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

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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[3]. The first phase will focus on the Graphene technology for a Tritium target and the demonstration of TES microcalorimetry with an energy resolution of better than 0.05eV for low energy electrons. These technologies will be evaluated using an existing MAC-E filter, suitable for underground installation, with 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 program, we plan to exploit and develop the unique properties of Graphene to implement an intermediate program for direct directional detection of MeV dark matter[4]. This program will evaluate the radio-purity and scalability of the Graphene fabrication process with the goal of using recently identified ultra-high radio-purity CO_2 sources. The direct detection of the CNB is a snapshot of early universe dynamics recorded by the thermal relic neutrino yield taken at a time that predates the epochs of Big Bang Nucleosynthesis, the Comic Microwave Background and the recession of galaxies (Hubble Expansion). Big Bang neutrinos are believed to have a central role in the evolution of the Universe and a direct measurement with PTOLEMY will unequivocally establish the extent to which these predictions match present-day neutrino densities.

[1]Betts, et. al, 2013. "Development of a Relic Neutrino Detection Experiment at PTOLEMY: Princeton Tritium Observatory for Light, Early-Universe, Massive-Neutrino Yield", `http://arxiv.org/abs/1307.4738`.

[2] A. G. Cocco, G. Mangano, M. Messina, "Probing low energy neutrino backgrounds with neutrino capture on beta decaying nuclei." JCAP. (2007) 0706:015. `http://dx.doi.org/10.1088/1742-6596/110/8/082014`.

[3]D. Mei, A. Hime, "Muon-induced background study for underground laboratories," Phys. Rev. D73 (2006) 053004.

[4]Hochberg, et. al, 2016. "Directional Detection of Dark Matter with 2D Targets", `http://doi.org/10.1016/j.physletb.2017.06.051`. Cavoto, Luchetta, Polosa, "Sub-GeV Dark Matter Detection with Electron Recoils in Carbon Nanotubes", `http://arxiv.org/abs/1706.02487`.

Overview

The basic concept for the detection of the Cosmic Neutrino Background (CNB) was laid out in the original paper by Steven Weinberg in 1962 and further refined by the work of Cocco, Mangano and Messina in 2007 in view of the finite neutrino mass discovered by oscillation experiments. An experimental realization of this concept was proposed based on PTOLEMY. As described below, PTOLEMY is an explicit set of technologies and approaches that systematically target with the goal of overcoming long-standing barriers to the direct detection of the CNB.

In summary, the experimental challenges for the PTOLEMY proof-of-principle are:

1) Reduce the molecular smearing in the CNB target to below 0.05eV,
2) Achieve an electron energy measurement resolution of 0.05eV to separate the CNB signal from the β-decay spectrum,
3) Demonstrate high radio-purity in the Graphene target and low background rate in the CNB signal region – concurrent with a physics program in MeV dark matter searches,
4) Demonstrate intrinsic triggering capability for selecting endpoint electrons, and
5) Design and simulate a scalable target mass with high acceptance kinematic filtering.

Of these experimental challenges, substantial progress has already been made on 1) and 2) with world's best records in hydrogenation of Graphene (Princeton) and $\Delta E_{FWHM} = 0.12$eV energy resolution for 0.8eV IR photons at 300mK (INRIM, Torino). To further evaluate and validate the proof-of-principle for these developments, a low background evaluation setup is needed. An existing MAC-E filter from Princeton can be shipped to LNGS. The filter is to be equipped with a precision HV system under development at LNGS to reference and step down the 18.6keV kinematic energy of endpoint electrons to match the dynamical range of the TES calorimetry. Possible reference sources for the evaluation include a precision electron gun, short-lived calibration EC line sources and a very low activity tritium-loaded Graphene sample of 1nanogram (370kBq). In the current system, the stability of the HV from surface measurements appears to be subject to cosmogenic discharging phenomena. Low background conditions are also needed to further evaluate the sensitivity to the radio-purity of the Carbon in the Graphene. By partnering with industry the goal is to evaluate Graphene fabricated using recently identified ultra-high purity CO_2 sources. A complementary physics program based on high radio-purity 2D Graphene targets is proposed to further the research into backgrounds originating from the Graphene target, under 3), and to add directional detection sensitivity to MeV dark matter searches. On point 4), the identification of semi-relativistic endpoint electrons will reduce non-electron background and provide triggering information for the calorimeter measurement. The technique of single electron detection from cyclotron emission spectroscopy was pioneered by the Project 8 collaboration and in PTOLEMY the approach is to use this technique for triggering on endpoint electrons. The development of RF techniques is advancing within Project 8 and at this stage the implementation of triggering will be estimated through simulation as part of the scalability studies. The fifth goal of scalability is most efficiently investigated in the domain of simulation of EM fields and particle tracking while also pursing through industry contacts the possibilities for low-cost wafer-level fabrication processes for Graphene. The scalability studies will be done concurrently with the experimental program at LNGS and may involve evaluation prototypes at a later phase to validate simulations results.

