Statement of Work: PTOLEMY
for the Simons Foundation

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The deliverables of PTOLEMY under the 2015 Simons MPS Targeted Award have yielded new results that exceeded expectation. PTOLEMY began as a feasibility study and has evolved in two years' time into a compelling case to proceed to a technical design phase. The scope of work for the next three years is to complete the design of the Simons Cosmic Neutrino Telescope, the first instrument of its kind, and to validate with direct measurement that the non-neutrino backgrounds are below the expected signal from the Big Bang. An array of telescopes of this design will reach discovery sensitivity for the Cosmic Neutrino Background. The number and deployment of these telescopes around the world will depend on the next phase of PTOLEMY developments described below.

The past two years of PTOLEMY achievements have established a compelling case to proceed to telescope design. The cryogenic calorimeters aim to reach 0.05eV energy resolution, an order of magnitude beyond the original target and the highest resolution of any calorimeter. The Graphene substrate is stable under 40% loading fraction of hydrogen, the highest on record, and we believe 100% loading will be achieved soon. The Simons prototype at Princeton has become the basis of a new world-wide collaboration consisting of seven countries (Netherlands, Spain, Sweden, Israel, Italy, UAE, USA) and 20 institutions (shown in Figure 1). The Scientific Committee of the Gran Sasso National Laboratory (LNGS) in Italy will meet on March 26-27, 2018 to decide whether the PTOLEMY prototype will be granted the opportunity to operate at LNGS, a world-premiere low background facility. The goal of operating underground is to demonstrate that the Graphene target, calorimeter and precision high-voltage system and electromagnetic filters can achieve the low background requirements needed to proceed to a full implementation of the cosmic neutrino experiment. A relatively small target system proven to have high radio-purity can be scaled to a large area system with known background levels. The cosmic neutrino telescopes will not need to be located deep underground, but we need to start in a low background environment to understand what backgrounds and background-induced instabilities are relevant.

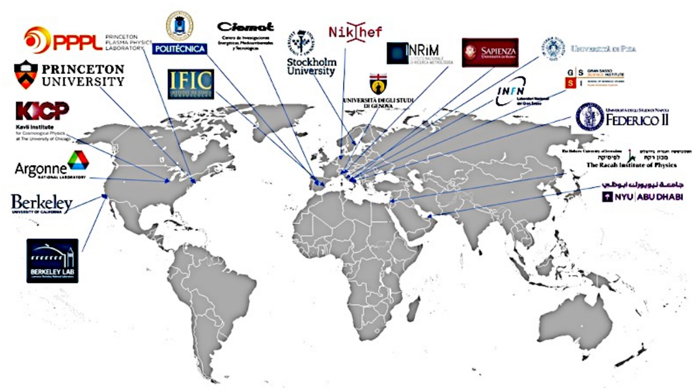

Figure 1. PTOLEMY Collaboration

Exciting new ideas for late-time inflationary and non-inflationary predictions from the 2017 Simons "Origins of the Universe" MPS Targeted Grant will provide new opportunities to search for non-standard anisotropies in the cosmic neutrinos. Similarly, the direct measurements per neutrino mass of the CNB from a future Simons Cosmic Neutrino Telescope will provide the only test of cosmic neutrino physics at a precision comparable to the new frontier of CMB measurements from the 2016 Simons "Simons Observatory" MPS Targeted Grant. We are also very enthusiastic about the central role of further collaboration with the CCA in the Flatiron Institute to bring together exact numerical predictions about the Universe across all three MPS Targeted Grants.

The specific tasks to achieve the above goals for the next three-years of an overall five-year MPS Targeted Award for PTOLEMY are described below. The proposal is to continue the same level of yearly support from the first two years at $200K/year to complete the remaining three years of a full five-year program for a total 2015-2020 MPS Targeted Award of $1M to establish the first telescope to look back in time to the first second after the Big Bang.

Task 1. *Installation of the Simons PTOLEMY prototype at LNGS:* For this task, a contractor will design an underground area at the LNGS to host the Simons PTOLEMY prototype. An example of a recently installed area is shown in Figure 2. The underground area will serve as a highly visible center for the leading-edge experimental effort and provide the services needed to operate and to validate the resolution and low background capabilities of the neutrino telescope. This task will be completed in 2018.

Figure 2. Example of an underground experimental area at LNGS.

The following components of the PTOLEMY prototype will be shipped on loan to LNGS:

- Dilution Refrigerator (Kelvinox MX400 - Oxford Instruments). Lowest base temperature is 7mK and up to 400mW of cooling power is provided at 100mK. KADEL 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 for benchmarking the performance of PTOLEMY cryogenic calorimeters
- Spectrometer components:
    - 1.9T Oxford Instruments 85/310 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 provides an ultra-high stability voltage reference of 10^{-5} with a novel HV system developed at LNGS based on precision voltages held on capacitors and monitored with field mill sensing.
    - Spellman 210-30R HV Supply
    - Oerlikon Leybold TurboVAC 450 iX (160CF) and ScrollVAC SC15D pumping system

Task 2. *High Radio-purity Graphene synthesis and instrumentation:*
The non-neutrino backgrounds in the signal region for cosmic neutrino detection will be characterized at the background rate levels that can be scaled to the mass of a full-scale experiment. The technique will be to measure the energy spectrum over an energy window of several keV and apply an assumption of the background shape into the 0.05eV region of the signal. The mass of the Graphene target will be scaled up with different configurations of the Graphene structure from planar single-layer graphene to carbon-nanotube geometries of high mass density. The evaluation of electron-induced backgrounds relies on a complete understanding of the electron transport properties in Graphene, including scattering, transmission and absorption. These studies are underway at the CIEMAT laboratory in Spain in collaboration with Graphenea Inc. to produce CVD grown Graphene.

