2018-2019 Boston QuarkNet Center Annual Report

**December 6, 2018**

 We had a good start to our QuarkNet year at Roxbury Latin School with eight teachers in attendance. Long-time regulars Mike Hamblin, Mike Hirsh, George Odell, and Mike Wadness (with his two young sons) were joined by more recent recruits Tim Fitzgibbon and Jamison Smith and first-timer Jon Kelley. Host Rick Dower presented a program devoted to the supermassive black hole, called Sgr A\*, at the center of the Milky Way .

 After opening convivial conversation and snacks. Rick showed photos of his 2007 trip to the large telescopes in northern Chile, especially the four 8.2 m telescopes of the VLT (Very large Telescope) operated by the European Southern Observatory (ESO). Light from the four mirrors of the VLT, each corrected for atmospheric fluctuations by adaptive optics, are combined to make precise observations of the positions and spectra of stars orbiting the Sgr A\* black hole. Several observations presented for analysis in the activity tackled by the participants were made at the VLT. After viewing a preliminary Youtube video about Sgr A\* (<https://www.youtube.com/watch?v=IfA_wM9aMJY> ), participants dove into the exercise. They used Newtonian gravity and observations of stellar orbits to determine the black hole mass (4.1 x 106 solar masses) and determined the closest approach of one star (S2), in a highly eccentric orbit, to the black hole. Finally, they examined data from the May 2018 periapsis passage of S2 and calculated the effect of the transverse Doppler shift (due to time dilation for the fast moving star) and the gravitational red shift (due to the presence of Sgr A\*). They could then see how those effects compared to the observational spectral shifts detected by the ESO group. All of us were impressed with how much physics could be done in a Newtonian analysis of the motions of the star S2 - finding out more about the structure of the Milky Way and testing our theories of special and general relativity.

**February 7, 2019**

  We held our winter meeting last night at our usual gathering place in the Roxbury Latin School Physics Lab thanks to the hospitality of Robert Moore. The teachers in attendance (Rick Dower, Tim Fitzgibbon, Mike Hamblin, Jon Kelley, Robert Moore, George Odell, Jamison Smith, and Mike Wadness) enjoyed some convivial conversation and snacks before settling down to the main activity of the evening.

  Rick showed two YouTube videos related to the fist detection of gravitational waves:

“The Absurdity of Detecting Gravitational Waves” (<https://www.youtube.com/watch?v=iphcyNWFD10>) from Veritasium and

“LIGO detects gravitational Waves” (<https://www.youtube.com/watch?v=B4XzLDM3Py8>) from MIT.

 Several other good videos are listed if you search the YouTube site for “gravitational waves.”

  With those videos as prelude, we began working through an analysis of the numerical relativity fit to the LIGO discovery detection, GW150914. Much of the work involved applying Newtonian mechanics to the signal from the inspiring black holes with occasional use of a formula from general relativity. It was intriguing to see how some of the various spectacular numbers related to this event can be reasonably approximated in a Newtonian analysis. We were able to get through half of the exercise before breaking up for the evening.

**March 23, 2019 – CMS Masterclass at Northeastern University**

 Joining Professors George Alverson and Darien Wood from Northeastern University today were 29 students and 7 teachers from schools in Massachusetts, Rhode Island, and Vermont. The Rhode Island group was surprised that the commuter rail train was packed with 20-somethings on the way to Boston early Saturday morning. Later they realized that the first recreational marijuana shop in the Boston area was opening this morning. Fortunately, the students were too busy listening to their teacher talk to them about particle physics to pay much attention to the unexpected passengers.

 On arrival the students saw a demonstration of an electron beam tube and the deflecting action of a magnet. The students introduced themselves and their favorite physics lab of demonstration. Then we got underway with a review of the schedule by Mike Wadness and an introduction to CERN, the LHC, and the CMS detector by Prof. Alverson. During a short break the students had an opportunity to see alpha particle tracks in a cloud chamber. Mike led the students in some preliminary event image analyses to prepare them for the work of the afternoon. Lunch and conversation with professors, grad students, and teachers allowed students to ask question and talk about their observations and their ambitions for the future.

 After lunch, students toured a biophysics lab in which the force necessary to stretch strands of DNA was analyzed. The main afternoon activity was examining images and classifying particle interactions in data obtained from the CMS detector. The data showed the decay of W+, W-, Z , and Higgs particles along with some event that were difficult to classify. Each pair of students had a different set of 100 events to examine. After some conversation about interpretation of the collective student results, we joined a videoconference with students at the Johns Hopkins QuarkNet center in Baltimore. Physicists at Fermilab and QuarkNet staff moderated the conference. Our student spokespeople commented on our results and their significance and answered question about them. After listening to the Baltimore group comment on their results, we responded with some questions, heard some final comments from the moderators, and signed off. Students and teachers agreed that it was an interesting and successful day.