Proposed Program of Work

In this section contains a breakdown of each of the proof-of-principle milestones described in the Overview and details the program of work to complete those measurements.

Goals 1) and 2)

The evaluations of goals 1) and 2) will proceed in parallel, as the procedure for evaluating the molecular smearing of the substrate is common to the benchmarking of the TES calorimeter energy resolution. The underground installation is for full system tests from source to calorimeter in the sense of a spectrometer lab facility. Initial evaluations of the Graphene target quality and similarly the IR photon response of the TES micro-calorimeter will first go through bench top measurements before being installed in LNGS.

The components of the PTOLEMY spectrometer consist of the following:

- Dilution Refrigerator (Kelvinox MX400 - Oxford Instruments). Lowest base temperature is 7mK and up to 400mW of cooling power is provided at 100mK. Custom cryostat with a sample space exceeding a volume of 10^3 cm^3 and with a vacuum path connecting to a horizontal port matching the vertical height of the horizontal bore magnets.
- StarCryo Precision X-Ray TES Calorimeter and SQUID readout system.
- 4.7T Oxford Instruments 200/330 horizontal bore superconducting magnet.
- 7.05T Oxford Instruments 300/183 horizontal bore superconducting magnet.
- Central vacuum tank hosting a 9-segment high precision HV electrostatic filter. The MAC-E filter achieves a 1% energy resolution and a novel HV reference system developed at LNGS based on precision voltages held on capacitors with field mill sensing. Oerlikon Leybold TurboVAC 450 iX (160CF) and ScrollVAC SC15D pumping system.
- Robot arm (Genmark) for loading wafers in vacuum.

These components are shown in Figure 0-1 in their current location in the Princeton University Physics Department. The procedures for the shipment, installation and operation for the commercial equipment from Oxford Instruments are all documented in manuals.

The first step is to install the dilution refrigerator, then the calorimeter and readout electronics. We would verify that we can reproduce bench top measurements with a small IR photon calibration source within the DR. In parallel, the central vacuum tank would be pumped down and the HV cables through the feedthroughs would connect the nine electrodes to the divider. The stability of the voltages would be monitored and adjusted until they reach bench top precision and stability through field mill measurements. The next step is to make a windowless interconnect between the DR and the central vacuum tank. This can be done initially without magnetic field. In this configuration a reference electron source, starting with a precision electron gun, would be used to verify the precision of the voltage reference with the TES micro-calorimeter measurement. Upon achieving this milestone, the magnets would be energized in order to use an EC line source or low activity β-decay source to verify the precision of the microcalorimeter. This measurement would achieve the proof-of-principle on the energy resolution and with comparison of a very low activity β-decay source on the Graphene will succeed in achieving goals 1) and 2).

