# Searching for Dwarf Companions of the Milky Way and Beyond in the LSST Era

A workshop sponsored by NOAO and the LSST Corporation
Oct 11-13, 2017 in Tucson, AZ


Keith Bechtol * (LSST)
Peter Behroozi (Steward)
Vasily Belokurov (Cambridge)
Gurtina Besla (Steward)
Ana Bonaca (CFA)
Jeff Carlin (LSST)
Masashi Chiba (Tohoku U.)
Yumi Choi (Steward)
Alex Drlica-Wagner (Fermilab)
Nicolas Garavito-Camargo (Steward)
Jennifer Kadowaki (Steward)
Dongwon Kim (UC Berkeley)
Sergey Koposov (Carnegie Mellon)
Simon Krughoff (LSST)
Dougal Mackey (ANU)
Nicolas Martin (MPIA)
Chris Mihos (Case Western)
Heidi Newberg (RPI)
Knut Olsen * (NOAO)
Helio Perrotoni (RPI)
Annika Peter (OSU)
Ragadeepika Pucha (Steward)
Steve Ridgway * (NOAO)
Robyn Sanderson (CalTech)
Josh Simon (Carnegie)
Colin Slater (UW)
Jay Strader (MSU)
Gabriel Torrealba (Cambridge)
Kathy Vivas (CTIO)
Beth Willman (LSST)
Dan Weisz (Berkeley)
Andrew Wetzel (UC Davis)
Rosie Wyse (JHU)
Dennis Zaritsky (Steward)

*Editors


Version 1.1

# SEARCHING FOR DWARF COMPANIONS OF THE MILKY WAY AND BEYOND IN THE LSST ERA - A WORKSHOP SPONSORED BY NOAO AND THE LSST CORPORATION, OCT 11-13, 2017 IN TUCSON, AZ.*

Keith Bechtol (LSST),[1] Knut Olsen (NOAO),[1] Steve Ridgway (NOAO),[1]
Peter Behroozi (Steward Obs), Vasily Belokurov (Cambridge),
Gurtina Besla (Steward Obs), Ana Bonaca (CFA), Jeff Carlin (LSST),
Masashi Chiba (Tohoku U.), Yumi Choi (Steward Obs.),
Alex Drlica-Wagner (Fermilab),
Nicolas Garavito-Camargo (Steward Obs),
Jennifer Kadowaki (Steward Obs), Dongwon Kim (UC Berkeley),
Sergey Koposov (Carnegie Mellon), Simon Krughoff (LSST),
Dougal Mackey (ANU), Nicolas Martin (MPIA),
Chris Mihos (Case Western), Heidi Newberg (RPI), Helio Perrotoni (RPI),
Annika Peter (OSU), Ragadeepika Pucha (Steward Obs.),
Robyn Sanderson (CalTech), Josh Simon (Carnegie), Colin Slater (UW),
Jay Strader (MSU), Gabriel Torrealba (Cambridge), Kathy Vivas (CTIO),
Beth Willman (LSST), Dan Weisz (Berkeley), Andrew Wetzel (UC Davis),
Rosie Wyse (JHU), and Dennis Zaritsky (Steward Obs)

[1] *Editer*

## ABSTRACT

The LSST wide-fast-deep survey is expected to revolutionize the discovery and study of dwarf galaxies in the Local Group, with important consequences for understanding galaxy formation and evolution. In the spirit of the LSSTC call to "help the community prepare", and AURA's on-going commitment to enabling astronomical research, NOAO was pleased to organize and host this 2+ day technically focused workshop on dwarf companion studies. Topics included: Theory context and guidance, Review of recent searches, Catalog and pixel based search techniques, The status of the missing dwarf problem, and Future directions. The workshop concept was for a short but in-depth conversation among active researchers, with a minimum of prepared presentations and an emphasis on group discussion within the plenary attendance. All participants contributed actively, as session presenters, moderators, scribes, and editors - all participants are authors of this report.

* Meeting website: https://www.noao.edu/meetings/dwarf-companions/

## Note from the SOC chairs

Most of the workshop time was devoted to open discussion in plenary session. There was sufficient time that it was rarely, if ever, necessary to leave a topic before it had been extensively explored with full participation.

The meeting was, in one word, exciting. Our scribes have done a great job of capturing both the variety of ideas and opinions, and the drift toward consensus, where that happened. All of the reports have been edited, some into almost a conventional report form, while many retain the more staccato style of the event. Some include indications of speakers (names, initials), but the ideas arrived so rapidly that there will be errors and many good ideas remain unattributed.

