Building The Milky Way

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Long-term participants available to coordinate if needed: James Bullock (UCI), Andrew Gould (OSU), Amina Helmi (AIU), Piero Madau (UCSC), Matthias Steinmetz (AIP)

This is a proposal for a 3 month program at the Kavli Institute of Theoretical Physics, to be held during Fall 2008, which will focus on developing understanding of the physical mechanisms at work during the formation and evolution of the Milky Way. The Milky Way is a unique galaxy, as it is the only large galaxy for which we can see individual stars, measure their 6D phase-space coordinates as well as their astrophysical properties such as their age and abundance. This provides both unique opportunities for enhancing our understanding of how galaxies form and challenges for interpreting experiments dependent upon the properties of our Galactic environment.

The Milky Way offers an unparalleled record of galaxy formation, through its structure, dynamics and stellar populations. Experiments such as RAVE, SEGUE, Pan Starrs and, eventually, LSST, GAIA and SIM will provide high precision data sets measuring the structure and dynamics of the Milky Way. There is an urgent need to develop theoretical tools to fully utilize these data sets. Furthermore, by combining high precision measurements from studies of these different aspects of the Milky Way it will become possible to constrain its path from pre-galactic building blocks to present day galaxy.

The Milky Way is also an invaluable testing ground for examining some of our basic ideas about the growth of structure in the cosmos, as it offers some of the clearest indications that structure in our Universe formed hierarchically. The bulge component, and possibly some of the disk and halo, of the Milky Way are thought to have formed from progenitor populations similar in size to the twenty or so known satellite galaxies of the Milky Way, but at a different phase in their evolutionary cycle. Theoretical calculations provide some guidance for the properties of these hierarchical building blocks, but are not yet at a stage where detailed predictions can be made to suit the datasets the community will soon have access to. These calculations suffer two main ills: limited resolution in numerical simulations and a poor understanding of disk galaxy formation in ΛCDM. Indeed, many of the problems that face the current cold dark matter paradigm (e.g. the over abundance of predicted satellite galaxies relative to those observed, the lack of dark matter within the solar circle, the chemistry of halo stars versus the chemistry of satellites) occur on Milky Way scales. These issues must be understood before we can claim to have a "concordance cosmology". What is needed now is the simultaneous development of theory capable of making detailed predictions for comparison with current and future observational data sets and techniques to accurately test these predictions.

While what is learned from studying the Milky Way can be extrapolated to the formation of galaxies as a whole—a case where "thinking globally, acting locally" can produce real results, the Milky Way, as our home in the cosmos, is, of course, interesting in its own right. It is the environment in which searches for dark matter, both through direct detection and via annihilation products, must take place. As such, the efficacy of such experiments depends crucially on our ability to refine our knowledge of our Galactic environment.

1. SCIENTIFIC PROGRAM

We envision bringing together researchers in several diverse areas of research that focus on distinct aspects of Milky Way structure and composition. The aim of the program would be to facilitate interaction and discussion leading to advances in our understanding of the theoretical physics needed to fully characterize the Milky Way and to use it as an example of galaxy formation in general. We have identified three inter-related subtopics that would be covered by our program. These are: Milky Way Dynamics, Chemistry and Context, which we now discuss in turn.

1.1. Dynamics

There are many dynamical tracers within the Galaxy that offer a critical window to its evolutionary history. These same dynamical tracers serve as key tests of competing galaxy assembly scenarios. Metrics such as the frequency of dwarf satellites, the physical structure of tidal debris, the phase-space distribution of stars in the bulge, disk and halo of the Milky Way all test predictions of galaxy formation theory. Numerical simulations have been essential in understanding the detailed mapping between these observables and theory, and state-of-the art predictions for this mapping continue to be an extremely active area of research as simulations become more powerful and more capable. We are now entering an epoch in which these predictions can, in principle, be put to the test with the advent of large surveys (RAVE, SEGUE, Pan Starrs, eventually LSST, GAIA, and SIM) where 4D-6D information on millions to billions of stars is becoming a reality. The tools for how to analyze these data sets or translate them to a Milky Way model are not well developed. A goal of our program will be to develop the theoretical machinery required to extract the full benefit from these extraordinary datasets, which would otherwise lose much of their potential. Convening experts in numerical simulation and statistical techniques as well as researchers responsible for the surveys themselves will ensure substantial gain in our theoretical understanding of the phase-space distribution of the Milky Way.

