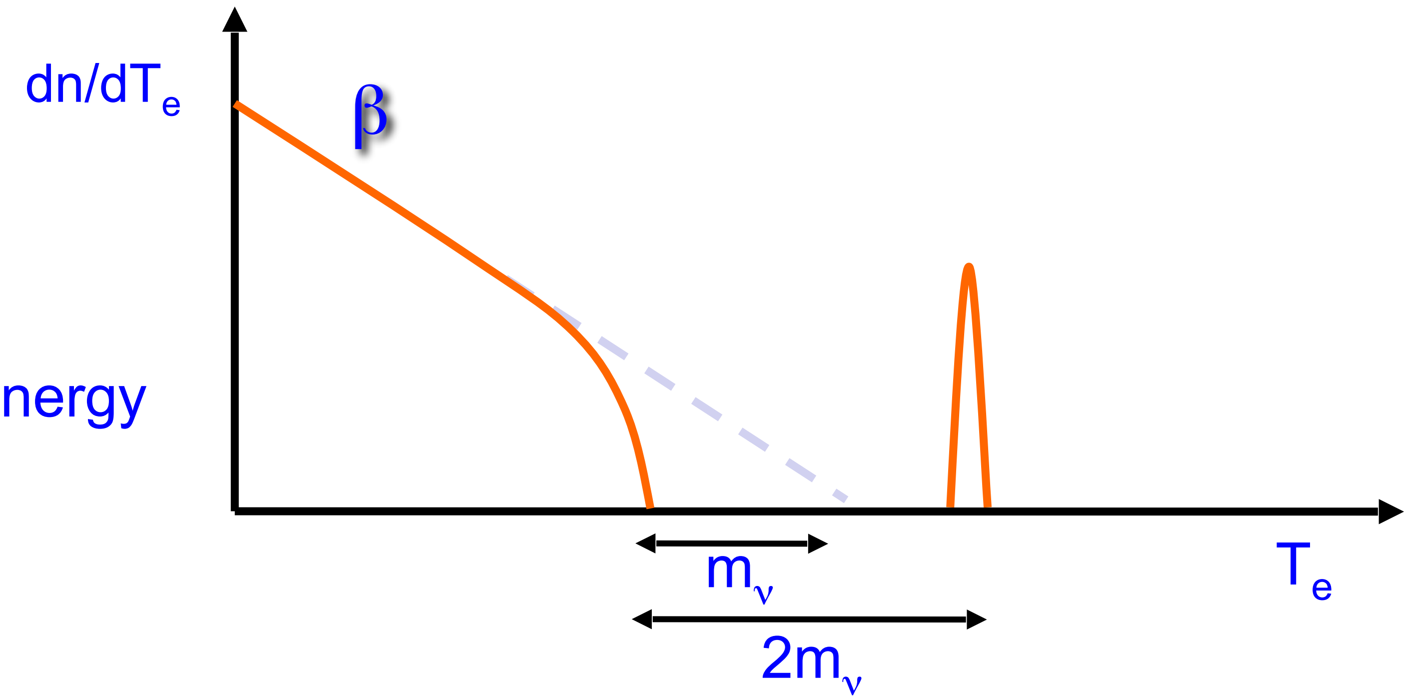
Observing the last energy bins of width Δ

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

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 $\Delta < m_\nu$

Signal to background ratio



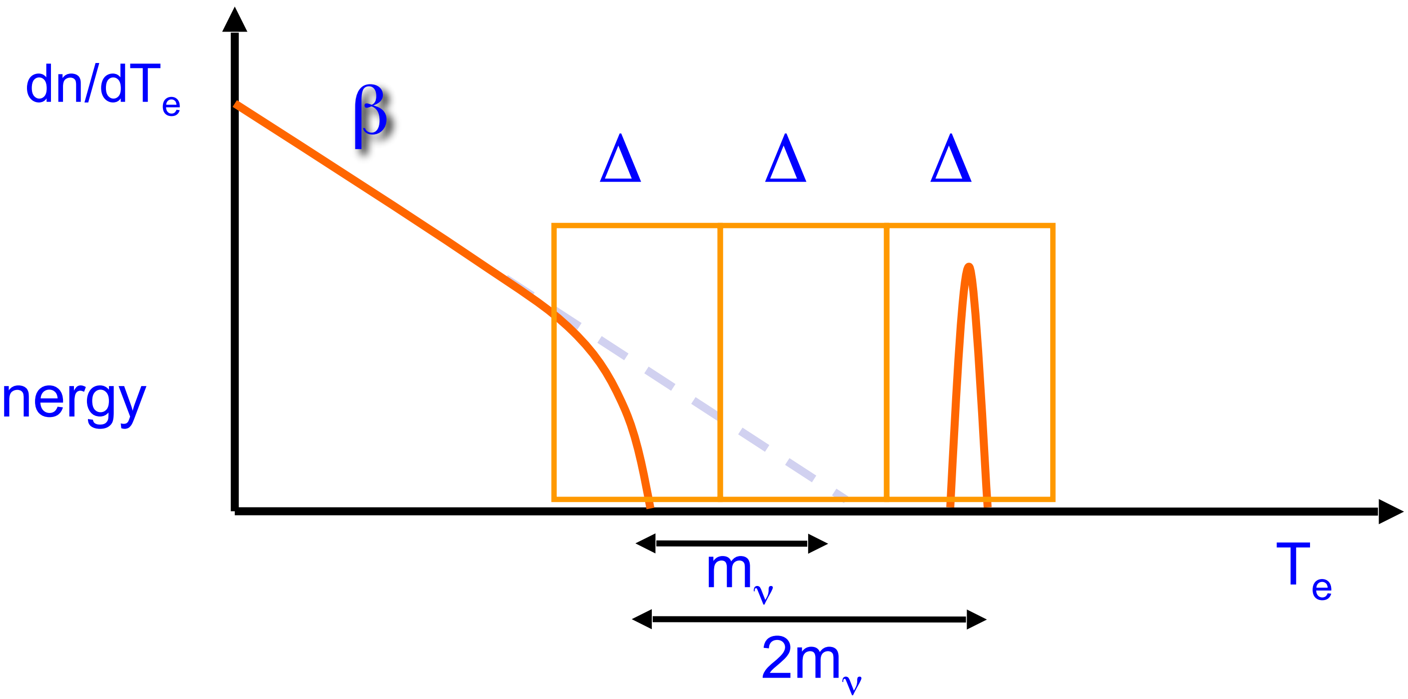
Observing the last energy bins of width Δ

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

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 $\Delta < m_\nu$

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

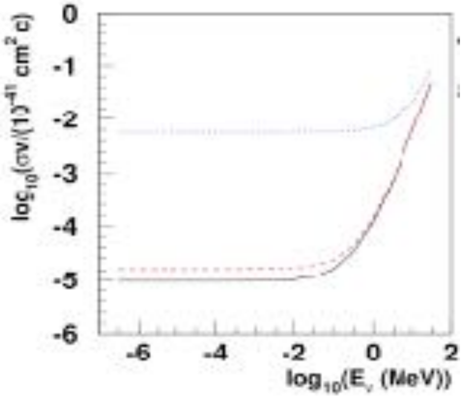
It works for $\Delta < m_\nu$

NCB Cross Section

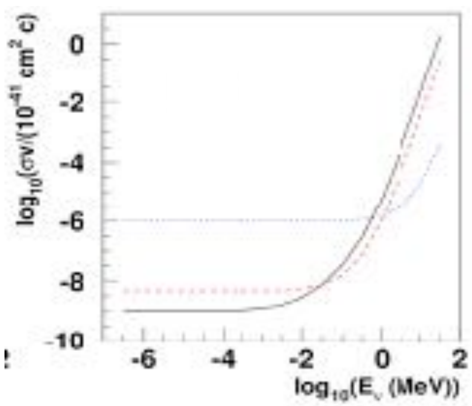
as a function of E_ν, Q_β for different nuclear spin transitions

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

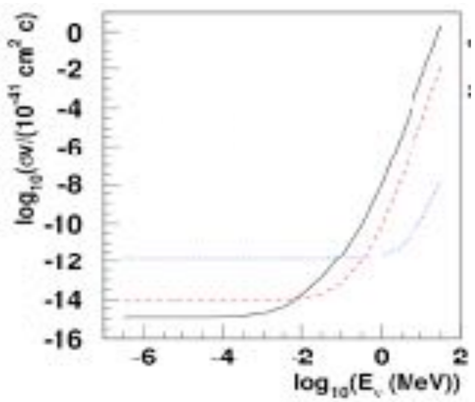
allowed



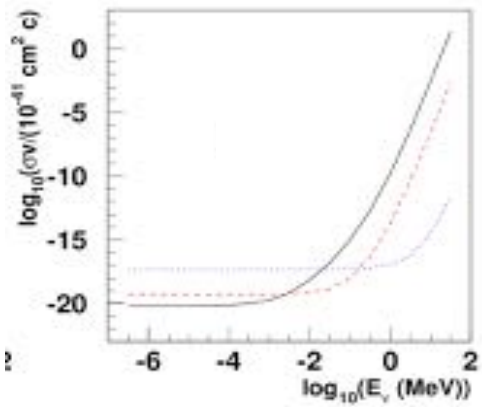
1st unique forbidden



2nd unique forbidden



3rd unique forbidden

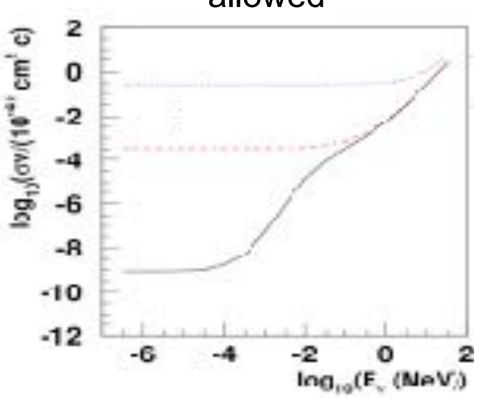


β− (top)

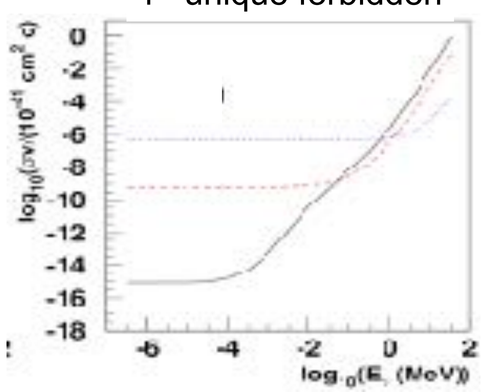
β+ (bottom)

———	Q_β = 1 keV
- - - - (red dashed)	Q_β = 100 keV
······ (blue dotted)	Q_β = 10 MeV

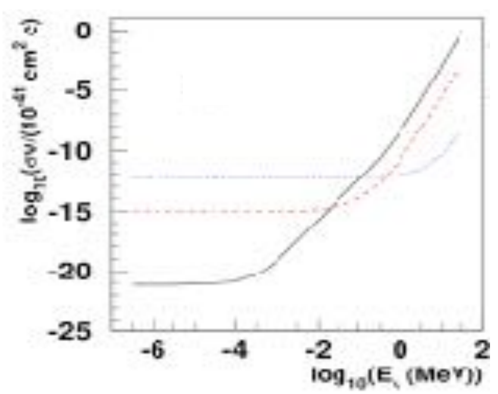
allowed



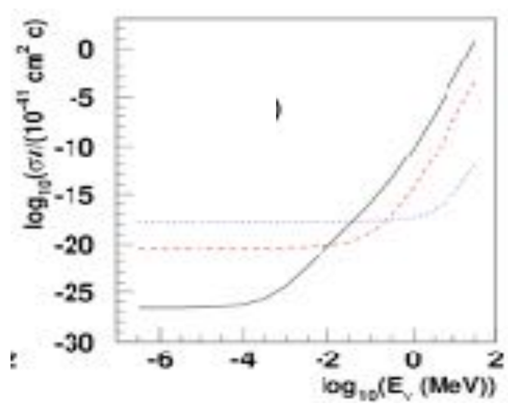
1st unique forbidden



2nd unique forbidden



3rd unique forbidden



NCB Cross Section

results achieved so far

- Exist a process (NCB) that allows in principle the detection of neutrinos of vanishing energy!
- The cross section (rate) does not vanish when the neutrino energy becomes negligible!
- NCB cross section can be evaluated by means of known quantities ($t_{1/2}$) and the ratio of the nuclear shape factors.