One outcome of the workshop is a concise set of recommendations for the Milky Way/Local group community and for the LSST survey design process. These are collected in section 13.

We hope that this record of the workshop proves useful to the participants, to LSST, and to the community.

## 1. INTRODUCTION

Presenter: Knut Olsen; Scribe: Steve Ridgway

The dwarf companion galaxies of the Milky Way, Local Group, and Local Volume are critical probes both of the dark matter halos that are the seeds of forming galaxies and of the physical processes that shape their formation. The ultrafaint dwarfs discovered by the Sloan Digital Sky Survey (SDSS) and, more recently, by wide-field survey cameras on 4-8-m telescopes provide ample evidence of the complex process of hierarchical galaxy assembly as well an ample number of puzzles that challenge our theoretical understanding. The Large Synoptic Survey Telescope (LSST) will provide an extraordinarily rich dataset for the detection and characterization of faint dwarf galaxies. With the start of the 10-year Survey fast approaching, the time is ripe for the community to prepare seriously for the opportunities for dwarf galaxy science that LSST will provide, and to provide input and advice to the LSST project team.

Through a generous grant provided by the LSST Corporation, we organized this workshop, held October 11-13 in Tucson, AZ, with focus on the scientific and technical issues facing dwarf galaxy science in the era of LSST. The workshop was thoroughly science based, but technically oriented, in accordance with the practical needs of survey design. The workshop was organized to encourage discussion, with topics, moderators and scribes. Slides were utilized for discussion purposes, and are linked from the workshop webpages, but were not organized into formal talks, and were not intended to be introductory, thorough, or bibliographically complete. Participants were encouraged to exercise inclusive meeting practices in order to engage all and expose a wide range of points of view and opinions, and the objective of open while vigorous discussion was accomplished.

The workshop began with a review of goals (summarized below) and methodology. Discussion of the recent history and status of the discipline clarified the opportunities that exist for extended analysis of existing data. Looking ahead, newly arriving datasets, such as the Dark Energy Survey, as extended by "crowd sourced" additions, offer important opportunities for proving the tools that can capitalize on the LSST survey.

The workshop reviewed LSST process and products, and found that the baseline survey can be expected to provide important improvements in data quality, as well as quantity and sky coverage, of strong benefit to dwarf companion science. Discussion revealed that our science can benefit greatly from small changes to the survey plan. Dwarf companion science requires significant specialized data processing, which may be within the scope but not the planning of LSST data management, and could significantly benefit from modest changes to the current (Nov 2017) LSST baseline survey planning. Specific suggestions and requests were formulated for communication to the LSST project, science collaborations and community. Each of these is developed in detail below.

Work will be required to develop the motivation for investment required to support dwarf galaxy science, to publicize it, to identify and engage appropriate sources of support. A subsequent follow-on activity to this workshop may be timely and required on the timescale of a few years.

This meeting report is crowd-sourced from the participants, and the sections reflect the personalities of the moderators, the scribes and of course the discussion participants.

## 2. WHAT WILL BE THE BIG DWARF GALAXY QUESTIONS IN THE LSST ERA?

Presenters: Multiple;

Moderators: Keith Bechtol, Rosie Wyse; Scribe: Ana Bonaca

The main goal of this session was to set a theoretical background for the workshop, or in other words, to provoke the theorists in the room to tell the observers what to look for. More specifically, we wanted to establish the science drivers in 2020s, and whether we should be revisiting basic questions, such as how to differentiate between globular clusters and dwarf galaxies, or the dark matter content in dwarfs, or whether there will be new questions. Science topics discussed could be split in two categories: dwarf galaxies as cosmological probes and dwarfs as laboratories of galaxy evolution (see the session slides[1] for a detailed list of questions on both topics). The consensus at the end of the session was that we will need to consider these questions simultaneously, which will be possible for the first time thanks to the depth and volume of the LSST, and high resolution and volume of state-of-the-art hydrodynamical simulations. The remainder of this section transcribes the full discussion that took place.

### 2.1. *Nature of dark matter*

AP: To learn what the dark matter is, we need both the halo mass function of dwarf galaxies and the mass profile within individual galaxies. It would also be great to go beyond the Milky Way.

ADW: Will we get get far enough down the mass function in the LSST era to distinguish different dark matter models?

AP: Yes, the mass function constraints are becoming competitive.