**May 21, 2019**

 At our spring meeting this year, Robert Moore, Mike Hamblin, Jonathan Kelley, George Odell, Tim Fitzgibbon, Mike Hirsh, Jamison Smith, Mike Wadness, and Rick Dower celebrated two recent events: (1) International Metrology Day on May 20 and (2) the Event Horizon Telescope (EHT) release on April 10 of the shadow image of the supermassive black hole at the center of galaxy M87. On International Metrology Day, Planck’s constant (along with the electron charge and Boltzmann’s constant) became defined and, consequently, the kilogram became a quantity defined by fundamental constants of nature rather than a physical artifact (“le grand K” kilogram mass platinum-iridium cylinder at the BIPM in Paris). At a celebratory colloquium at MIT on Monday (May 20) Wolfgang Ketterle (Nobel Prize 2001) gave a talk about the redefinition in which he argued that 1 kg is equal to the mass equivalent of the energy of 1.4755214 x 1040 photons of the Cs hyperfine transition photon with frequency 9,192,631,770 Hz that is used to define the second of time. We joked about counting photons while enjoying a picnic supper in anticipation of the evening’s main event.

 Joe Farah was a student in Mike Wadness’s AP Physics Class at Medford high a couple years ago. With Mike’s encouragement, Joe went to two QuarkNet Particle Physics Masterclass events at Northeastern. He became so intrigued by particle physics that on the evening after his graduation from Medford, he called Melissa Franklin at Harvard to ask her if there was any work for him to do during the summer with her ATLAS group. There wasn’t, but she gave him a week trial to see if he could be of use to the group. As the result of much hard work, that week turned into a summer of work with the group. When the group project was finished, Joe asked Prof. Franklin to recommend another group to which he could contribute his efforts. He landed with the EHT group. Although they had no places for undergraduates, they made a place for Joe. His continued work with the EHT group while maintaining his studies at UMass Boston, led to his participation as the only undergraduate on the papers (all six) published by the group in the April 10, 2019 issue of *The Astrophysical Journal Letters*. (The papers are open access if you would like to see or read them.)

 Joe described for us the process of using the telescopes of the EHT array and the mathematical process of Very Long Baseline Interferometry to construct the shadow image of the supermassive (6.5 x 109 *M*Sun) black hole at the center of the M87 elliptical galaxy in the Virgo cluster. The image is a remarkable 100 microarcseconds across and clearly shows the apparently empty space within a ring of light produced by orbiting light and radiation from plasma in an accretion disc orbiting the black hole. Joe also explained several of the internal checks used to verify the validity of the image. Joe’s talk and his work were wonderful indications of the effects produced by the inspiration of the QuarkNet program.

**August 14-15, 2019**

 Nine curious physics teachers: Scott Carlson, Rick Dower, Gerry Gagnon, Amanda Harnden, Mike Hirsh, John Kelley, George Odell, Paul Sedita, and Mike Wadness, gathered in the Physics Lab at Roxbury Latin for our summer workshop on Neutrinos led by Rick and Paul. Paul brought knowledge gained in helping to construct the MINERvA neutrino detector at Fermilab and experience with previous Neutrino workshops to enhance our efforts. Rick organized the Workshop and gave a talk on the history of the neutrino in physics.

 We started the first day with an exercise suggested by Paul answering the question, “When throwing one die, what is the most likely number of throws that occur before a “1” comes up?” The quick intuitive answer of “six throws” is incorrect, as we demonstrated experimentally. When a histogram of the number of throws until a “1” is plotted, one sees an exponential decay. With exponential decay in mind, we next worked with neutrino data from the MINERvA experiment found on the MINERvA “Neutrinos in the Classroom” website to measure the mean lifetime of muons produced by neutrino interaction. A conversation, via video link, with Rob Fine at Fermilab about the MINERvA detector rounded out the morning before we walked down the hill for lunch.

 After lunch, participants updated their QuarkNet profiles on the QuarkNet website. Then Rick gave his talk “Neutrinos: Mystery and History.” That was followed by a break for a celebration of the 20th anniversary of QuarkNet in Boston (and cake – see photo). We finished the day with a Neutrino Film Fest with several of Don Lincoln’s videos about neutrinos and some wrap-up reflections on the day’s activities.

 The second day began with a variation of the QuarkNet Data Activity ”What Heisenberg Knew.” Rick distributed copies of the paper by Anton Zeilinger and colleagues describing their examination of the Heisenberg Uncertainty Principle with C-70 Fullerene molecules. An enlarged version of their data and graph of Delta-x and Delta-p allowed measurement of either data points or graph points, from which we could see that the product of position and momentum uncertainties was approximately equal to Planck’s constant. That led us into an examination of the MINERvA data from the Neutrino Masterclass that contained neutrino interactions with neutrons to produce proton and muon resultant particles. Before discussing the results we broke for lunch in order to prepare for the after lunch talk by Spencer Axani of MIT on modern neutrino experiments, especially Ice Cube, on which he has worked.

 Spencer’s talk was well received for the insights that it provided and some first-hand recollections of conditions at the South Pole Research Station. Spencer also showed us examples of his “Cosmic Watch” portable, battery powered muon detectors. After spending two hours with us, Spencer left to catch his train back to Boston, and we spent some time discussing sources of the neutron transverse motion observed in our data analysis from the morning – complete with references to Heisenberg and the characteristic of a Fermi gas. The Workshop concluded with participants completing the QuarkNet Teacher Survey to provide data for our funding agencies. George Odell remarked early in the Workshop, “This is the most fun I have had with a QuarkNet Data Activity.” I think that all will agree that the two days added to our understanding of neutrinos, muons, and cosmic rays along with the camaraderie of our shared experiences in teaching physics.

Rick Dower