Relic Neutrino Capture Rates

Cocco, Mangano, Messina: JCAP 0706 (2007) 015

- Target mass: **100 grams of tritium** (2 x 10^{25} nuclei)
- Cross section $\sigma(v/c)=(7.84\pm0.03)\times10^{-45}\,cm^2$ (**known at <0.5 %)**
- Estimate of Relic Neutrino Capture Rate:

($56\ \nu_e/cm^3$) (2 x 10^{25} nuclei) (10^{-44} cm^2) (3 x 10^{10} cm/s) (3 x10^7s)= **10 events/yr**

Relic Neutrino Capture Rates

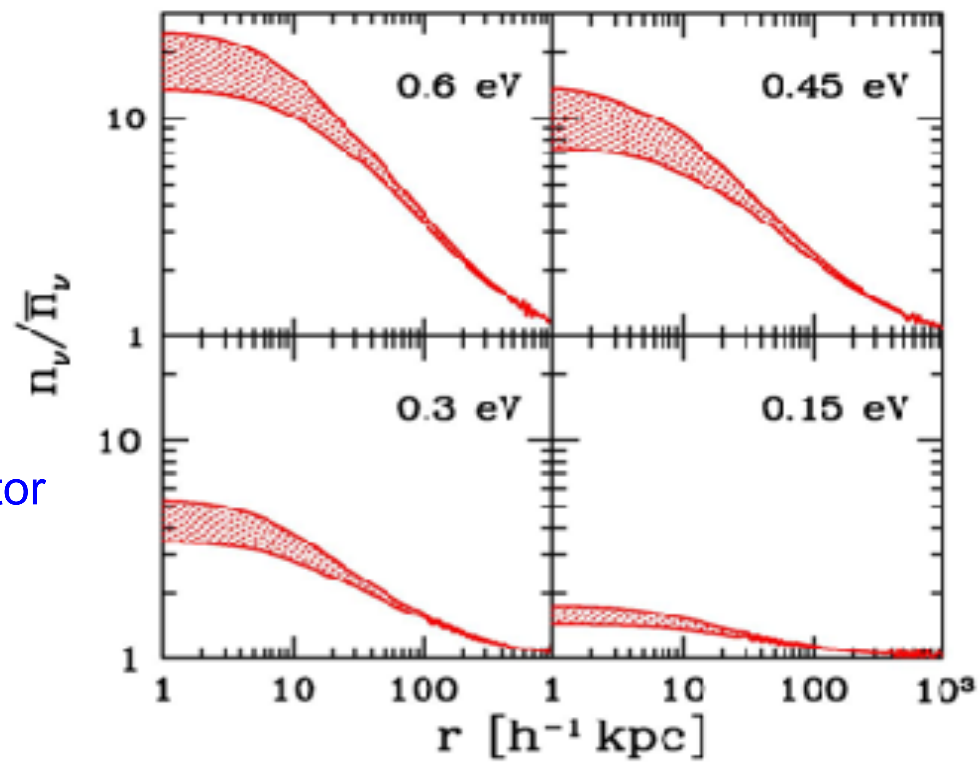
Cocco, Mangano, Messina: JCAP 0706 (2007) 015

- Target mass: **100 grams of tritium** (2 x 10^{25} nuclei)
- Cross section $\sigma(v/c)=(7.84\pm0.03)\times10^{-45}\text{cm}^2$ (**known at <0.5 %)**
- Estimate of Relic Neutrino Capture Rate:

($56\ \nu_e/\text{cm}^3$) (2 x 10^{25} nuclei) (10^{-44} cm^2) (3 x 10^{10} cm/s) (3 x10^7s)= **10 events/yr**

Gravitational clumping could potentially increase the local number of relic neutrinos.
For low masses ~0.15eV, the local enhancement is ~<10%

Ringwald and Wong (2004)
Villaescusa-Navarro et al (2011)
PF de Salas, S Gariazzo, J Lesgourges, S. Pastor
JCAP 09(2017)034



Relic Neutrino Capture Rates

Cocco, Mangano, Messina: JCAP 0706 (2007) 015

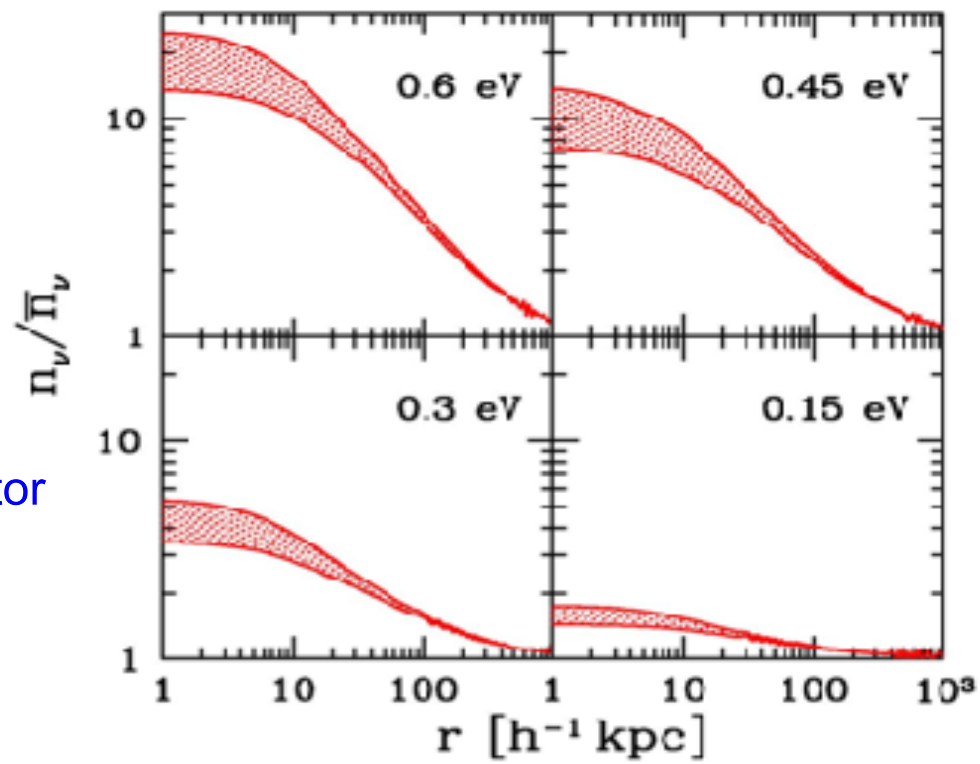
- Target mass: **100 grams of tritium** (2×10^{25} nuclei)
- Cross section $\sigma(v/c)=(7.84\pm0.03)\times10^{-45}cm^2$ (**known at <0.5 %)**
- Estimate of Relic Neutrino Capture Rate:

($56\ \nu_e/cm^3$) (2×10^{25} nuclei) ($10^{-44}\ cm^2$) (3×10^{10} cm/s) (3×10^7s)= **10 events/yr**

A. J. Long, C Lunardini and E Sabancilar JCAP 08(2014)038

Gravitational clumping could potentially increase the local number of relic neutrinos.
For low masses ~0.15eV, the local enhancement is ~<10%

Ringwald and Wong (2004)
Villaescusa-Navarro et al (2011)
PF de Salas, S Gariazzo, J Lesgourges, S. Pastor JCAP 09(2017)034



The

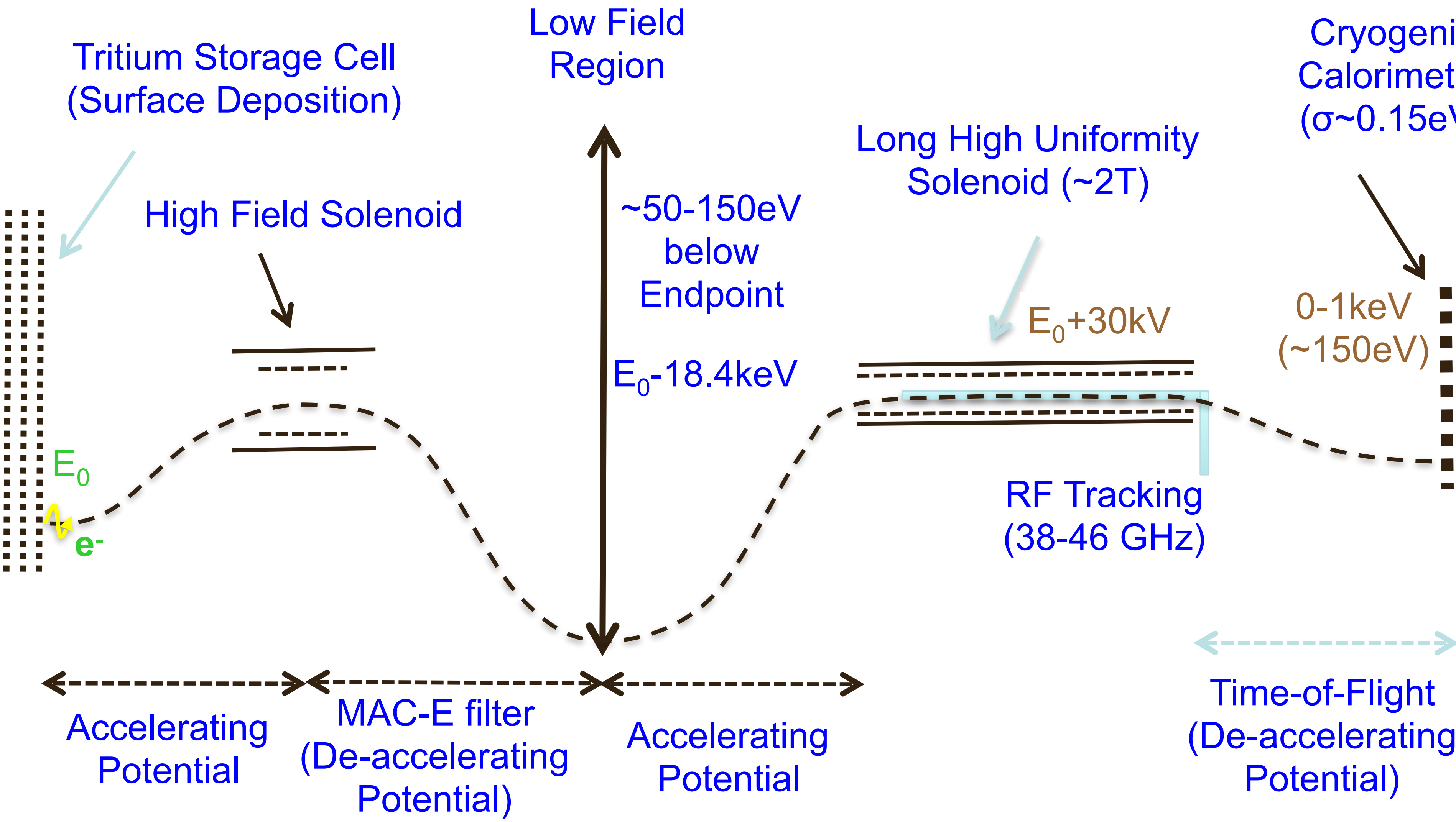
PTOLEMY

PonTecorvo**O**bservatoryforLight,**E**arly-Universe, **M**assive Neutrino **Y**ield

Experiment

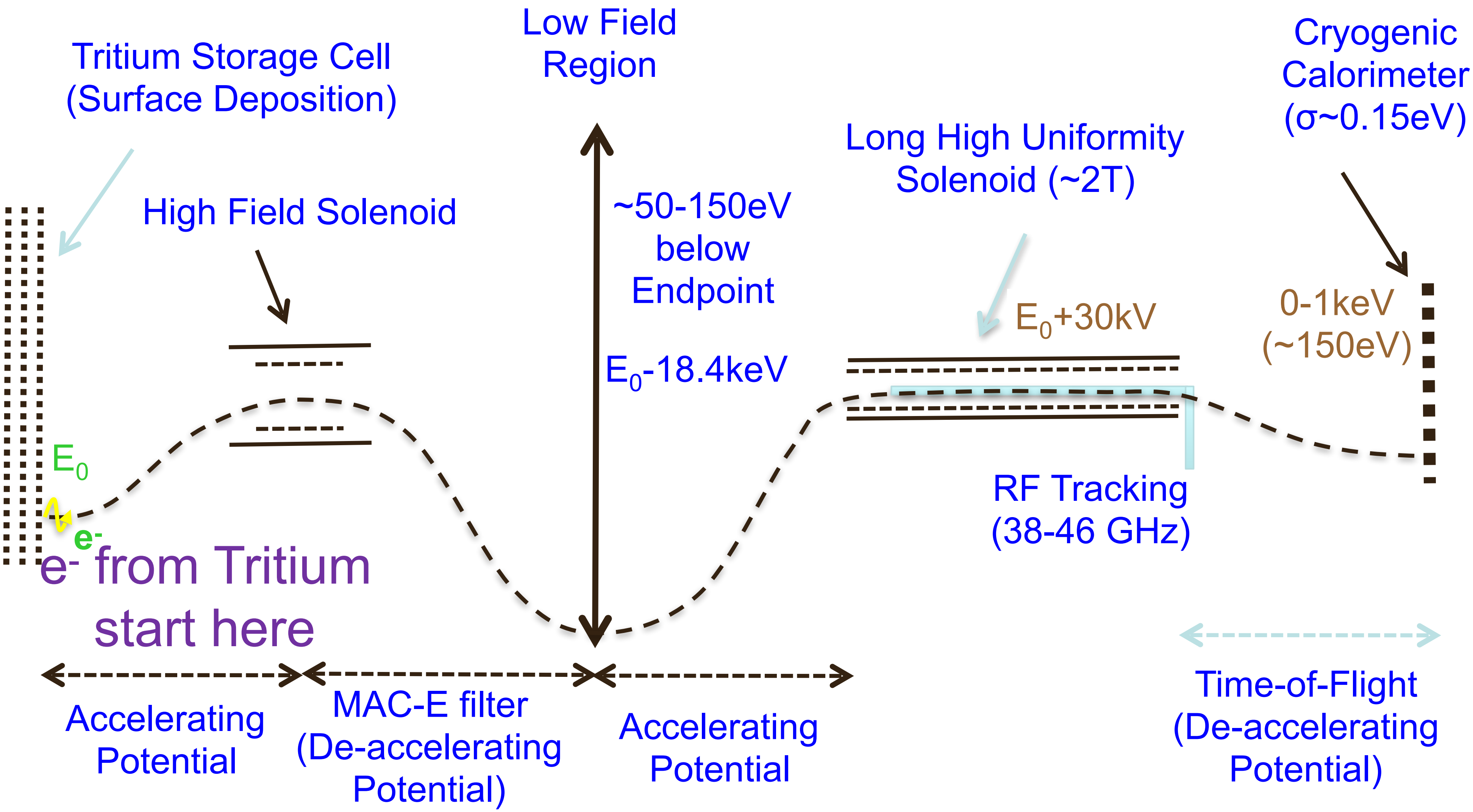
PTOLEMY Experimental Layout

Princeton Tritium Observatory for Light, Early-universe, **Massive-neutrino** Yield