[1] https://docs.google.com/presentation/d/1Tdipl3_cT72t6XkHblVzonFbZ5OXbeLNzq2jyTbceHU/edit

NM: The reason this doesnt exist yet is excessively idealistic mapping of velocity dispersion to the enclosed mass – we'll need to merge questions of galaxy evolution and cosmology (properties of the galaxy should inform how to measure the mass profile better).

### 2.2. *Stellar streams as probes of dwarf galaxies*

HN: How can we use streams as probes of disrupted dwarfs?

RS: There are two ways to address this: 1) LSST will get a more complete census of dwarfs, so well be able to narrow down the expectation for the number of disrupted streams in simulations.

KB: How does the Milky Way mass scale with the number of dwarfs?

AW, RS: It scales roughly linearly with mass, so the expected number of satellites is uncertain by a factor of two.

AW: Measuring the inner density profile will be harder, and will probably be possible only for the Milky Way satellites.

RS: ... and 2) the simulations are only becoming informative now, due to the small dynamical range in simulations of the previous generation.

AP: Given a halo and a stellar mass for the Milky Way, one can constrain the accretion history from properties of the stellar halo (e.g., Deason et al. 2016).

RS: In detail, we will be able to do this only for the Milky Way, and we can't generalize too much, so we will need other galaxies for a variety of accretion histories.

GB: Inner halo profile in the dwarf (i.e., core/cusp) will also affect the stream structure.

### 2.3. *Dwarfs beyond the Milky Way*

KB?: One unique aspect of the LSST era will be moving beyond the Milky Way in studies of dwarf galaxies. What can we learn from unbiased surveys of dwarfs around field galaxies? Will the Milky Way satellites then be less interesting?

GB: 100 Mpc is a relevant scale for cosmological simulations, and we are now getting close to making predictions for dwarf clustering on those scales, which we will be able to check with LSST.

DZ: Should we be looking for isolated dwarfs instead of the Milky Way satellites? Or would perhaps field binary dwarfs be better probes of inner mass profile?

AP: Ideally, we would want to study dwarfs in as many environments as we can get.

JS: Environment shouldn't matter too much, as things get back to equilibrium fairly quickly, but perhaps it would be worthwhile taking this out of the question.

KB: Theoretically, should there be 1000s of dwarfs in the field?

AW: In principle yes, from what we can tell using zoom-in simulations; by the time LSST comes around, we'll be able to simulate ultrafaint dwarfs (UFDs) around a Milky Way-like galaxy.

MJ: Currently, only zoom-in simulations resolve UFDs.

DW: Shouldn't there be fewer UFDs in the field due to clustering?

AW: Yes.

KB: Is it hard to predict the number of UFDs in the field?

AW: Yes, because zoom-ins are selected from a larger box, so it's hard to map the simulation volume (in terms of the large scale environment – void, filament, etc.) to our own.

ADW: Is simulating the Milky Way easier in that context? How well does a simulated Milky Way map to the real one?

RS: An imperfect match of the simulated to the real Milky Way is not a problem for every test of dark matter, just for the mass function, for example, the inner profile of dark matter within the dwarfs is unaffected by large-scale environment.

AP: How many other stellar halos can we explore in LSST?

DW: Draco-like objects are being found in Virgo, at 16 Mpc.

JS: But we won't be able to study their properties, just count them.

RS: We should also think about WFIRST, as there will be overlap with LSST.

### 2.4. *How to leverage information from disrupting dwarfs*

ADW: Is the radial distribution of dwarfs in the Milky Way halo interesting?

AP: Yes, but it is very related to galaxy physics; to name an issue – when do we stop calling a disrupted galaxy a galaxy, and start calling it a stream?

RS: The line is probably going to smudge in the LSST era, as we should find more transitional objects, especially in the outer galaxy.

NM: This is already an issue, e.g., it is unclear whether BooIII is bound or not.

AW: What is the theoretical guideline?

JS: perhaps there won't be that many such objects? For example, there are not that many globular clusters that are disrupting.

RS: But globular clusters are much denser environments than dwarf galaxies, and thus harder to disrupt.

NM: What is the proper way to compare observed disrupting systems to simulations?

ADW: If full 6D information is present (for the bulk motion, but not internally), we can use that to calculate the orbit and check whether a system is disrupting.

NM: The principled way to solve this would be to consider streams and dwarfs simultaneously, not as separate categories.

