

## **From the Gamma-ray Bubbles to the Cosmic Microwave Background: The Origins of the Super-massive Black Holes, Dark Matter, and the Universe**

I have a broad range of research interests in many areas of cosmology and astrophysics. The core purpose of my research activities is to advance the frontier of physics by observing the Universe. This includes discovering unexpected gigantic structure in the Milky Way, searching for signals from dark matter particles in gamma rays and cosmic rays, and finding evidence for primordial gravitational waves as a smoking gun signal of the cosmic inflation. In addition to using existing telescopes across the electromagnetic spectrum, I lead research groups towards next generation spaceborne gamma-ray detectors and ground-based telescopes to measure the faint polarized signal of the Cosmic Microwave Background. I will cover these broad research areas in the public lecture and the three departmental colloquia, with a focus on interesting recent findings.

### **The public lecture: Double Bubble Trouble in Our Milky Way: Surprises When You Look Up with Gamma-ray Goggles**

**Abstract:** Astronomers have been studying our home galaxy — the Milky Way for centuries, however, we still find it full of surprises. In this talk, I will describe a spectacular mysterious phenomenon we recently discovered in our Milky Way: a pair of gigantic expanding bubbles (known as the Fermi bubbles) shining most brightly in energetic gamma rays. The whole structure has a size of  $\sim 50,000$  light years, almost the size of the Milky Way disk, and may be only a few million years old. The outlines of the bubbles are quite sharp, and the bubbles themselves glow in nearly uniform gamma rays over their colossal surfaces, like two incandescent bulbs screwed into the center of the galaxy. This double-bubble structure is most likely created by some episode of large energy injection from the center of the Galaxy, like huge jets of accelerated matter blasting out through a gigantic belch of the super-massive black hole, with a mass 4 million times that of our sun located at the heart of the Milky Way. Or the double bubbles could have been formed by a population of giant stars, born from the plentiful gas surrounding the black hole, all exploding as supernovae at roughly the same time. I will discuss how we will be able to distinguish the two scenarios with future powerful telescopes. Furthermore, while looking at the Fermi bubbles near the galactic center, we have found a promising signal that could potentially be associated with dark matter particles — the mysterious component that makes up 80% matter of the Universe. It extends a significant distance from the galactic center, and has a lot of the properties that you would expect from a dark matter signal. In fact we were motivated to search for evidence of dark matter in gamma rays from the inner galaxy, but ended up with finding the unexpected pair of bubbles. It would be a supreme irony if we found the Fermi bubbles while looking for dark matter and then while studying the Fermi bubbles we discovered dark matter.

### **First colloquium: Discovery of the Fermi Bubbles**

**Abstract:** Our home galaxy is full of surprises. While looking for dark matter signal from the Galactic center using data from the Fermi Gamma-ray Space Telescope, we have discovered a pair of giant gamma-ray bubbles in the Milky Way, extending  $\sim 50$  degrees above and below the Galactic center (known as the Fermi bubbles). These structures could result from a past energetic accretion-driven outflow from the central supermassive black hole, or Galactic winds from

an extensive nuclear starburst. Furthermore, I recently found evidence for large-scale double-jet structures symmetrically distributed around the Galactic center and emanating through the bubbles. These collimated jets could be resulted from the relativistic outflows originated from the Sgr A\* in the Galactic center, and may be what caused the Fermi bubbles to inflate. If confirmed, these jets would be the first spatially resolved gamma-ray jets ever seen. These jet features provide further evidence that the Fermi bubble structure might have created by past activities from the central black hole. I will discuss a series of X-ray, radio, and UV observations using Chandra, XMM-Newton, Jansky VLA, and Hubble to study the Fermi bubble structure through multiwavelength observations. With the help from extensive simulations, we expect to learn about the plasma properties at the bubble interface with the Galactic halo, the accretion history of the central supermassive black hole, along with the impact of the Fermi bubbles on the halo of intra-Galactic gas halo.