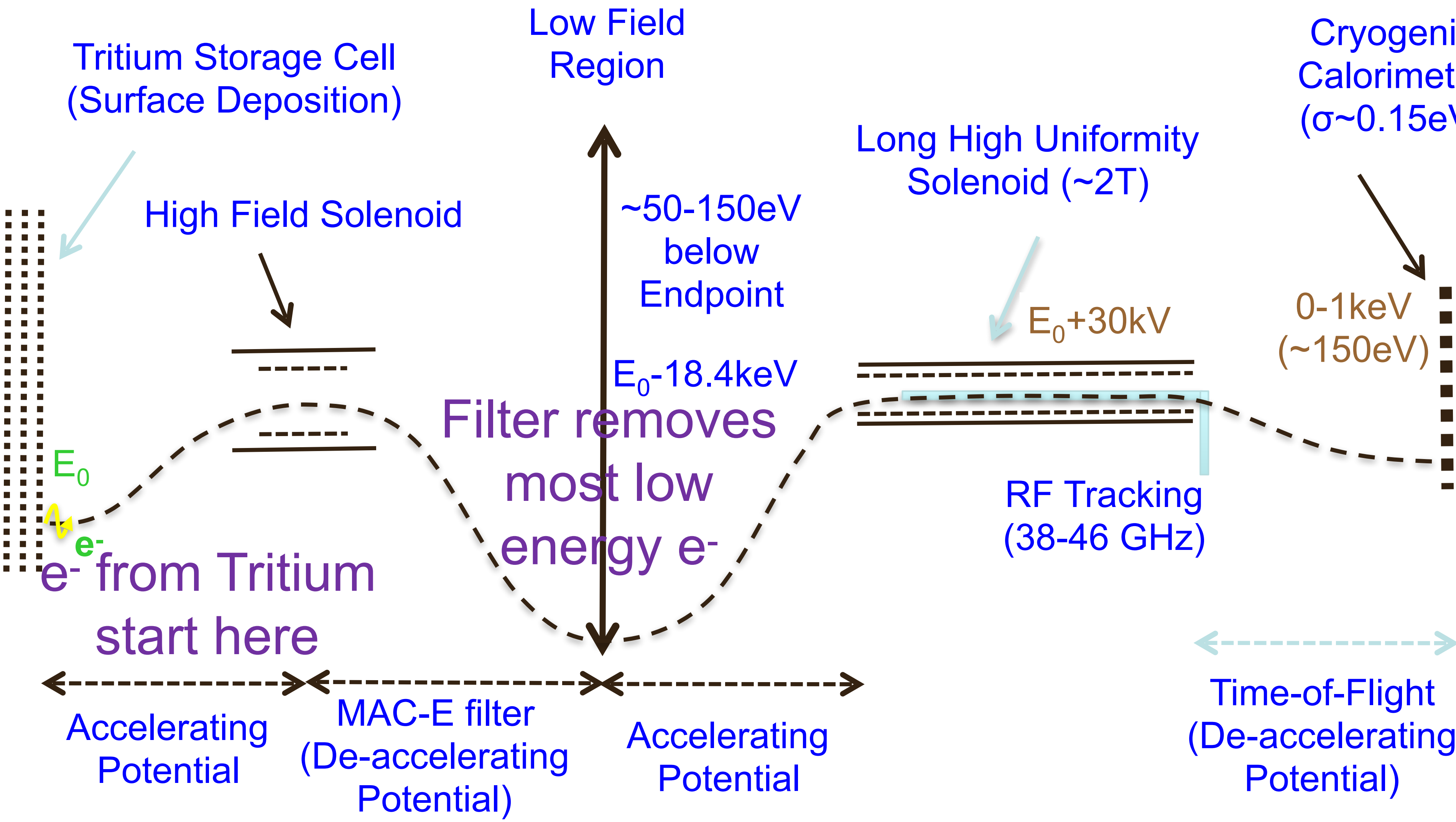
PTOLEMY Experimental Layout

Princeton Tritium Observatory for Light, Early-universe, **Massive-neutrino** Yield



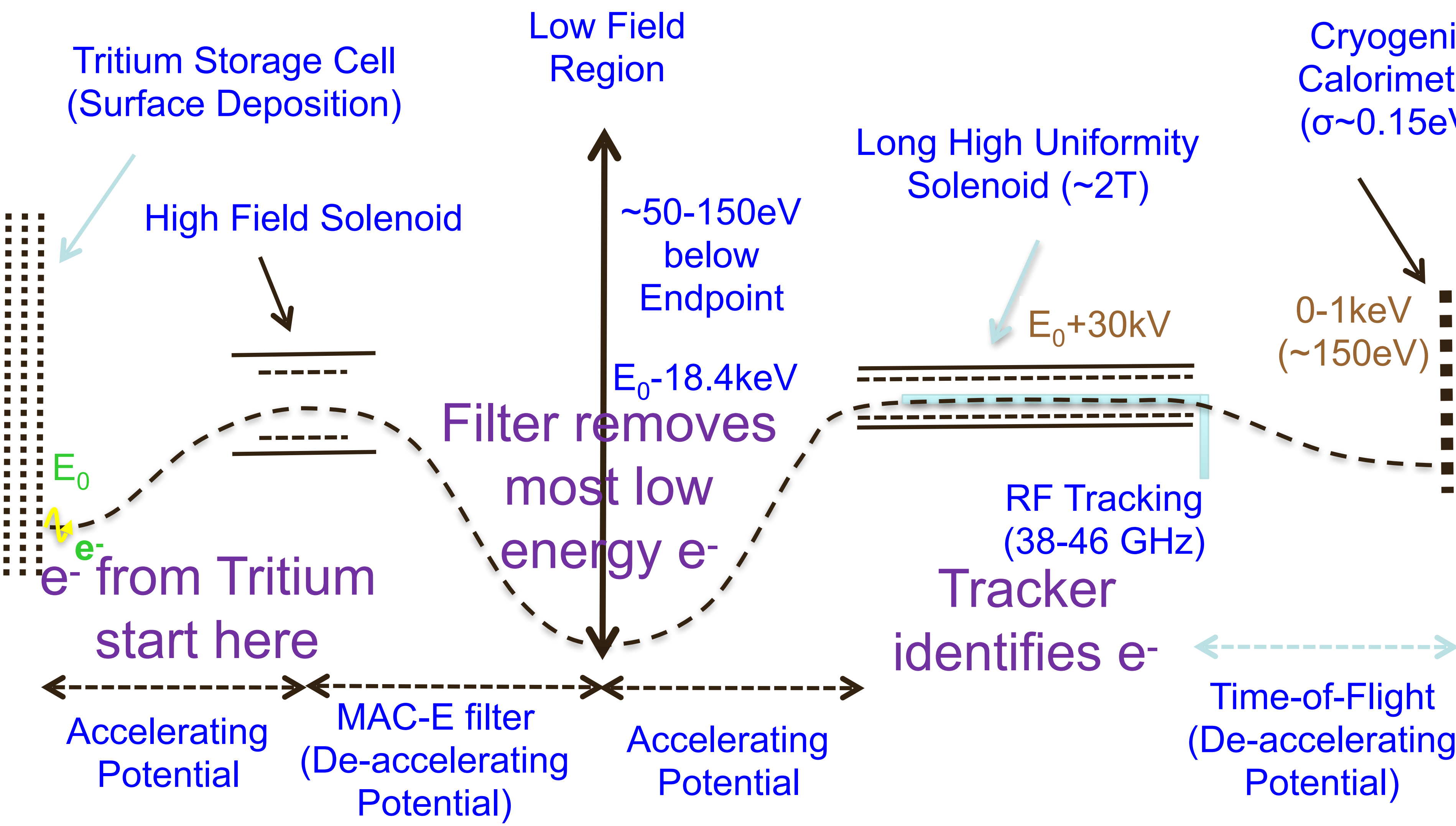
PTOLEMY Experimental Layout

Princeton Tritium Observatory for Light, Early-universe, **Massive-neutrino** Yield



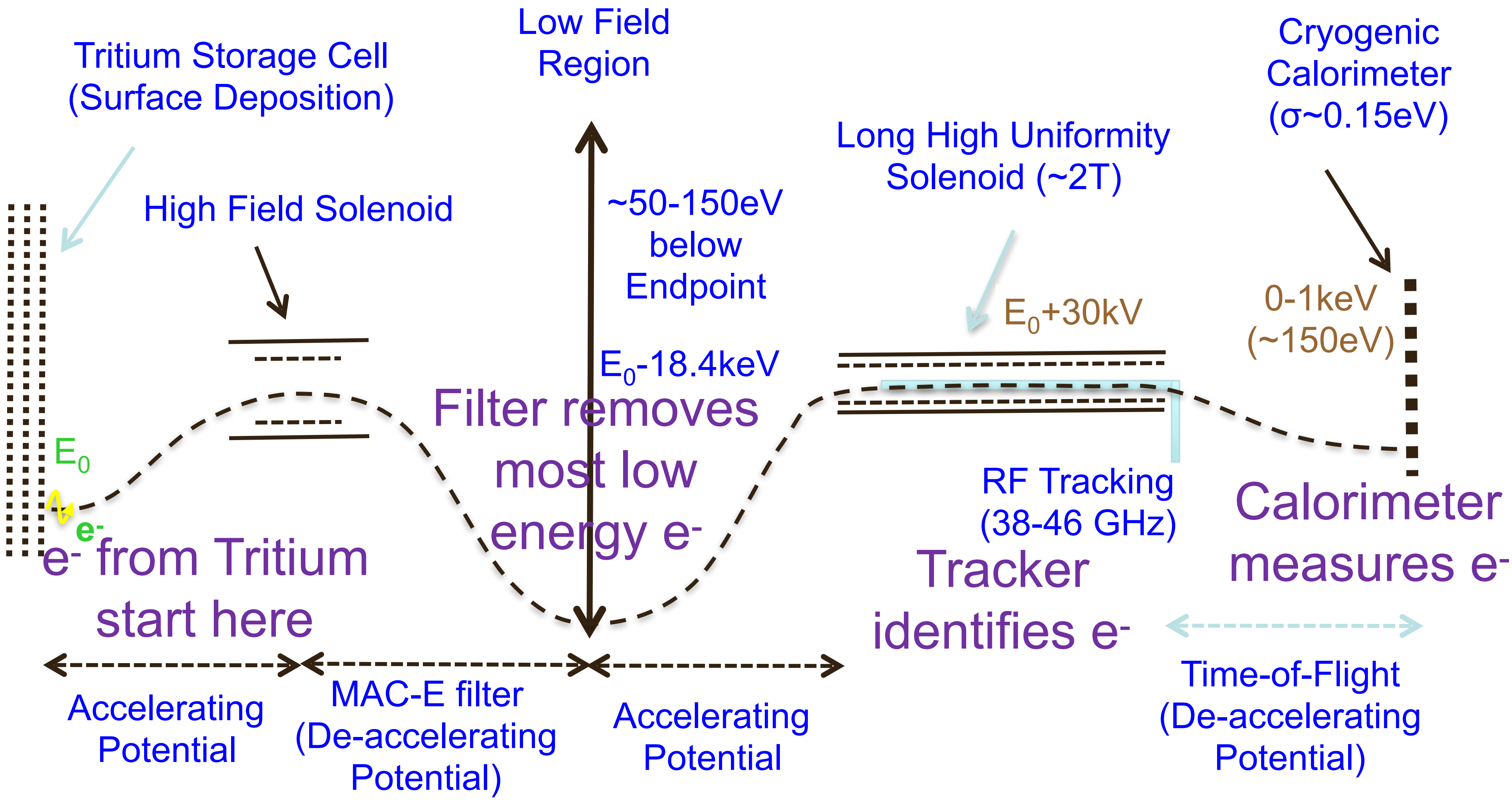
PTOLEMY Experimental Layout

Princeton Tritium Observatory for Light, Early-universe, **Massive-neutrino** Yield