DZ: Looking at different statistics, like star-star correlation functions, would perhaps be more informative (there should be a peak for bound objects).

RS: This has been done for Bullock & Johnston (2005) halos and indeed, bound and unbound structures can be differentiated.

JS: We could create a star-star correlation function with a catalog of RR Lyrae, too.

RS: That would be a good test for comparing observations and simulations, but we'd need a large sample of tracers, where differences from different mass accretion histories become evident in the star-star correlation function.

HN: Would it be easier to do this in the velocity space? Perhaps velocities are harder to measure, but we wouldnt need to go as far out in to the halo?

JC: This has been done with LAMOST, but the constraints are not too competitive at the present (consistent with all of halo having been accreted, Carlin et al. 2016)

KB: What is the punchline at the end of the day? Are these new observables informative? Say, can they distinguish different reionization histories?

RS: It is unclear whether we have enough simulations to do that.

AW: But the data should be constraining.

GB: ... but likely not definitive.

KB: Will we get any qualitative new insights?

DW: If we found a younger stellar population in a low mass field galaxy, that would be new and unexpected.

VB: We can already discern between cosmological accretion histories and BJ05 from correlation statistics using SDSS and RR Lyrae data (ref?).

## 3. SUCCESSES AND CHALLENGES OF RECENT DWARF GALAXY SEARCHES

Moderator: Alex Drlica-Wagner; Scribe: Andrew Wetzel

We discussed a wide variety of ongoing searches for dwarf galaxies. We reviewed recent searches for dwarf galaxies around the Milky Way using data from SDSS, Pan-STARRS, DECam, VST ATLAS, and HSC. We discussed searches for dwarf galaxies around M31 by PAndAS, and We discussed searches for dwarf galaxies around nearby systems, including satellites of galaxy clusters down to satellites of dwarf galaxies, using MADCASH, SMUDGES, and U*. We also considered searches based on HI and based on variable stars, such as RR Lyrae.

Note that LSST single epoch depth will be comparable to the current depth of the HSC survey, though the median seeing of LSST (0.6 - 0.7 arcsec) likely to be slightly worse than HSC.

Note that M31 is not in LSST's (current) footprint, so LSST is not expected to provide (much) information for dwarf searches around that system.

### 3.1. *Ongoing work within the Milky Way*

Searches (and discoveries!) have continued with with legacy data, such as SDSS or Pan-STARRS. A rapid discovery phase was entered with the installation of DECam, supplemented by exciting discoveries from Pan-STARRs, VST ATLAS, and HSC. Detection and measurement algorithms continue to improve; however, major increases in senstivity come predominantly from superior data sets.

Even before LSST, significant work remains to understand the population of recently discovered dwarf galaxies. Spectroscopic and deeper photometric follow-up remain incomplete.

A key question: are the newly discovered dwarf galaxies near the LMC physically associated with the LMC? Are their properties, such as SFH, metallicity, and chemical abundances, systematically different from the previously known population? SMASH and MagLiteS hope to answer the question about whether there is an overdensity of dwarf galaxies on the other side of the LMC.

Crater 2 represents a particularly interesting discovery, given its large size and small internal velocity dispersion. Is this object consistent with current models? Is its size a result of (internal) formation history, or (external) tidal interactions with the Milky Way? How many Carter 2-like objects are being missed by current algorithms.

### 3.2. *Searches beyond the Local Group*

Searches for dwarf galaxies beyond the Local Group have been successful and have significant promise for the LSST era. Depending on distance and instrument resolution, these discovers commonly target unresolved (or partially resolved) stellar popultions. The MADCASH survey recently found 2 satellite dwarfs around an isolated LMC-mass galaxy. SMUDGES has found low surface brightness dwarf galaxies near Coma(?). U* is using LBT to find satellite dwarf galaxies near star-forming hosts. Preliminary analyses suggest that U-band may significantly help with rejecting low-surface brightness background features, i.e., galactic cirrus. LSST will push these searches out to several Mpc.

### 3.3. *Physical classification: dwarf galaxies versus globular clusters*

It was clear even from early SDSS data that differentiating dwarf galaxies from globular clusters would be difficult. While these populations historically lay in distinct regimes of surface brightness (size versus luminosity), newer discoveries of ultra-faint systems fill in this parameter space and thus blur the distinction between these classes of objects. This represents a potential difficulty for interpreting future discoveries, given that globular clusters are thought to form in/around galaxies while dwarf galaxies are expected to be primordial. However, new simulations suggest that the formation of globular clusters and dwarf galaxies may be intimately linked. What is the connection between globular clusters and dwarfs? How many globular clusters formed within dwarf galaxies, in particular, dwarf galaxies that may still survive? Is it possible to measure cosmological/fundamental properties of dark matter halos using a population of "dwarf galaxies" that possess some (currently unknown) contamination from globular clusters?