Figure 0-1. *PTOLEMY prototype located in Jadwin Hall Physics Department, Princeton University (9 June 2017) showing the readout rack (far wall), Kelvinox MX400 dilution refrigerator (gas handler and pumps), 4.7T Oxford Instruments 200/300 superconducting magnet, central vacuum tank (copper electrodes and HV feed-throughs) and 7.05T Oxford Instruments 300/183 superconducting magnet.*

Goal 3)

The development goals of high radio-purity Graphene targets are two-fold. The first is to yield a low background target for the CNB measurement, and the second is for the deployment of high sensitivity detectors using the unique properties of Graphene. The proposal is to focus initially on the later goal and to conduct a significant MeV dark matter search with novel Graphene-based detectors, described on [4]. The count rate requirements are more stringent for MeV dark matter searches due to the broad energy spectrum of recoil electrons (described below). For the low background target development, with a projected CNB event rate of 10 events/year for a full scale target the background rate count in a 0.1eV energy window at the 18.6keV endpoint must be no more than 1 selected event per year. Due to the narrow energy window for the signal and the additional background rejection expected from goal 4), the CNB background from ^{14}C at the levels achieved in Borexino are sufficient to achieve this goal. The Graphene target will follow high radio-purity wafer-level fabrication procedures[5]. The support structures will use materials that have achieved high radio-purity[6].

With a small-scale deployment of PTOLEMY-G^3, a fiducialized volume of 10^3 cm^3 consisting of 100 stacked 4-inch wafers will search down to approximately $\bar{\sigma}_e = 10^{-33}$ cm^2 at 4 MeV in one year, uncovering a difficult blind spot inaccessible to current nuclear recoil experiments. This new approach will open up for the first time direct directional detection of MeV dark matter, a capability that no other light dark matter proposal has and which would be highly complementary to a detection, for example, in DAMIC or SENSEI.

[5] Low background contamination lithography has been demonstrated, see for example "Cryogenic Dark Matter Search detector fabrication process and recent improvements" by Jastram et. al, 2015. NIM A: 772:14-25.

[6] X. Chen, et al., "PandaX-III: Searching for Neutrinoless Double Beta Decay with High Pressure 136Xe Gas Time Projection Chambers," Sci. China Phys. Mech. Astron. 60 (6) (2017) 061011. `arXiv:1610.08883`, `doi:10.1007/s11433-017-9028-0`.

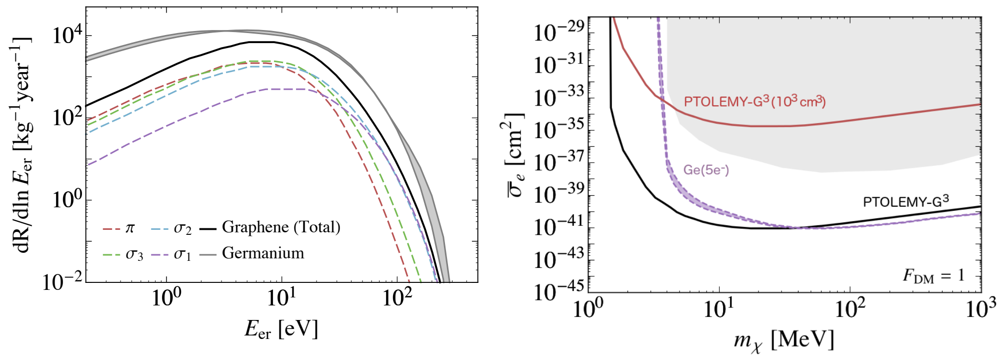

Figure 0-2. (left) *Differential rate for a 100 MeV DM particle scattering off an electron in graphene is shown with the solid black line with* $\bar{\sigma}_e = 10^{-37}$ *cm*^{2} *and* $F_{\rm DM}(q) = 1$. (right) *Expected background-free 95% C.L. sensitivity for a graphene target with a 1-kg-year exposure (black). A first experiment with a G*^{3} *volume of 10*^{3} *cm*^{3} *(target surface of 10*^{4} *cm*^{2}*) will search down to approximately* $\bar{\sigma}_e = 10^{-33}$ *cm*^{2} *at 4 MeV.*