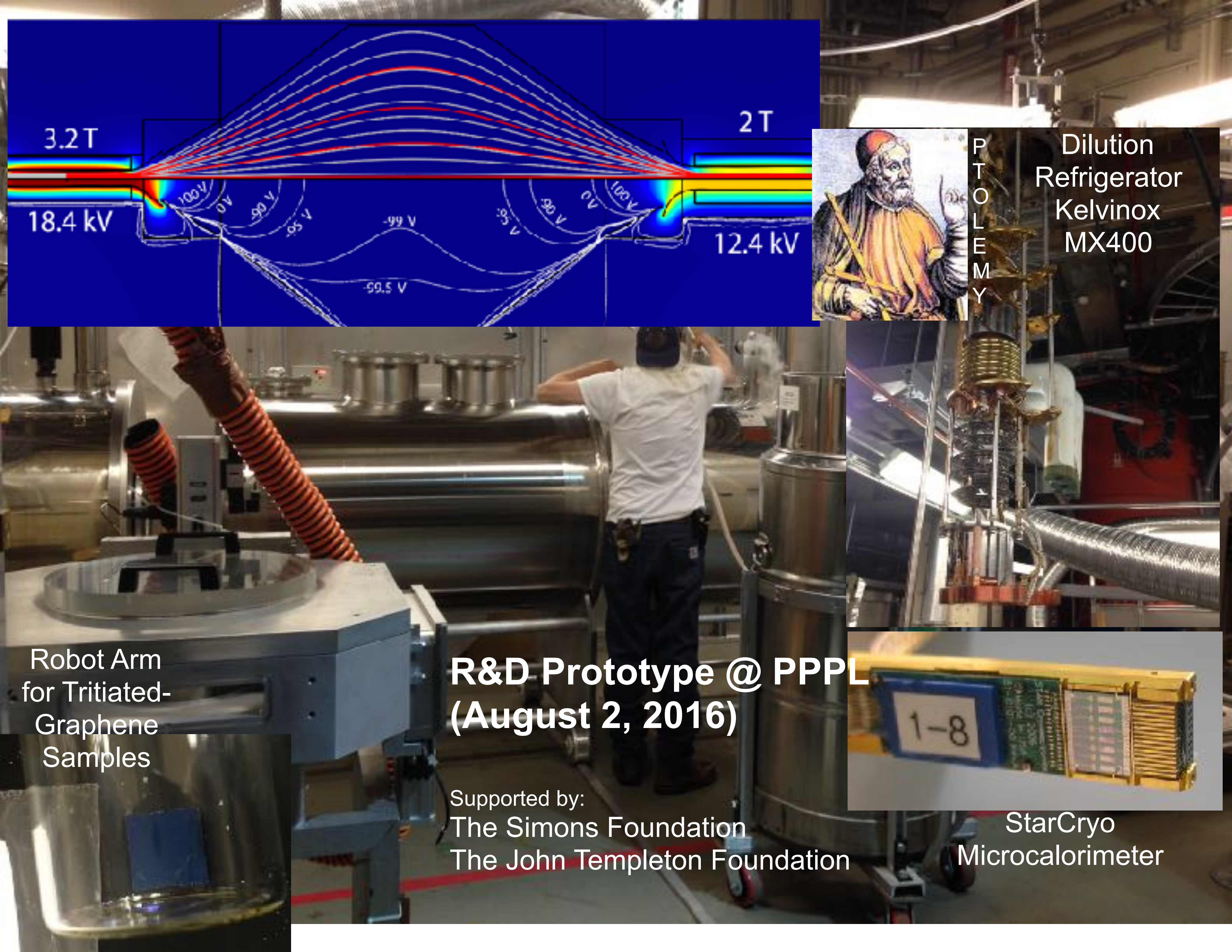
PTOLEMY Experimental Layout

Princeton Tritium Observatory for Light, Early-universe, **Massive-neutrino** Yield

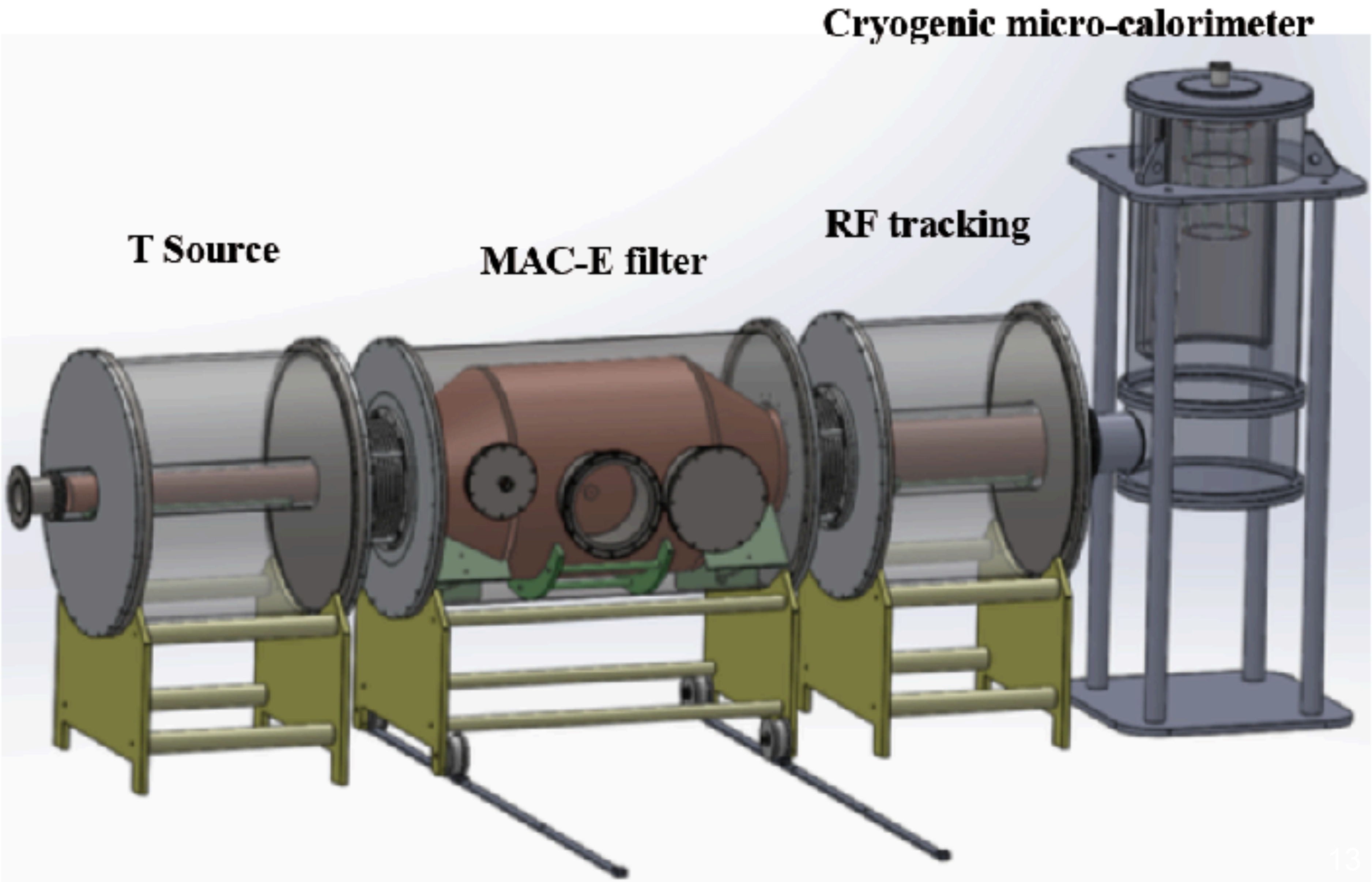


R&D Prototype @ PPPL (August 2, 2016)

Supported by:
The Simons Foundation
The John Templeton Foundation


3.2 T
18.4 kV
2 T
12.4 kV
-99 V
-99.5 V
PTOLEMY
Dilution Refrigerator Kelvinox MX400
Robot Arm for Tritiated-Graphene Samples
R&D Prototype @ PPPL (August 2, 2016)
Supported by:
The Simons Foundation
The John Templeton Foundation
1–8
StarCryo Microcalorimeter

The PTOLEMY prototype



Major Challenges

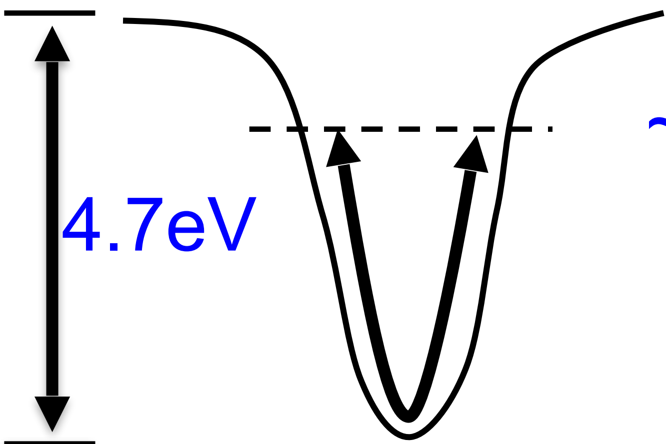
- Compress a 70m spectrometer length – KATRIN's length – down to ~cm scale and replicate it ~x10^4-10^6 and reduce e flow by 10^{14}
- Reduce molecular smearing
  - New source (Tritiated-Graphene)
- Measure the energy spectrum directly with a resolution comparable to the neutrino mass
  - High-resolution electron microcalorimeter
- New ExB filter concept
- RF trigger system
- Low ^{14}C

Molecular Broadening

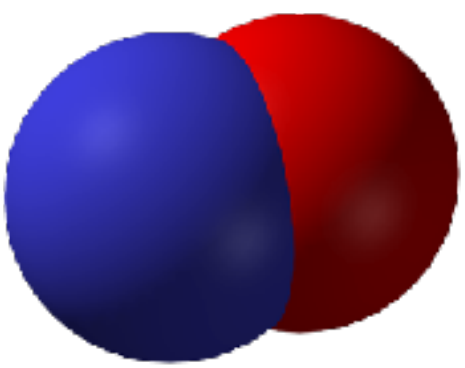
Tritiated-Graphene

- <3eV Binding Energy
- Single-sided (loaded on substrate)
- Planar (uniform bond length)
- Semiconductor (Voltage Reference)
- Polarized tritium(directionality?)