### 3.4. *Star-galaxy separation*

A common theme, and perhaps the most significant barrier in searches for resolved Milky Way dwarf galaxies, comes for separating stellar objects from (barely resolved) background galaxies. Due to the rapidly rising number of galaxy counts with decreasing luminosity, background galaxy contamination often sets the effective magnitude limit of current surveys. The star-galaxy classification challenge will be worse for LSST, as it pushes to fainter luminosities. Problematically, the colors of distant red galaxies are almost the same as the colors of main sequence turn-off stars within the local Universe. Progress in this area is critical. HSC data will likely serve a vital role in understanding and solving this issue.

### 3.5. *Techniques for future searches*

New maximum likelihood techniques should represent a statisitically rigorous way to maximize information content in dwarf galaxy searches with resolved stars. However, in practice, this sophisticated methodology has not been significantly more successful in discovering dwarfs with DES than previous searches. This is likely due to systematic challenges resulting in large contamination from imaging artifacts, photometric measurement features, etc. Contamination levels are dependent on the significance threshold applied. Even for relatively high significance thresholds, the contamination level can be $\sim 90\%$. Nearly all of these contaminants are obvious artifacts when investigated visually. Automating this process is essential to perform statistically rigorous studies of the dwarf galaxy population. It remains unclear how well fully automated searches will perform in the LSST era.

How do we get rid of false positives? What new statistics for dwarf galaxies should we use? Should we include proper motions (in addition to astrometric positions) in our searches? How can machine learning techniques be used to reject "obvious" contaminants.

Many of the new discoveries in the LSST era are likely to be distant, low luminosity, and/or low surface brightness. Recent discoveries provide evidence that hundreds more dwarfs remain to be found around the MW in the LSST era. It will be important to improve the reduction/discovery pipelines to optimize for these objects.

Most current searches cut detections to be only high signal / noise (S/N). Therefore, many satellites may be buried at lower S/N, and thus remain undetected. How can we improve our search methods to tease out systems at lower S/N? By modeling the background/noise/etc, can we *statistically* constrain the luminosity function of dwarf galaxies? This requires some understanding/modeling of contamination, which is hard to do if contamination is predominantly systematic/artifact driven.

At least one RR Lyrae star has been found in each dwarf where time-domain searches have been performed. Looking for overdensities of RR Lyrae may be a promising avenue for searching for dwarf galaxies. This technique promises to be particularly useful (1) for more distant dwarf galaxies, and (2) for looking across the disk of the MW, where crowding and dust are a significant limitation. The high-cadence observations from LSST will be ideal for this type of time-domain search.

## 4. LSST DATA PRODUCTS AND SERVICES FOR DWARF GALAXY SCIENCE

Presenters: Simon Krughoff, Colin Slater;

Moderator: Kathy Vivas; Scribe: Dougal Mackey

LSST construction update:

Cerro Pachon: Getting ready to put on the LSST dome

Telescope under construction in Spain, elevation structure assembly begun

Primary mirror done, stored at aircraft hangar in Tucson

88 science-grade sensors delivered, will be integrated into rafts (3x3 module of sensors). 189 total sensors in the camera

ComCam is a single raft. Will be used for small-scale testing of the telescope before the delivery of the full camera.

LSST data products:

LSST Data Products Definition Document. This is the source of knowledge! See http://ls.st/dpdd. The DPDD defines what will be measured, but does not dictate the details of the implementation.

Level 1 processing (Alert Processing): prompt - difference imaging, streams of alerts

Level 2 processing (Data Release Processing): deep coadds, detections, both static sky and variability metrics, proper motions, high-fidelity. Forced photometry on individual visits.

Releases done on an annual cycle. Need template imaging for the nightly processing.