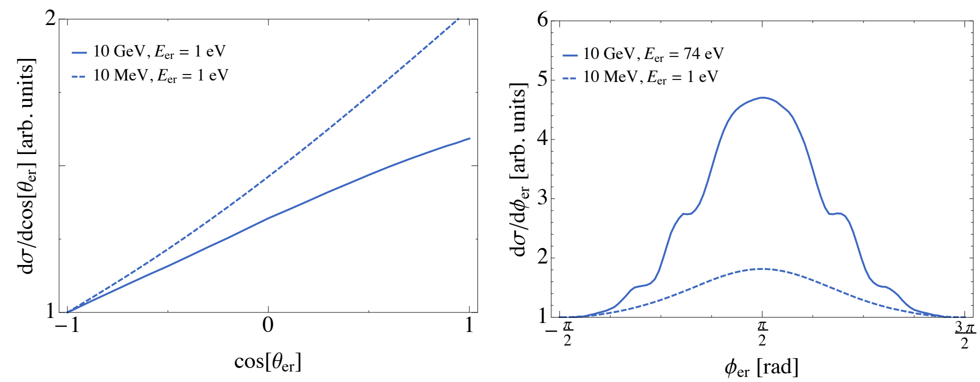

Figure 0-3. *Predicted angular distributions for DM masses 10 MeV (dashed) and 10 GeV (solid) in a DM stream with* $v_{\rm stream} = 550$ *km/s in the lab frame.* (left) *Polar distribution of the final-state electron when the stream is oriented perpendicular to the graphene plane and points along* $\cos\theta = 1$. (right) *Azimuthal distribution of the final-state electron when the stream is oriented parallel to the graphene plane and points along* $\phi = \pi/2$. *The outgoing electron direction is highly correlated with the initial DM direction.*

The G-FET sensor has a tunable meV band gap, a full three orders of magnitude smaller than cryogenic germanium detectors. This sensitivity is used to switch on and off the conductivity of the G-FET channel by 10 orders of magnitude in charge carriers in response to the gate voltage shift from a single scattered electron. A narrow, vacuum-separated front-gate imposes kinematic discrimination on the maximum electron recoil energy, where low energy recoil electrons above the graphene work function follow FET-to-FET directional trajectories within layers of the fiducialized G^3 volume. Each FET plane will be vacuum sealed on top and bottom during assembly. The target will be kept at cryogenic temperatures and have no line-of-sight vacuum trajectories from the outer vacuum region to the sealed FET planes. Residual gas backgrounds will be cryopumped to the outer boundaries of the fiducialized volume.

With an area per plane of 10^6 cm^2, the overburden of cosmic-ray muon flux is an important concern for dead-time associated with a cosmic-ray veto. The instrumented target is designed to have no more than a percent-level fill factor of support material, mostly epoxy or a similar material to support the graphene