$T\text{-}T \rightarrow (T\text{-}He^3)^*$

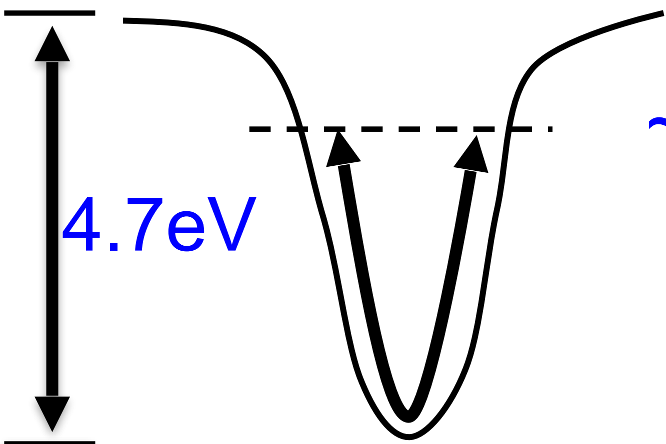


~3eV He^3 recoil at endpoint

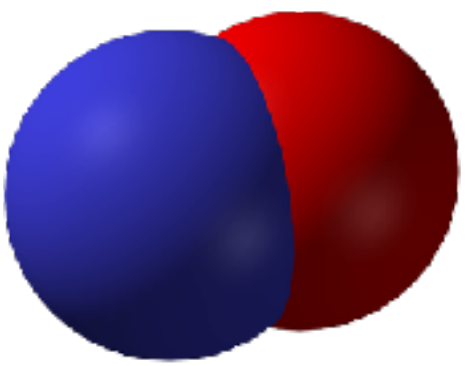


Molecular Broadening

T-T → $(T\text{-}He^3)^*$

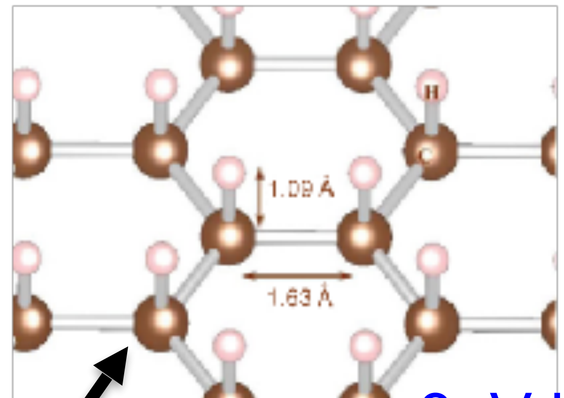


~3eV He^3 recoil at endpoint



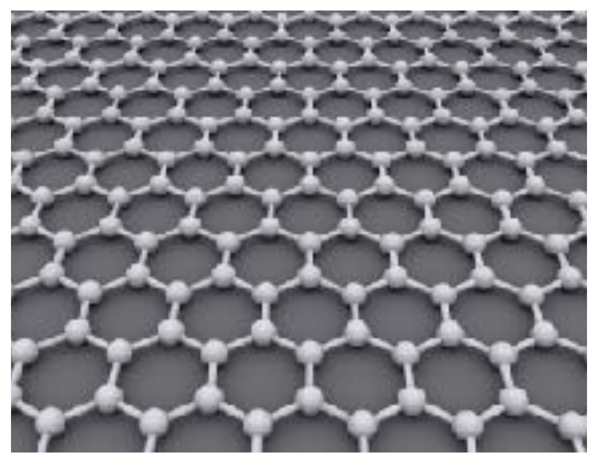
Tritiated-Graphene

- <3eV Binding Energy
- Single-sided (loaded on substrate)
- Planar (uniform bond length)
- Semiconductor (Voltage Reference)
- Polarized tritium(directionality?)

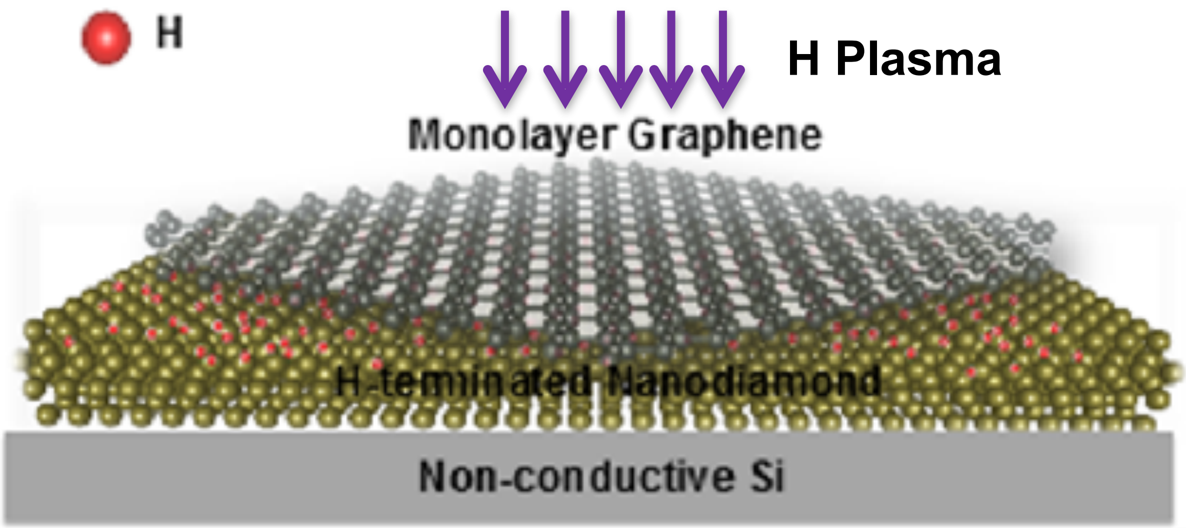


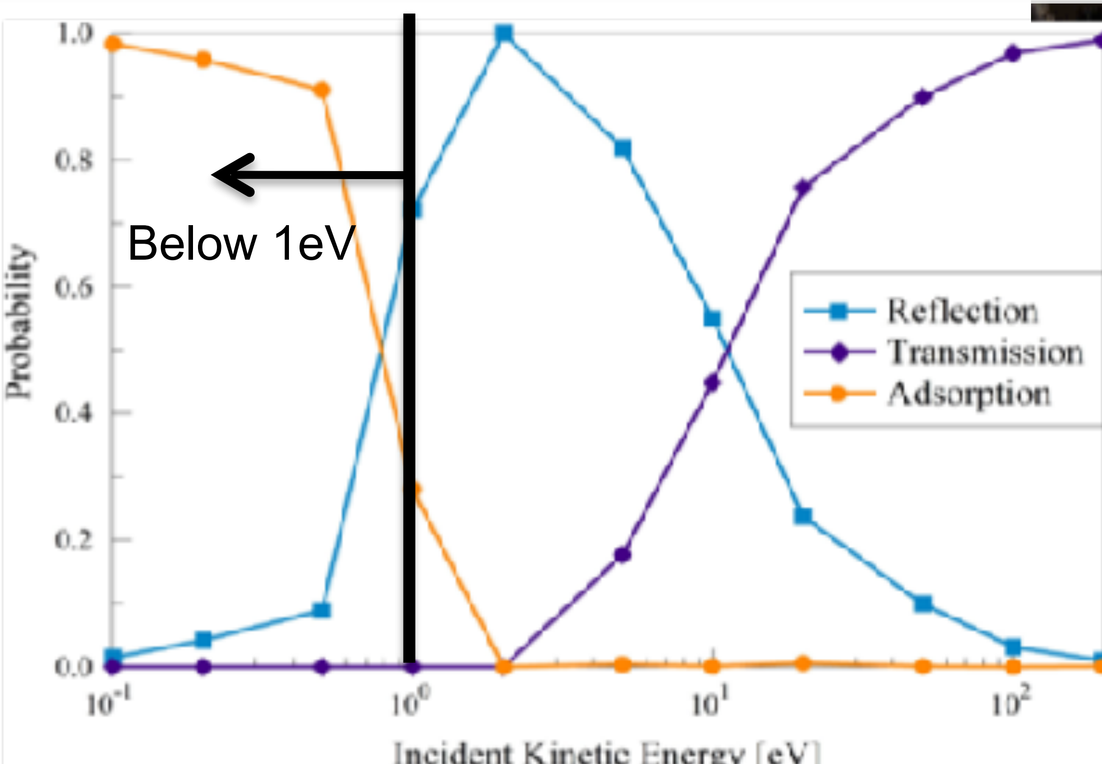
<3eV binding energy

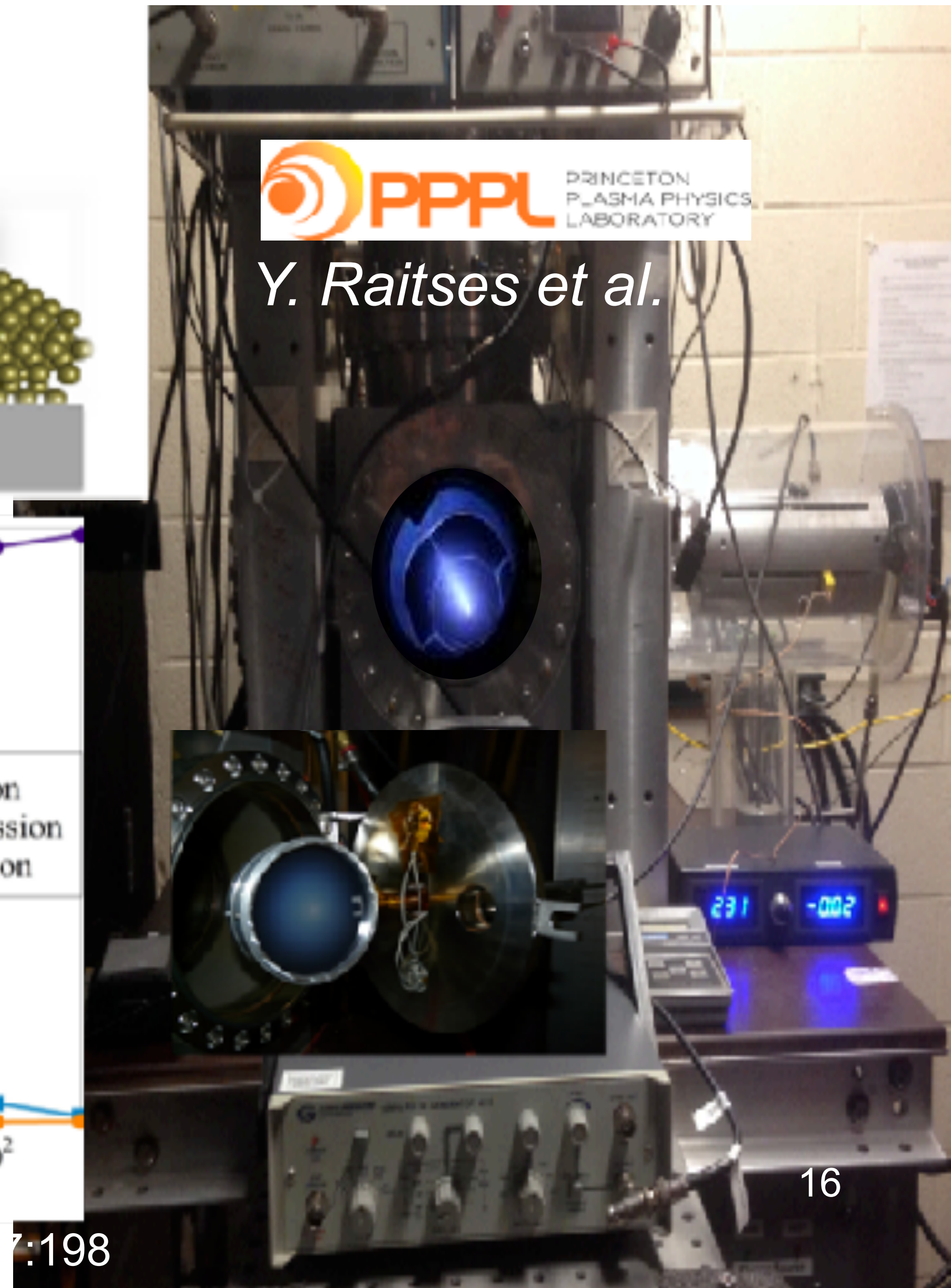
Graphene



Cold Plasma Loading

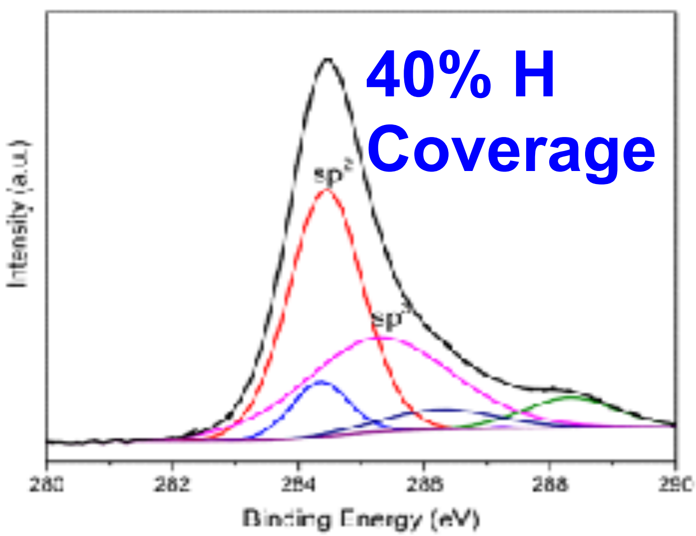






Cold Plasma Loading at PPPL

XPS (X-Ray Photoelectron Spectroscopy) Analysis: sp^2 is from unhydrogenated C atoms. sp^3 is hydrogenated C atoms. The area ratio of sp^2 and sp^3 is used to calculate H coverage.