Pipeline:

Single visits $->$ coadds (for detection) $->$ objects

Objects $->$ single visits $->$ forced photometry + multifit measurements

Objects are the union of detections on coadds and detections in difference imaging

Objects will be fit with moving point source model, colors, variability statistics

Lessons from HSC:

Significant fraction of objects are blended at LSST depth

Background subtraction is hard problem (coupled to source detection, deblending)

LSST Science Platform:

Science Platform vision document: http://ls.st/lsp

Group of user-level tools and ecosystem of data access utilities

Utilities: Data releases, stream of alerts, user databases, user files, user computing, software tools

Portal: leveraging existing utilities to provide an interface useful for viewing images and querying databases.

JupyterLab: web-based interface to notebooks – python-based, rich environment, plots, interactive python environment

JupyerLab Demo:

Example notebook at: http://ls.st/zgo

Variety of authenticators.

LSST stack installed, terminal shell, text editors, python console

Python 3-only after May 2018

In this demo, running in a container in the Google compute cloud. Will be deployed in the LSST cloud as construction progresses. The user database and user file system will be local to the data providing access to all those tools

You can augment environment with your own modules. E.g., `pip install --user <module>`

Extensible environment

Test out ideas in notebook

Farm out analysis on Science Platform cluster – 25K cores.

There will be disk quotas and batch queue quotas

Recovery for sessions that are idle. Persistence of notebooks.

LSST Project is not formally planning on providing crossmatches with other survey catalogs, but will enable users to do so.

NOAO DataLab offers complementary tools and access to other surveys.

Offline analysis? What are the use cases? There will be some utilities for transferring data to other places.

Users will have access to the full data provenance. (This has not been promised in an official document yet.) Another question is whether the provenance is included in data products.

Sky is divided into large areas called tracts. Common projection. Dodecahedron roughly. 12 tracts across the sky. HSC is using smaller tracts. A full field of view contained within a single tract. Subdivided into rectilinear grids called patches . You can get all the images that went into a patch.

The Stars, Milky Way, and Local Volume Collaboration provides a venue for further discussion of dwarf galaxy science with LSST. See: http://milkyway.science.lsst.org.

## 5. WHAT MEASUREMENTS WILL WE NEED?

Moderators: Annika Peter, Vasily Belokurov; Scribe: Gabriel Torrealba

LSST will reach a sufficient photometric depth that it is expected a very wide variety of dwarf galaxies will be accessible. These will populate almost all conceivable environments, from the neighbourhoods of large galaxies, to galaxy clusters, to the field. The range in distances will extend from the Milky Way and the Local Volume out to $\sim 60 - 100$ Mpc (although of course the dwarf galaxy limiting magnitude is a function of the distance).

The apparent morphologies of dwarfs will vary from completely resolved stellar systems in the Local Group (most of which are likely to be comprised largely of ancient metal-poor stellar populations) to partially-resolved (lumpy) objects or completely unresolved smudges at larger distances. Because the star-formation histories of dwarf galaxies are strongly variable from system to system, these objects are likely to exhibit a broad span in stellar populations, including systems which are blue and whose light is dominated by ongoing star formation.

Naturally a broad variety of different techniques are required to search for objects with such strongly differing morphologies. Algorithms range from resolved searches that use an isochrone filter to locate spatial overdensities of stars with apparently similar ages/metallicities/distances, to unresolved pixel-based searches that search for faint background residuals after all the known objects have been subtracted from an image. Various such techniques were discussed in subsequent sessions. Here it was noted briefly that these searches require certain key data properties to be accessible, ranging from robust star-galaxy separation for resolved searches to information on the scale of individual pixels for unresolved searches. It is not clear that all the required information/data is currently part of the LSST data production plans – this should be investigated and discussed (for example, will researchers have direct pixel-by-pixel access to the relevant images?).

The key area where LSST will open new parameter space is by pushing to substantially lower surface brightness than is presently possible (Is there some number we can put on this?). On the traditional size-luminosity plane, the surface brightness limits of extant surveys manifest as a dearth of objects in the direction of large size and low luminosity. There is no reason to believe that this dearth of objects is due to an intrinsic lower cut-off to galaxy surface brightness, although using cosmological galaxy formation models to explore this question is certainly of substantial interest. Every time a survey has pushed further into this part of the parameter space, new objects have been discovered whether that be the original SDSS discovery of ultra-faint dwarfs around the Milky Way, or the more recent discovery of ultra-diffuse dwarfs in various galaxy clusters.

Given all the above, an important question is whether we are likely to transition from the current situation where the detailed properties of individual dwarfs (at least in the Local Group) are of significant intrinsic interest, to a regime where we are more concerned with the statistical properties of much larger samples (and where possessing detailed information about any single target is unnecessary). This depends to some extent on the questions being addressed – for example what is the luminosity function of dwarfs as a function of distance and/or environment, or what is the dark matter content of dwarfs.