### **Second colloquium: Indirect Search for Dark Matter Particle**

**Abstract:** The inner Galaxy is an ideal target to search for signatures of dark matter particle annihilation, especially in high energy gamma rays. In this talk, I will give a summary of the current status of the search of dark matter particle from high energy astronomical observations. In some dark matter models, dark matter particles can annihilate or decay into two photons, producing a spectral line in gamma rays. The detection of a high energy gamma-ray line in the Galactic center or other galaxies/galaxy clusters would be a smoking gun for dark matter particles. Recent data from the Fermi Gamma-ray Space Telescope revealed an evidence of excess of photons in the Galactic center with energies near 130 GeV. Given the importance of the potential discovery of dark matter annihilation signal, we have changed the survey strategy of the Fermi satellite for one year: instead of uniformly surveying the full sky, increasing the exposure towards Galactic center by a factor of two. In addition, the Dark Matter Particle Explorer (DAMPE) satellite will be launched later this year with the energy resolution more than one order of magnitude better than Fermi. It will significantly improve the sensitivity to find dark matter induced gamma-ray line feature. Besides the potential line signature of the dark matter particle, recent analysis also revealed a significant  $\sim$ GeV excess from the Galactic center region, which has been claimed as a potential signal from dark matter annihilation. The revealed spectrum and spatial distribution is consistent with a few tens of GeV Weakly Interacting Massive Particle (WIMP) annihilate to standard model particles in the inner Galactic halo. Despite the claimed quite significant detection, systematic uncertainties due to contamination from diffuse gamma-ray emission produced in the interstellar environment along the line of sight, and unresolved point sources could be significant and hard to remove, because of the relatively large point spread function of Fermi at  $\lesssim$ 1 GeV. Sub-GeV is crucial to distinguish both the spectrum and the overall spatial distribution of this potential dark matter signal from other astrophysical models e.g. millisecond pulsar models. I will discuss the instrument concept of a high angular resolution telescope that I have recently proposed, dedicated to the sub-GeV gamma-ray detection. The proposed mission named PANGU (PAir-production Gamma-ray Unit) has significantly improved PSF, thus will be able to reveal the nature of this excess by enabling more reliable analysis towards inner Galaxy. Furthermore, indirect dark matter search in sub-GeV gamma ray is also complementary to future direct search and collider search for low mass dark matter candidates, which is not yet well constrained by other means.

### Third Colloquium: Searching for Primordial Gravitational Waves from Inflation: Results from Current Experiments and the Future Plan

**Abstract:** The Cosmic Microwave Background (CMB) is the oldest observable light in the universe, and has proven to be an extremely important tool in modern observational cosmology. Inflation, the superluminal expansion of the universe during the first moments after the Big Bang, predicts a Cosmic Gravitational-Wave Background, which in turn imprints a faint but unique signature of “B-mode” polarization of the CMB at degree angular scales. Detection of the B-mode signature from inflation would constitute strong evidence for inflation and a test of inflationary models at the energy scale of grand unified theories. The series of BICEP experiments, which observed from the South Pole since 2006, are polarization-sensitive microwave telescopes that observe the CMB at degree angular scales and are specifically designed to search for this signature of inflation. BICEP2 is the second experiment in a four-stage line of degree-scale polarimeters at the South Pole. BICEP2 was operated during 2010-2012 and produced ultra deep maps at 150 GHz of a 380 square degree patch of sky. Extracting the B-mode of the polarization pattern a  $>5$  sigma excess is found over the standard cosmological model at angular scales of a few degrees. Internal consistency tests demonstrate that systematics are small compared to the observed excess. Foreground contamination from polarized Galactic dust emission remains because of the observational uncertainty from higher frequencies, even including recent data from the Planck satellite. Cross correlation against existing 100 GHz maps confirms the excess and indicates a frequency spectral index consistent with CMB. The observed spectrum is well fit when including an inflationary gravitational wave component with the tensor/scalar ratio parameter  $r = 0.2$ . BICEP2 only observed 2% of the full sky. I will discuss the future effort of observing the full sky from ground based telescopes. In particular, I have recently proposed an unique site in Tibet for future CMB observations to cover a large area of the northern sky, complementary to the current and planned CMB programs at the South Pole and Chile. At the Tibet site, we also plan to build a large aperture telescope with the goal of using the CMB as a “backlight” to study the evolution of massive clusters of galaxies, the distribution of dark matter at large scale, the total mass of the three active neutrino species, and to learn about the equation of state of the dark energy.