H coverage summary from the literature

2009 Science	DC plasma. H coverage 10%
2009 ACS Nano	Capacitive coupled RF plasma. H coverage 17%
2010 APL	RF hydrogen plasma. H coverage 9%
2011, Carbon	Oxford Plasmalab 1000. H coverage less than 10%
2011 Advance Material.	STM hydrogen dose, Hydrogen coverage max 25.6%
2014, Applied materials &interfaces	RIE system. H coverage 33%
2015, ACS nano	HPHT. H coverage 10%

Best results – aim to achieve saturation at 100% while preserving quality of Graphene

New Results! → **BNL Center for Functional Nanomaterials**

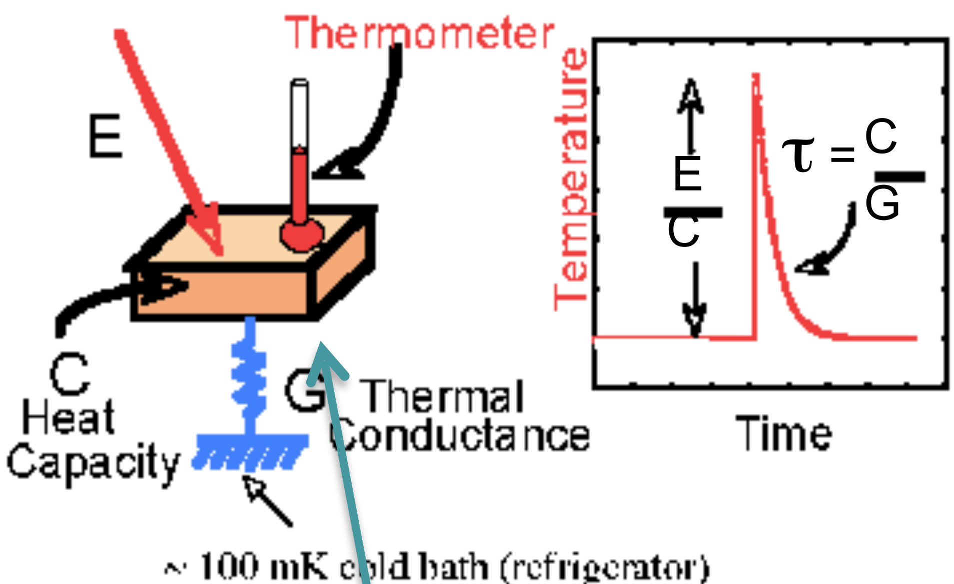
→ **Cryogenic Hydrogen loading and STM Analysis**

Calorimetric measurement

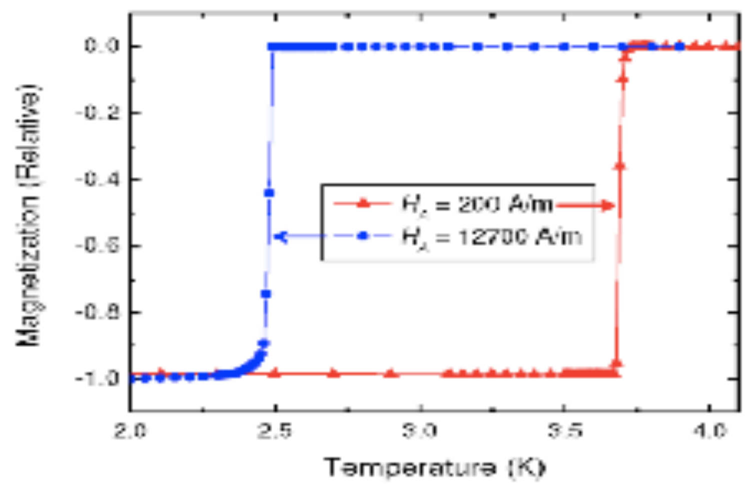
based on Transition Edges Sensors technology

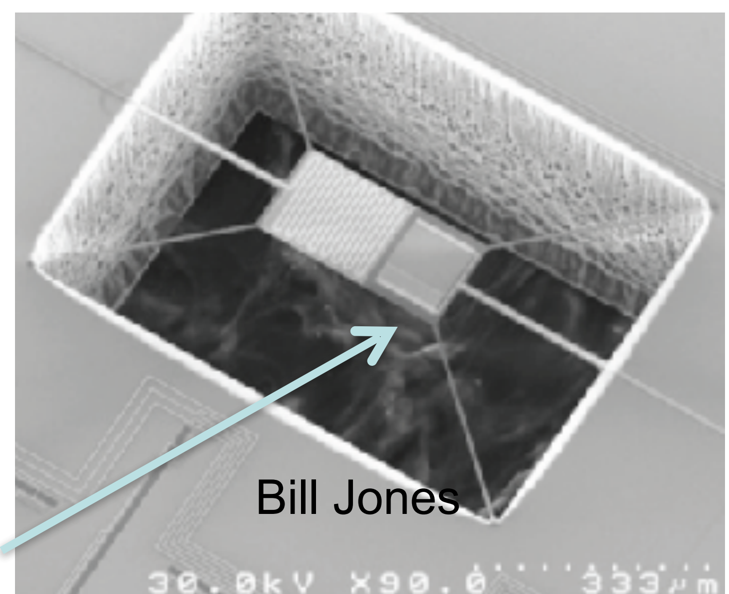
Resolution of ~0.55eV at 1keV and ~0.15eV at 0.1keV operating at 70-100mK under investigation (Clarence Chang ANL, Moseley et. al. GSFC/NASA)

Magnetic fields of few tens of Gauss may be able to thread through normal regions



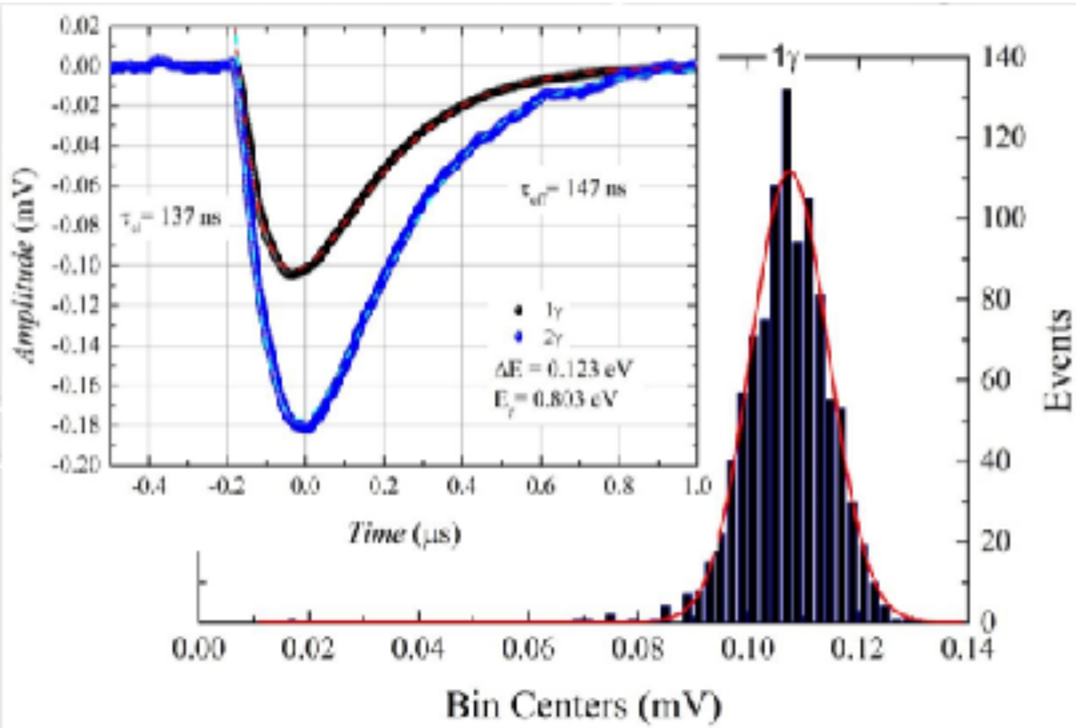
100 eV electron can be stopped in a very small absorber absorber i.e. small C





Microcal for IR Photons

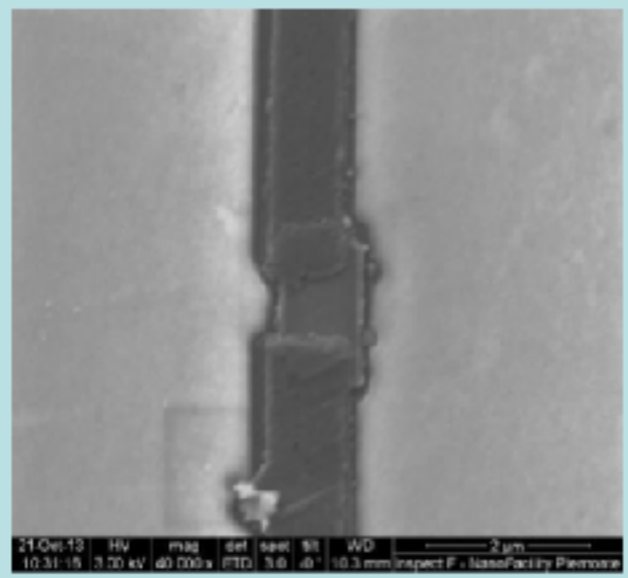
IR TES achieve 0.12 eV resolution at 0.8 eV for single IR photons