At Princeton, we propose to develop a new high radio-purity Carbon-12 source from CO_2 gas extracted from the Earth's mantle (more than 5 miles below the surface) coming from mines in southwestern Colorado. The technique is to use a metal catalyst to convert CO_2 to Methanol, evaluated with a Gas Chromatograph and fed into a CVD furnace for subsequent Graphene growth. The Graphene samples are cut into nanoribbons and made into single-electron sensing field-effect transistors using a technique developed at Princeton. The self-instrumentation of the Graphene is the only way to provide high sensitivity throughout the Graphene target to evaluate the background levels achieved with mantle CO_2 Carbon-12 sources. The expectation is that the Carbon-14 levels will be one billion times lower than at the Earth's surface. This work builds on the achievements of Dr. Fang Zhao, a postdoctoral researcher at Princeton University, from the first two years of the 2015 Simons MPS Targeted Award. By installing the prototype underground, at the depth of LNGS, we gain a sensitivity of 10^6 in cosmic ray background suppression required to quantify low level backgrounds. This enhancement in background sensitivity will enable us to scale to larger target areas at shallower depths for future deployment of an array of telescopes.

The scope of this task will include continued development of the hydrogenation of Graphene to 100% capacity using cold plasma loading techniques developed at PPPL. A small percentage admixture of the tritium isotope for resolution evaluation of the molecular smearing contribution will be conducted in the prototype with the high resolution cryogenic calorimeter and precision voltage reference.

Task 3. ***Operational performance milestones with the Simons PTOLEMY prototype at LNGS:***
The evaluation of high radio-purity Graphene samples will be conducted in the Simons PTOLEMY prototype at LNGS. The individual performance benchmarks of the high sensitivity Graphene target, the precision 10^{-5} voltage reference and the 0.05eV resolution cryogenic calorimeter will be achieved in a fully integrated system. Stability of the energy scale and calibration systems will be demonstrated over extended running periods. Background-induced instabilities, such as cosmic ray induced discharges in the HV system, may require further design work to overcome before proceeding to a telescope design. The hydrogenated graphene samples will be evaluated for their molecular energy smearing with the cryogenic calorimeter measurement following the magnetic spectrometer and electrostatic filter.

The magnetic spectrometer consists of a 7T Oxford Instruments horizontal bore superconducting magnet operated at 3.3T paired with a similar 1.9T OI superconducting magnet that is separated by 1.5m by means of a central vacuum chamber. The graphene samples will be evaluated with a 50mK TES from the Torino INRiM group interfaced to the magnetic spectrometer through a custom KADEL dewar. Collaboration on the TES is coordinated with Genova and ANL.

We anticipate that the operational status of the prototype at LNGS will further encourage collaborators with needed expertise to join the PTOLEMY effort. Collaborators working with the Project 8 collaboration will be encouraged to develop a single-electron RF trigger system for the telescope design for evaluation in the prototype. Transitioning from a passive MAC-E filter to a selective filter with single electron sensing is an important step to completing the design of the cosmic neutrino telescope.

This task requires cryogenic cool down costs for the magnets and periodic cryogenic refills to maintain stable magnetic fields. The HV system of the electrostatic spectrometer will also be operated and has associated costs for cables and other HV components. The dilution refrigerator cryogenic refills, stocking of disposable materials and partial contribution to a common Helium recovery system are part of this task. We will also support setup costs for the evaluation of the RF trigger. Technician time for the cryogenic work is part of the cost basis for this task.

Task 4. ***Computational simulation of large-scale magnetic geometry:***
In collaboration with the CCA at the Flatiron Institute, models for early Universe neutrino density anisotropies will be evolved forward in time under different assumptions for the gravitational instability of the three species of neutrinos based on their individual masses and equations of state for the dark energy. Concurrent with the investigation of alternative inflationary and non-inflationary epochs and reheating models, the experimental precision on angular scales will be modeled with nuclear cross section calculations for polarized tritium. Backgrounds and scanning of the sky with the Earth's motion will be folded into estimates of the measurement resolutions possible with an array of Simons Cosmic Neutrino Telescopes. Input from the LNGS prototype and projections of resolutions will be important to make technical choices on the final telescope design.

The final design of the telescope will involve extensive numerical studies of low energy electron propagation through the entire trajectory from neutrino capture on tritium, to Graphene interactions, to electromagnetic transport and filtering, RF triggering and cryogenic calorimeter measurements. The discovery and modeling of background sources will be coordinated between prototype operation and simulation to achieve the required precision to extrapolate to a large-scale system. This task includes limited support for summer students to engage in detailed computational work.

<u>Budget and schedule:</u>

The work for all four tasks will be completed within a three-year period starting April 1, 2018 and ending August 31, 2020. The breakdown of the proposed budget is attached below.