1.2. Chemistry

There exists an extremely rich and detailed body of data regarding the chemical properties of various components of the Galaxy. This chemistry is highly valuable to understanding the Milky Way's evolution because chemical abundance patterns are like clocks, timing events at different epochs and originating from different physical processes. Much theoretical work is still needed to understand the currently available data (e.g. supernova abundance patterns, the origin of the s-process, the origin of carbon enhanced low-metallicity stars), and future datasets will not resolve these theoretical impasses. Understanding the variation of abundance patterns between the Milky Way and nearby neighbors gives us an important clue to the buildup of the Milky Way. A major obstacle has been the existence of a substantial disconnect between theorists and observers working on separate aspects of this nuanced chemical tapestry. This disconnect has resulted in a fragmented understanding of the chemical archaeology of the Milky Way. A major goal of our program would be to bridge this gap by drawing together experts in each of these areas to exchange information and ideas in order to make more substantial progress.

1.3. Context

Revealing the nature of dark matter is fundamental to cosmology and particle physics. In the standard cosmological paradigm of structure formation (ΛCDM), the universe is dominated by cold, collisionless dark matter (CDM), and endowed with initial density perturbations via quantum fluctuations during inflation. In this model galaxies form hierarchically, with low-mass objects ("halos") collapsing earlier and merging to form larger and larger systems over time. Small halos collapse at high redshift when the universe is very dense, so their central densities are correspondingly high. When these halos merge into larger hosts, their high densities allow them to resist the strong tidal forces that act to destroy them. It is therefore a clear, unique prediction of ΛCDM that galaxies are embedded in massive, extended dark matter halos teeming with self-bound substructure or "subhalos".

Many of today's "observables" within the Milky Way and nearby galaxies relate to events occurring at high redshift, during and soon after the era of reionization. In this sense, galaxies in the Local Group ("near-field cosmology") are starting to provide a crucial diagnostic link to the distant universe ("far-field cosmology"). This area is one of the major drivers in the design and instrumentation of future ground and space-based facilities such as the ELT, JWST, GAIA and SIM. The number and spatial distribution of subhalos around their host, for example, provide unique information and clues on the galaxy assembly process and the nature of the dark matter. While most dark matter subhalos in the Milky Way appear to have no optically luminous counterparts, the substructure population has been shown to be detectable via flux ratio anomalies in strong gravitational lenses, through its effects on stellar streams, or possibly via gamma-rays from dark matter annihilation in their cores. The possibility of observing the fingerprints of the small-scale structure of CDM hinges on the ability of subhalos to survive the hierarchical clustering process as substructure within the host. If the dark matter is in the form of a supersymmetric particle produced in the early universe like the neutralino, then substructure will be lit up by the annihilation of such particles into gamma-rays. Since the annihilation rate is proportional to density squared, the predicted flux depends sensitively on the clumpiness of the mass distribution. Surviving nearby subhalos are among the brightest sources of annihilation radiation and could be detectable by the forthcoming satellites. Nearby dwarf galaxies, thought to be dominated by dark matter, provide important and complementary tests of CDM both via their annihilation signal as well as their central stellar velocities which probe the smallest scales where CDM faces it's biggest challenges. In this way, the Milky Way and its neighbors act as a cosmological crucible, or testbed for dark matter particle theories.

2. TIMING AND PLANNING

Our program is timed to take full advantage of the observational advances that will be occurring over the next five years.

Regarding potential participation, we attach below a list of leading researchers who would likely attend this program. Those listed in boldface have already expressed interest specifically in the program outlined above.

John Beacom
Tim Beers
Eric Bell
Gianfranco Bertone
James Binney
Joss Bland-Hawthorn
Leo Blitz
Mike Bolte

Masashi Chiba
Sergio Colafrancesco
Walter Dehnen
Juerg Diemand
Wyn Evans
Annette Ferguson
Chris Flynn
Ken Freeman
Carlos Frenk
Gerry Gilmore
Fabio Governato
Eva Grebel
Lars Hernquist
Vanessa Hill
Rodrigo Ibata
Mike Irwin
Zelko Ivesic
Kathryn Johnston
Andrey Kravtsov
Michael Kuhlen
Sebastien Lepine
Don Lynden-Bell
Steve Majewski
Mario Mateo
Andy McWilliam
Mike Merrifield
Ben Moore
Heather Morrison
Julio Navarro
Heidi Jo Newberg
Eve Ostriker
Jerry Ostriker
Jorge Penarrubia
Mary Putman
Hans Walter Rix
Connie Rockosi
Steve Shectman
Joe Silk

Tammy Smecker-Hane
Volker Springel
Eline Tolstoy
Scott Tremaine
Kim Venn
Martin Weinberg
Simon White
Beth Willman
Rosie Wyse