Results from INRIM (Torino) - Istituto Nazionale di Ricerca Metrologica

σ_E = 0.05**eV**

1 μm × 1 μm



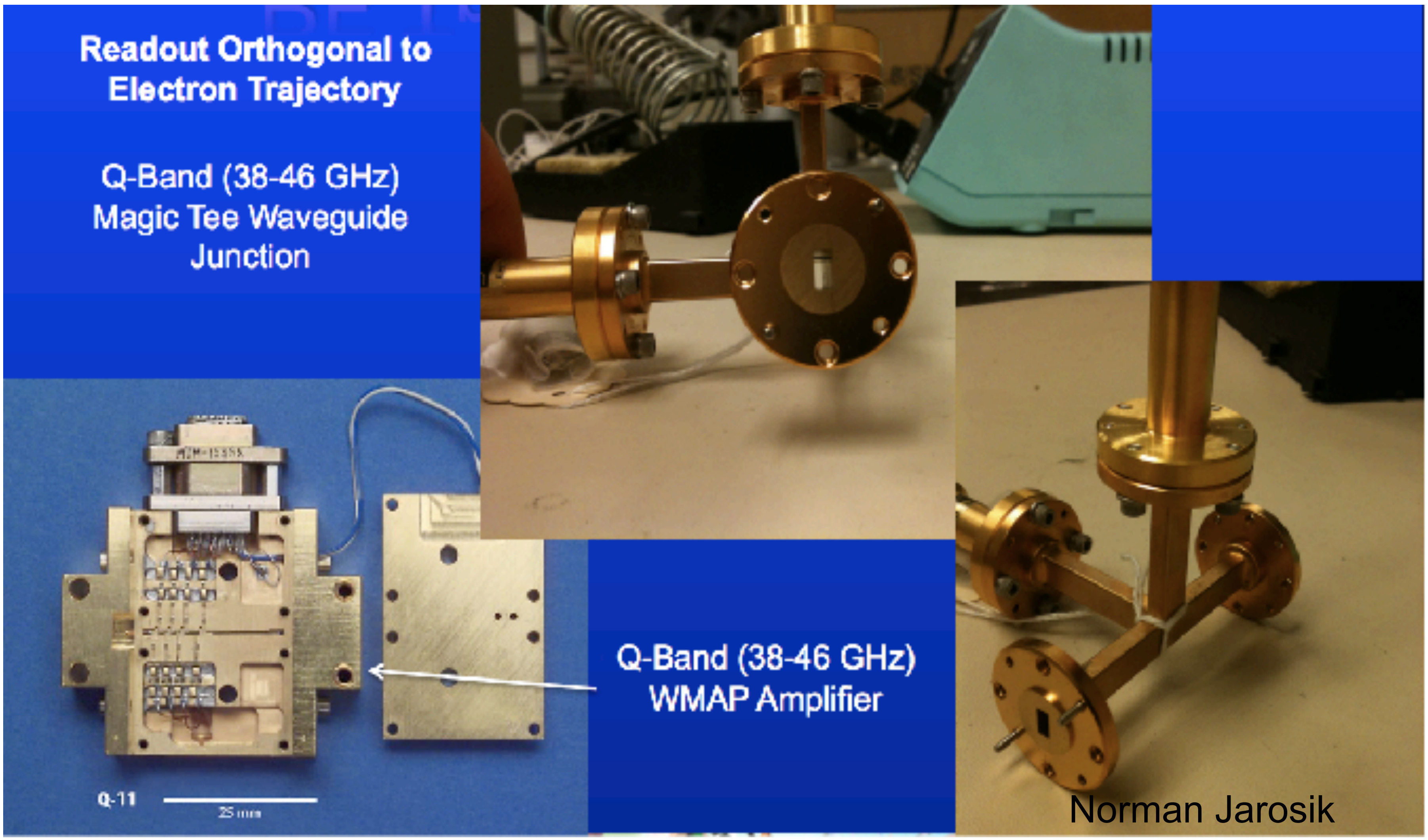
τ_{etf} = 147ns

ΔE_{FWHM} = 0.12 eV @ 1545nm

C. Portesi *et al*, IEEE Trans App Supercond, 25, 3, (2015)

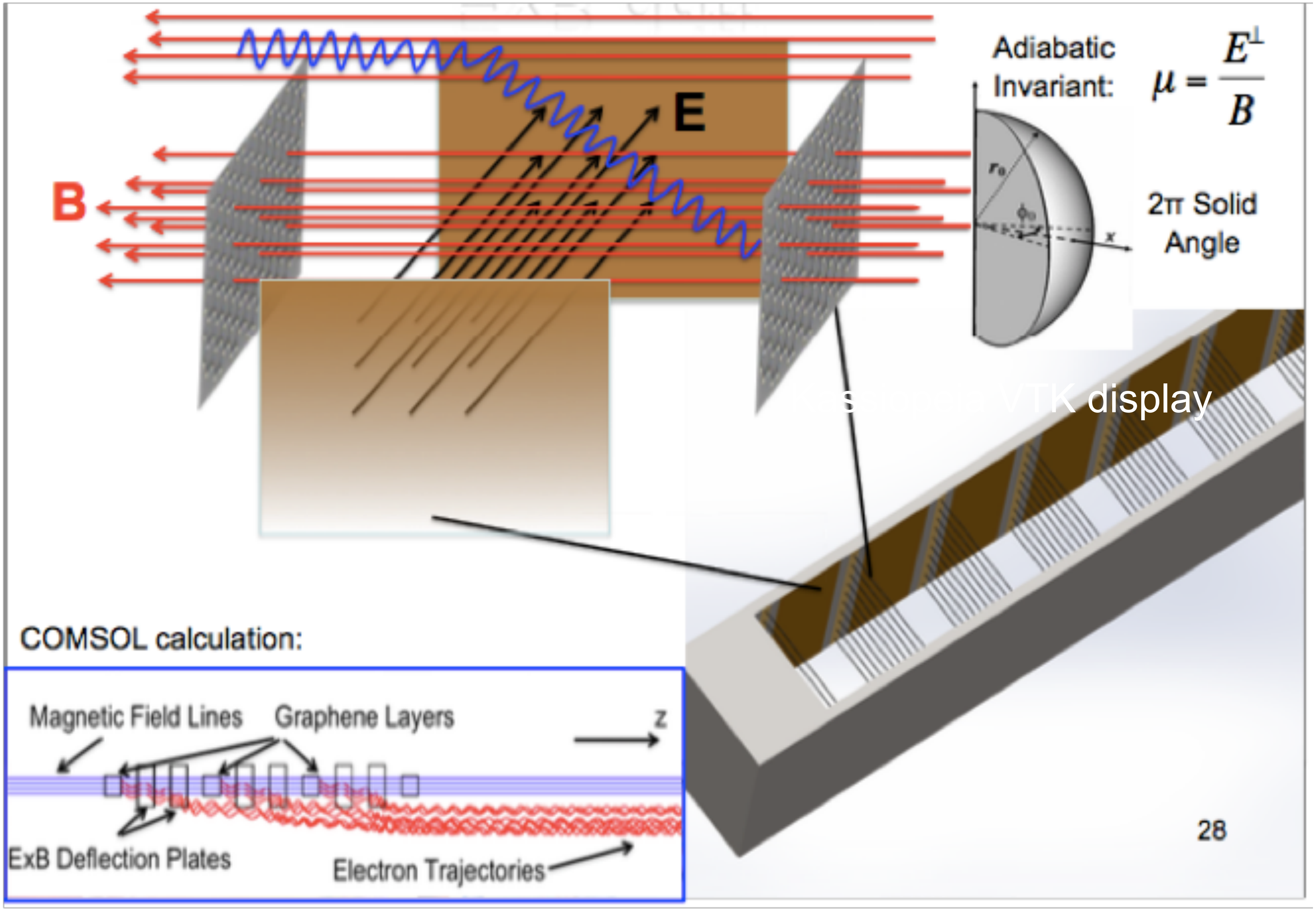
RF tracking and time-of-flight

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. The timing resolution expected is ~10ns depending on micro-calorimeter response.