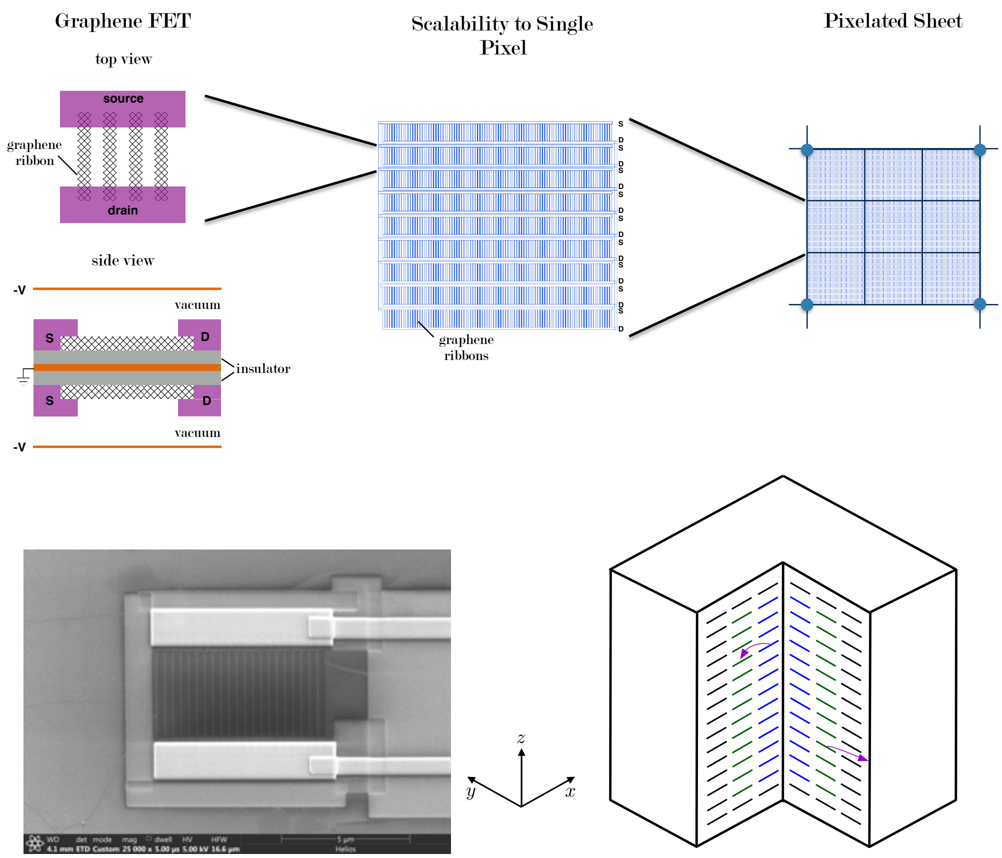

Figure 0-4. (top) *The FET plane will be double-sided, separated by two insulating layers and a bottom gate electrode. Top gate electrodes will provide the ~ -100 V needed to accelerate ejected electrons away from the electrodes and back towards the graphene planes. Multiple graphene FETs can be arranged into a single pixel (center) with interdigitated source and drain and multiple pixels are arranged into sheets that are stacked together to form a cube structure and multiple cubes are assembled to form a fiducialized volume.* (left bottom) *Prototype graphene FET sensor made at Princeton University consists of a source and drain separated by a planar graphene layer segmented finely into ribbons.* (right bottom) *Cutaway view of a conceptual design for graphene directional detection. When an electron is ejected from a graphene sheet, it is deflected by an electric field, where electrons follow a "FET-to-FET" trajectory.*

sheets at the corners as shown in Fig. 0-4 (right). The remainder of the target volume will be highly sensitive to charged particles entering the volume, and therefore the electric field regions that control the conductivity of the graphene FETs, including the regions between the vacuum-separated top gate electrode and the graphene and underneath the graphene with the insulator-separated bottom gate electrode, will be active regions for cosmic-ray vetos. With an overburden of roughly 3 km or greater, the total flux of muons across the entire graphene target falls below 10^{-1} s^{-1}. With a finite readout time of the FET planes, this rate would introduce less than 1% of dead-time depending to a lesser extent on the size of the fiducialized volume used in the veto.

The low backgrounds achieved by Xenon100 below 100 keV, `http://arXiv.org/abs/1101.3866`, parameterized with a rate formula 0.1 single scatter EM events/keV/kg/day, applied to the mean free path of

100 eV electrons in yields approximately 4 events/kg/yr. The fine segmentation of the G-FETs provide localization of backgrounds and the FET-to-FET coincidence further suppresses the background count rate. The intrinsic ^{14}C background from the Graphene target will profit from a newly identified source of CO_2 that is estimated to be three orders of magnitude lower in ^{14}C/^{12}C than achieved in Borexino. This source was recently identified in the collection of low background underground Argon and is a possible starting material for the plasma growth of Graphene targets. The AMS methods for verifying low-level ^{14}C/^{12}C are described in [7], and the AMS facilities described in this paper are now located at the Lalonde AMS Lab at the University of Ottawa.

Goals 4) and 5)

As described in the Overview, goal 4) is most efficiently developed by the existing Project 8 collaboration. Goal 5) will be evaluated using numerical simulation methods for EM fields. COMSOL is used for the calculation of the EM field maps, and GEANT4 is used for the full simulation of the particle tracking. An example of the particle tracking for the prototype setup is shown in Figure 0-5. There are two major challenges associated with scalability, one external and requires partnership with industry and one internal and requires a design for the CNB target that satisfies the needs for an underground installation.