Perhaps a more pressing question than "what should be looking for" is "how do we figure out what weve found?". That is, to what extent will we need to, and (more critically) be able to, obtain follow-up data for any newly-discovered objects – an option that is likely to be strongly limited by available facilities. However follow-up appears essential to robustly address questions including (i) at low significance levels, what is a real dwarf and what is a false positive? (ii) what are the distances of systems where few, if any, resolved stars are visible? (iii) what are the internal kinematics of nearby systems? (iv) what is a dwarf and what is a low-luminosity globular cluster, in the regime where sizes and luminosities are not unique discriminators? Clever application of photometric techniques will help to some extent (for example, using photo-z to remove contamination due to background galaxies, or using LSST proper motions to reduce foreground contamination or identify co-moving "groups" on the sky). There was a general consensus that pushing LSST observations in the u-band (perhaps up to double the current planned exposure duration) would be extremely helpful  this should be discussed further and investigated quantitatively for specific applications.

## 6. CATALOG-BASED SEARCH TECHNIQUES

Moderators: Sergey Koposov, Heidi Newberg; Scribe: Gabriel Torrealba

During this session we talked about the current status and challenges that catalogue based searches currently have and will have in the LSST era. The session started with a short presentation of one the methods currently in development, MaGIK, that uses a similar approach to the techniques that have been used in the past to discover dwarf galaxies around the MW. Another perspective presented based on catalogues is the modeling of tidal streams to find the dwarf galaxy progenitor properties. In short, Nbody simulations are performed for a model dwarf with given mass and radius, both light and dark, plus the time of disruption. This is then compared to the data - particularly the number of stars as a function of angle from the stream. This allows inference of the model properties, down to 10% precision in ideal conditions, of the objects in ways that are not possible for undisrupted dwarfs.

The session then moved to what are the challenges faced by catalogue-based dwarf galaxy searches. There are many algorithms and many methods, all very similar, but what are the common issues they face?. From the discussion, it becomes immediately clear than the main problem for the LSST era (and probably already now) will be the star-galaxy (SG) separation. At magnitudes fainter than 24 the galaxies outnumber the stars by a factor of $\sim$100 – additionally, different surveys have different metrics with different properties to measure the separation, further complicating the comparison of results. It is proposed then, that the ideal will be to find a way to describe the star-galaxy dichotomy in a fully probabilistic way. One of the main advantages of this is the ability to assess the probability of a given candidate of being a galaxy cluster, which will be the main source of contamination. Ideas on how to improve in this regard were then presented, and include: using the IMF and the distribution of galaxies in the CMD to efficiently filter them. Use color information to create filters in higher dimensions, but this needs precise isochrones, since a single-band model offset or calibration error could leave you with no stars. Assess the likelihood of being a galaxy cluster by running the search method in galaxies too. But the ideal will be to fully model galaxies and stars at the same time - if one could understand the properties and systematics of the data. Another alternative is to talk to people who are looking for galaxy clusters, and use their discovery algorithms to filter our contaminants. Finally, adding priors to the data (e.g. as a function of galactic latitude) to star galaxy separation could help, but it can be arguably very complicated.

How do we use proper motion information optimally? In principle, PMs will allow to detect things with large angular sizes and low surface brightness. In this sense, it is advisable to include this information in the search techniques, since it could uncover objects in areas of parameter space which are currently unexplored (see also Antoja 2015).

Another new dimension that enters with LSST is the availability of variability. This will bring new tracers useful in the search for dwarf galaxies. Particularly interesting are RR Lyrae stars, that are present in every UDG that has been explored so far, and hence a good candidate to include as a tracer in the searches. In this sense, combining the information from different tracers was also discussed as one of the main possible improvements to current searches. In particular, BHBs, Carbon stars, RRL stars, and metal poor stars can prove useful to improve the searches. The issue with this approach is that these are, comparatively, rare tracers. But combining them with traditional isochrone masks could alleviate this issue.

Another topic discussed is searches in the disk. Typically, due to extinction and crowding the disk poses challenges and technical difficulties that makes searches of dwarfs very difficult. Indeed, searches in the disk is a completely different exercise from the traditional searches.