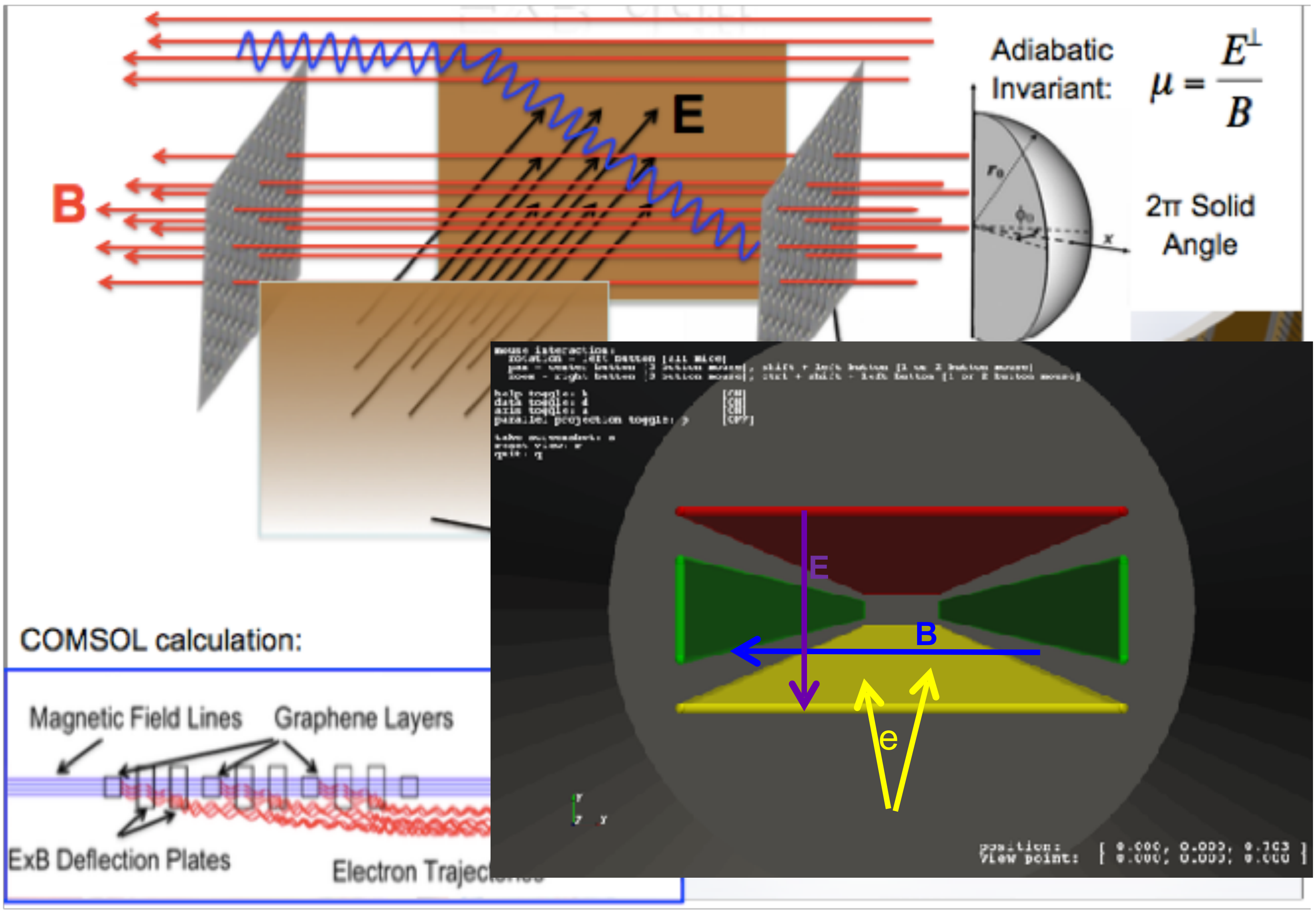
PTOLEMY multi-g

- Different geometries were investigated



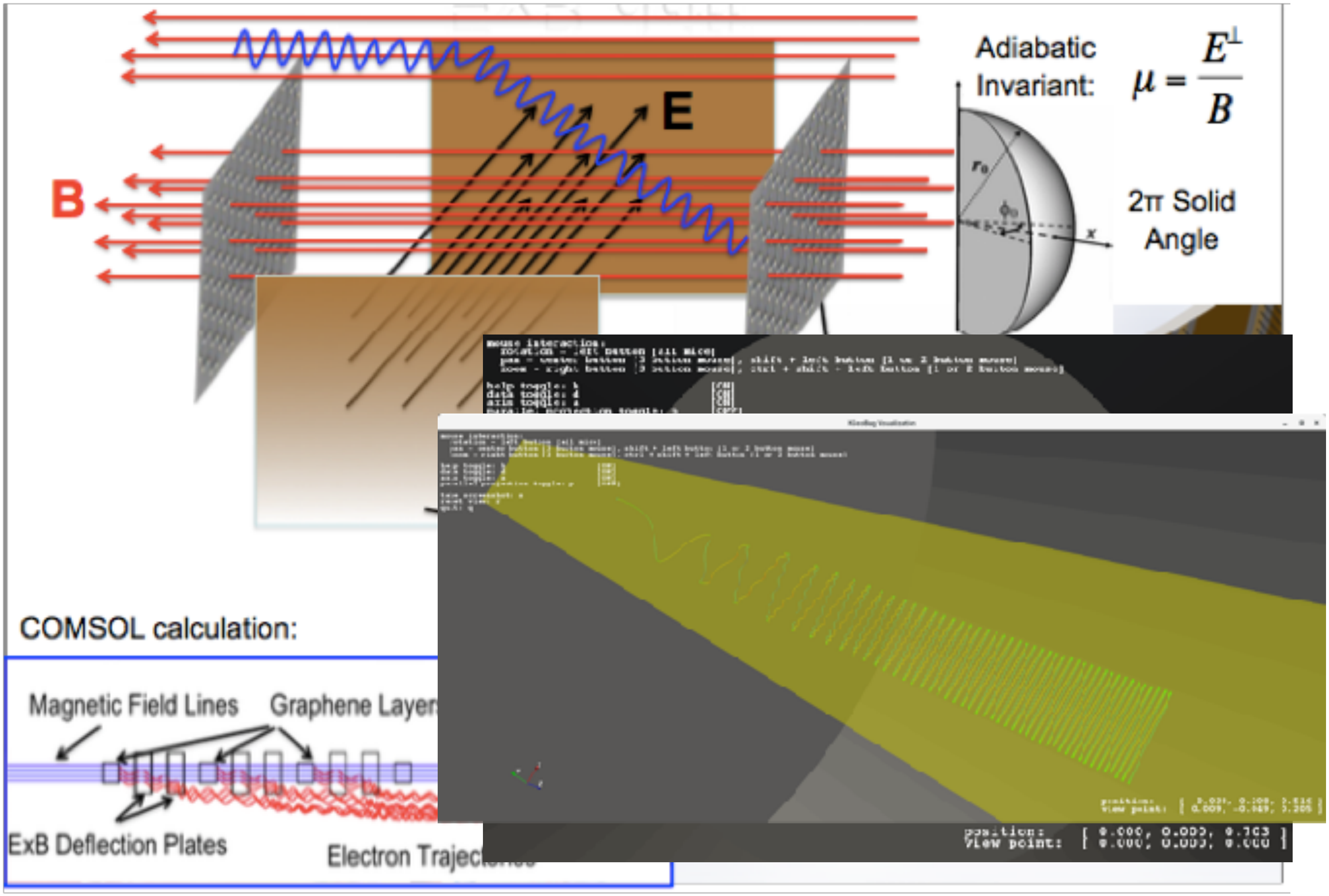
PTOLEMY multi-g

- Different geometries were investigated

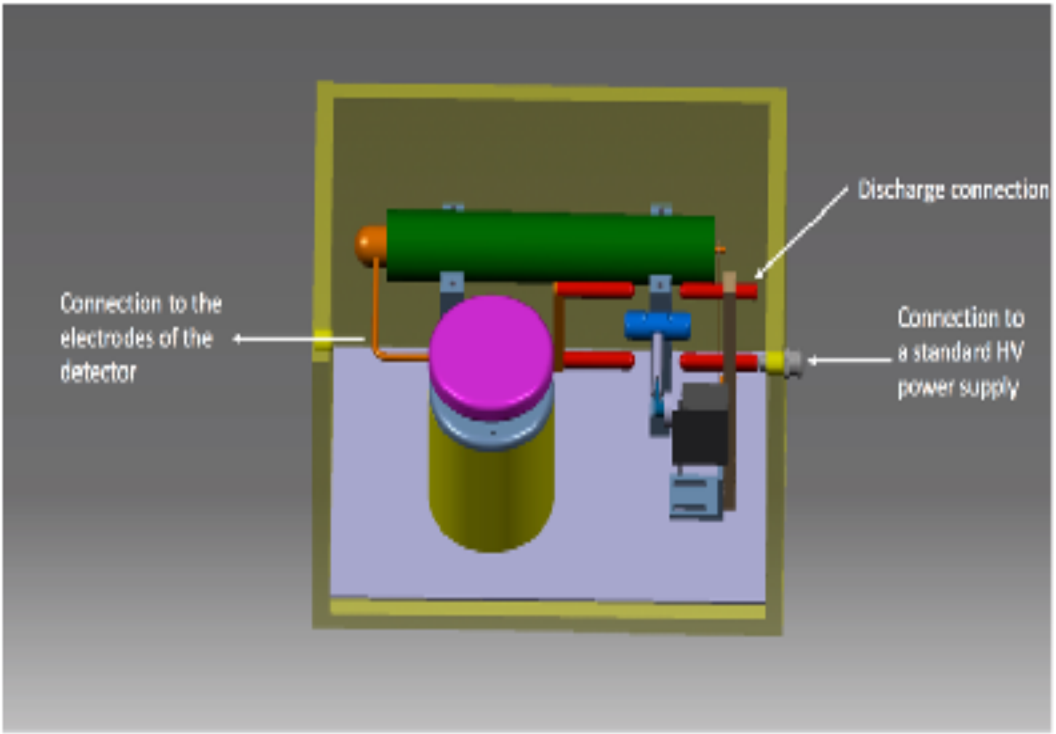


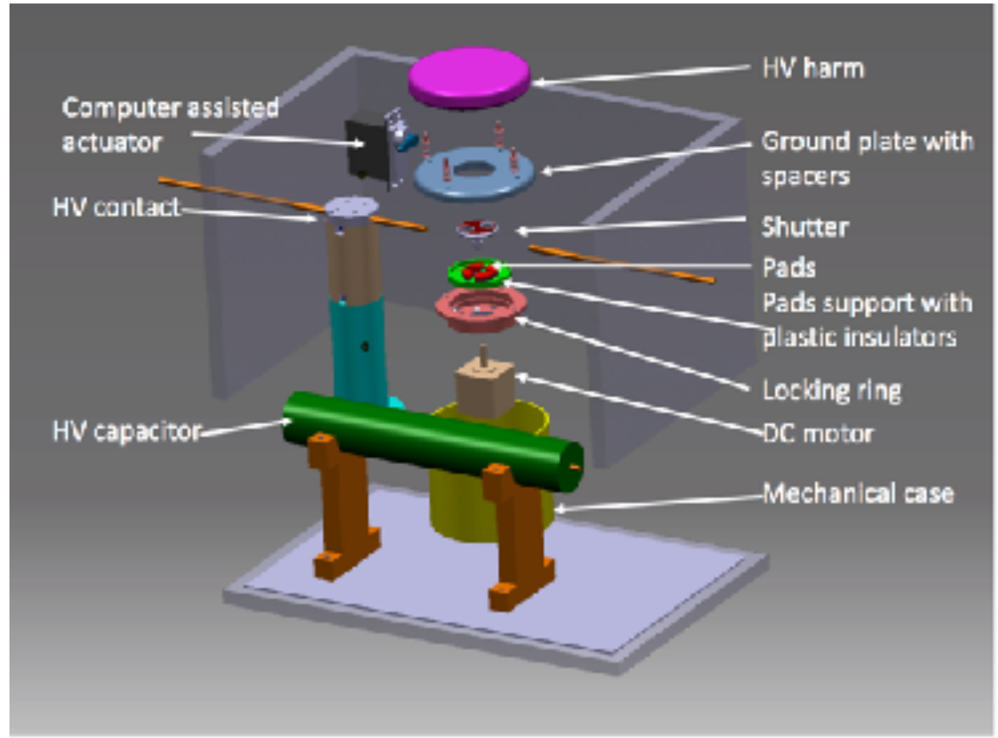
PTOLEMY multi-g

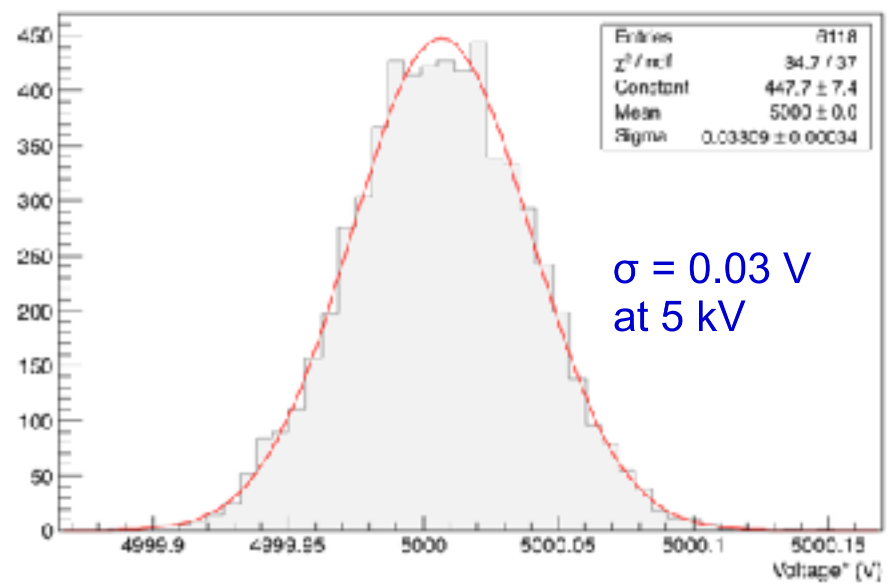
- Different geometries were investigated



High Voltage System and Monitoring







LoI submitted to the LNGS Scientific Committee and to the INFN-Commissione II

The LoI proposes to install and run the PTOLEMY prototype underground at LNGS to accomplish the proof of principle of the PTOLEMY experimental concept.

Waiting for approval

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

E. Baracchini[2], M.G. Betti[11], M. Biasotti[5], F. Calle[16], G. Cavoto[10,11], C. Chang[23,24], 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[17], E. Ferri[6], P. Garcia[14], G. Garcia Gomez-Tejedor[15], S. Gariazzo[17], F. Gatti[5], C. Gentile[25], A. Giachero[6], J. Gudmundsson[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[26], A. Molinero Vela[16], 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]

[1]Racah Institute of Physics, Hebrew University of Jerusalem, Jerusalem, Israel
[2]INFN Laboratori Nazionali del Gran Sasso, L'Aquila, Italy
[3]Gran Sasso Science Institute (GSSI), L'Aquila, Italy
[4]INFN Laboratori Nazionali di Frascati, Frascati, Italy
[5]Università degli Studi di Genova e INFN Sezione di Genova, Genova, Italy
[6]Università degli Studi di Milano-Bicocca e INFN Sezione di Milano-Bicocca, Milano, Italy
[7]INFN Sezione di Napoli, Napoli, Italy
[8]Università degli Studi di Napoli Federico II, Napoli, Italy
[9]Università degli Studi di Pisa e INFN Sezione di Pisa, Pisa, Italy
[10]INFN Sezione di Roma, Roma, Italy
[11]Università degli Studi di Roma La Sapienza, Roma, Italy
[12]Istituto Nazionale di Ricerca Metrologica (INRIM), Torino, Italy
[13]Nationaal instituut voor subatomaire fysica (NIKHEF), Amsterdam, Netherlands
[14]Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
[15]Consejo Superior de Investigaciones Científicas (CSIC), Madrid, Spain
[16]Universidad Politécnica de Madrid, Madrid, Spain
[17]Instituto de Física Corpuscular (IFIC), Valencia, Spain
[18]Stockholm University, Stockholm, Sweden
[19]Uppsala University, Uppsala, Sweden
[20]New York University Abu Dhabi, Abu Dhabi, UAE
[21]Lawrence Berkeley National Laboratory, University of California, Berkeley, CA, USA
[22]Department of Physics, University of California, Berkeley, CA, USA
[23]Argonne National Laboratory, Chicago, IL, USA
[24]Kavli Institute for Cosmological Physics, University of Chicago, Chicago, IL, USA
[25]Princeton Plasma Physics Laboratory, Princeton, NJ, USA
[26]Department of Physics, Princeton University, Princeton, NJ, USA

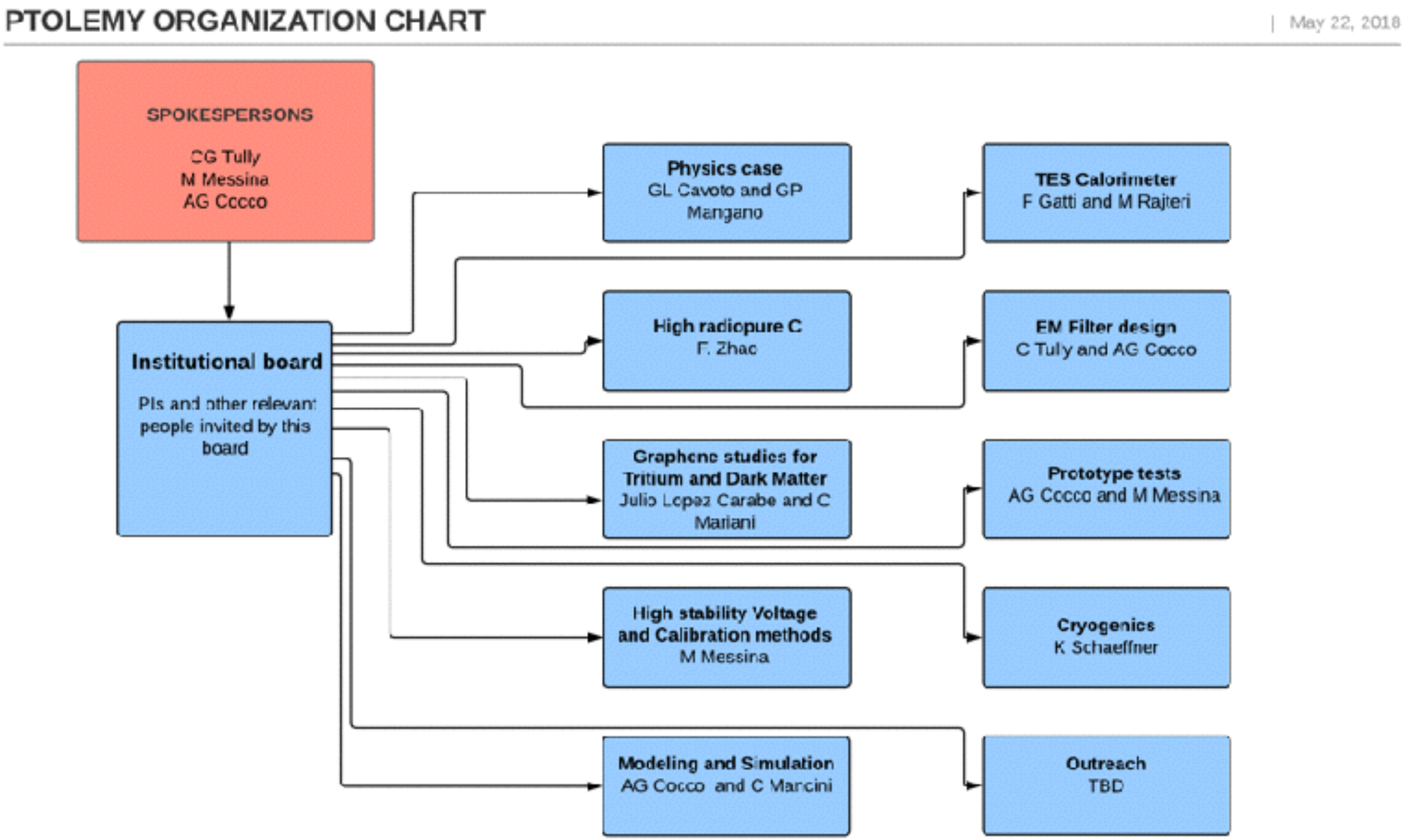
March 27, 2015

Abstract

We propose to achieve the proof-of-principle of the PTOLEMY project to directly detect the Cosmic Neutrino Background (CNB). Each of the technological challenges described in [1, 2] will be targeted and hopefully solved by the use of the latest experimental developments and profiting from the low background environment provided by the LNGS underground site. The first phase will focus on the graphene technology for a tritium target and the demonstration of TES micro-calorimetry with an energy resolution of better than 0.05 eV for low energy electrons. These technologies will be evaluated using the PTOLEMY prototype, proposed for underground installation, using precision HV controls to step down the kinematic energy of endpoint electrons to match the calorimeter dynamic range and rate capabilities. The second phase will produce a novel implementation of the EM filter that is scalable to the full target size and which demonstrates intrinsic triggering capability for selecting endpoint electrons. Concurrent with the CNB

World Map of the PTOLEMY collaboration

World Map of the PTOLEMY collaboration



Summary

What 10 years ago appeared to be challenging is presently much closer to be feasable.

Although a big amount of work is needed in order to properly design the detector

Models and simulations have been partially setup

Many more studies need to be done (e.g. E-gun, RF signal)

Many more (smart) ideas are needed

Collaborators are very welcome !!