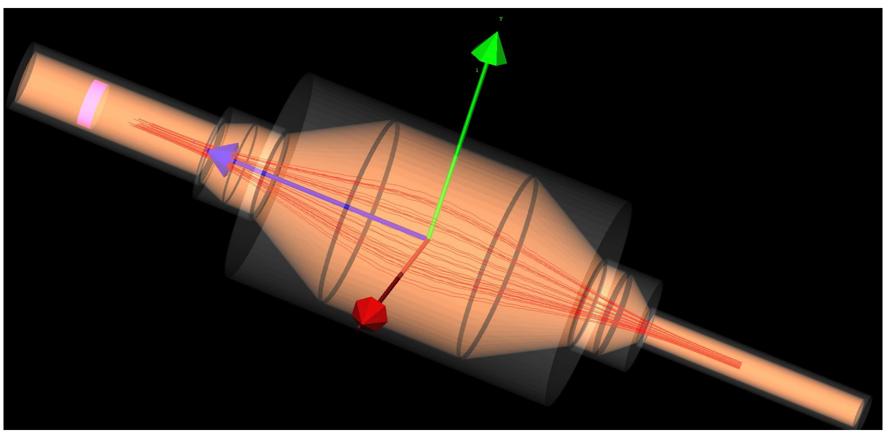

Figure 0-5. *GEANT4 particle tracking of endpoint electrons using a computed COMSOL EM field map.*

On the commercial side, the industrialization and drop in production costs for the Graphene targets will move forward due to the large number of potential commercial applications for Graphene. By initiating a collaboration with industry at this early stage, we can hope to have a product that matches the needs of the experiment by the time that goals 4) and 5) are achieved.

On the future of the CNB target, the scalable design is focused on individual modules that are compact and fully sealed under transport. The preliminary concept for modularity is to have 3 meter diameter (max) plates, either packed individually with a transport support structure or several stacked plates within a support structure. The idea would be to have some number of Graphene wafers (6) in the center of the module plate and the calorimeter wafers located at the edges with the RF tagging located in between. The module plate would be vacuum sealed before transport and during underground installation put inside a

[7] Litherland et. al, 2005. "Low-level ^{14}C measurements and Accelerator Mass Spectrometry" in AIP Conference Proceedings, vol. 785, p. 48. http://dx.doi.org/10.1063/1.2060452

cryogenic volume run by cryopumps. The goal for this design is to demonstrate that the CNB target under these conditions is securely contained by the molecular bonds to Graphene and by the barrier of the plate seal. The modules will be either under vacuum or back-filled to negative pressure with a gas that is later pumped out during underground installation. By initiating the underground project at this time with the existing prototype and very low levels of calibration samples, the process of understanding the scalability issues of the CNB target in an underground environment can begin.

After a proof-of-principle is successfully established with the prototype setup, a second stage of development to conduct the validation of prototypes demonstrating scalability concepts for the Graphene target and instrumentation.

Cost Estimate for PTOLEMY-G^3

PTOLEMY-G^3 is ready for a first phase experiment. Graphene sensor results are in progress and the existing PTOLEMY setup at Princeton University has the volume and cooling capacity to host PTOLEMY-G^3 with a fiducialized volume of 10^3 cm^3. Current, research-level production capacity of graphene exceeds 200 m^2 per year with prices of approximately $1 per cm^2. Substrate and graphene wafer costs are less than $200 per wafer (100 mm dia.), but current research-level processing costs are an order of magnitude higher. Wafer-level processing costs are $2,000 per wafer (100 mm dia.) to implement the G-FET array structure and applying expected yields. A 10^3 cm^3 fiducialized volume corresponds to a 100 wafer production run. Each readout card equipment with low noise buffers and a Kintex-7 readout is estimated at $800 with one readout card serving 10^6 FETs per wafer. This gives $280,000 as the core construction cost for PTOLEMY-G^3. Significant understanding of the wafer-level fabrication would be achieved with a pre-production of 10 wafers. The dominant production cost, wafer-level processing, could be further reduced through collaborations with industry.

Timeline

The current PTOLEMY prototype at Princeton University is funded by the Simons Foundation and John Templeton Foundation. This funding extends through 2017 into mid-2018. In the current location in the absence of overburden, the evaluation of highly sensitive FET wafers will have significant hit occupancy due to cosmic ray interactions. The environment is not suitable for establishing Graphene FETs as low noise, low background detectors for direction detection of light dark matter. The proposal is to begin setup and installation of a PTOLEMY G-FET setup at LNGS beginning as early as September 2017. This can be started with components of the existing prototype at Princeton University.

Subject to a positive decision and coordination process with LNGS that would identify a space to install a dilution refrigerator, the first step is to install the cryogenic system to evaluate the hit rate of a Graphene FET array underground. The system could be initially commissioned on the surface to facilitate efficient setup of the refrigerator and readout electronics for the Graphene FET system. The system would then be moved underground to take data. The first results of the G-FET measurements underground would be landmark step in directional detection of MeV dark matter and the system would be scaled up to a fiducialized volume of 10^3 cm^3 to provide first results down to $\bar{\sigma}_e = 10^{-33}$ cm^2 at 4 MeV. After careful evaluation of the radio-purity and concurrent development of 10^{-21} ^{14}C/^{12}C AMS separation and Graphene growth methods, a larger fiducialized volume could be installed with the opportunity of searching down to $\bar{\sigma}_e = 10^{-39}$ cm^2 for MeV masses. Concurrent with these developments, the evaluation of high precision TES calorimetry for 0.05eV energy resolution for electrons with ∼10eV kinetic energy would achieve an important milestone for CNB detection methods. A precision HV system would allow the measurement precision in combination with a MAC-E filter from the PTOLEMY prototype to establish calorimeter methods to be the highest sensitivity approach for endpoint spectrum measurements with a resolution below that of the neutrino mass. Further development of the Graphene target and calorimeter methods open up the potential to provide a diverse physics program and to go after long sought after signatures on the horizon of Big Bang Nucleosynthesis in the early Universe.

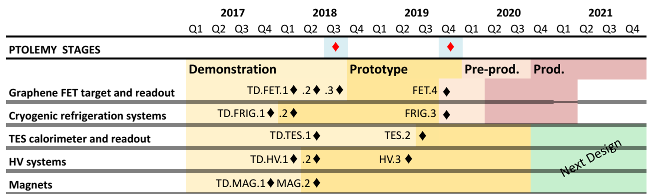

Figure 0-6. *Preliminary timeline of milestones for PTOLEMY at LNGS.*

PTOLEMY HIGH LEVEL MILESTONES	Title	Reference	Date
Graphene FET target and readout			
	Shipment of individual Graphene FET demonstration wafers to LNGS	**TD.FET.1**	Jan-18
	Wafer-sized FET plane	**TD.FET.2**	Mar-18
	Productiondelivery for 10^3 cm^3 volume	**TD.FET.3**	Sep-18
	Large-scale volume production begins	**TD.FET.4**	Dec-19
Cryogenic refrigeration systems			
	Evalution of services and space requirements for installation of dilution refrigeration cryostat at LNGS	**TD.FRIG.1**	Nov-17
	Installation of dilution refrigerator	**TD.FRIG.2**	Mar-18
	Large-volume producton begins	**TD.FRIG.3**	Dec-19
TES calorimeter and readout			
	Installation of few channel system in dilution refrigerator at LNGS	**TD.TES.1**	Jun-18
	Multiplexed readout	**TD.TES.2**	Jun-19
HV systems			
	Demonstrator system	**TD.HV.1**	Jan-18
	3-segment system installed on MAC-E filter	**TD.HV.2**	Jun-18
	9-segment system installed on MAC-E filter	**TD.HV.3**	Mar-19
Magnets			
	Evaluation of services and space requirements for installation of superconducting magnets at LNGS	**TD.MAG.1**	Nov-17
	Installation of magnets	**TD.MAG.2**	Jun-18

Figure 0-7. *Preliminary timeline of milestones for PTOLEMY at LNGS with details.*