The question of the importance satellite searches in the disk was also raised – do we really need to search there if we could characterize the population without it? In generally people agreed that it is indeed interesting. A reason given satellites in the plane provide a completely different scenario. From a dynamical perspective giving they are objects with velocities completely different from what you observe otherwise. Also, it is arguably a region of interest because the distribution of satellites in the MW is known to be anisotropic and the plane could hide a significant number of dwarfs (note that an important fraction of the expected LMC dwarfs will be hidden by the plane). Furthermore, the presence of RRL can alleviate to some extent some of the challenges presented by extinction, and could be used by themselves to look for dwarfs and substructure at low galactic $b$.

Another important topic was the numbers of false positives and how to deal with them. The first question is, how far down do we need to go? could we put theoretical priors to this question? In this sense it was argued that it is best to always go to the limit – we want to be sure of finding a satellite if it is in the candidate lists, even if this means examining a high rate of false positives. Additionally, a clean sample and a full sample serve different purpose – one for statistical inferences and one for discovery – and both can be addressed simultaneously. Another reason is that we are dominated by systematics, hence, how do we properly compare the number of confirmed candidates with the theoretical expectations? This is not trivial, because you cannot expect to model the false positives, which hence are *very difficult* to characterize. Finally, it was also noted (several times) that it is critical to move away from vetting all candidates by eye!.

Additional topics mentioned but not discussed:

> Non circularity of the dwarfs – we search for circular dwarfs, but dwarfs are typically not be round! – how do we deal with this issue? should we look for elongated objects? is this feasible?
>
> Also, an interesting related question is the surface brightness limit – are there dwarfs hiding below the 31 limit? how do we push this limit further?

## 7. PIXEL-BASED SEARCH TECHNIQUES

Moderators: Chris Mihos, Dennis Zaritsky; Scribe: Steve Ridgway

Pixel-based analysis is the term used here to refer to search techniques that are based on the analysis of star associations that are detected as an ensemble, but not resolved into distinct point sources. Pixel-based methods are applicable to more distant galaxies. These will offer less detailed data, with resulting specific difficulties, such as confirming classification and distance. However, larger number of dwarf galaxy detections and characterization can support, and exploit, statistical study of these objects.

The pixel-based method requires outstanding knowledge and correction for backgrounds — night sky levels, foreground galactic cirrus, background sources, and instrumental scattered light. It relies on high quality data from telescope-instrument combinations designed for control of extended scattered light (e.g., PSF halos and reflections). The design considerations and specifications for LSST optics, and the expected high quality of detectors, promise outstanding characteristics (among facilities of comparable aperture size) for pixel-based analysis. However, the verification of this will only arrive with commissioning observing in 2019-2021.

Fully exploiting a fine instrument capability additionally requires attention to observing methods. Dithering is needed, suitable for identifying and correcting for scattered light in the telescope and camera optics. Measurement of the extended PSF on scales of tens of arcminutes is important for the most careful work.

Analysis of pixel-based data usually progresses by modeling all sources in the image that are detected by conventional means - stars, galaxies - and subtracting the models or masking contaminated pixels - leaving a nominally “blank” image. The targets of interest will remain as subtle variations in the residual “background”. They can be detected, e.g., by binning, convolution with typical models, or visual inspection. It is particularly important that this analysis should be applied to individual images, prior to stacking, since scattered light patterns change with telescope pointing, such that modeling and subtracting scattered light need to occur before making the final image stack. The source-subtracted individual images may then be stacked, to improved S/N and further suppress stochastic background errors.

Source-subtracted images are to be produced in the LSST data pipeline - but at present there is no plan to either preserve the subtracted images, or to form a stack of subtracted images. The former may place an excessive demand on the LSST data system - in that case, LSST is asked to facilitate access to raw data for possible user reprocessing by correcting for scattered light and masking of compact sources before stacking. Forming and serving a stacked subtracted image may be a realistic objective for LSST DM - possibly, this may not need to be kept at full resolution.

One possible complication of pixel-based techniques is proper rejection of background sources vs compact sources within the object itself. At extremely low surface brightness, most compact sources are likely to be background galaxies, but some sources may be star clusters or star forming regions associated with the low surface brightness dwarf. Masking them from the analysis can significantly bias the derived properties (magnitudes, colors) of the galaxy, a particular problem for low surface brightness star-forming dwarf systems. In such a case, a combination of pixel-based and catalog-based analysis may produce more information. These implications for LSST of dwarf galaxy science are summarized below.

# 8. BEYOND THE MILKY WAY

Moderator: Jay Strader; Scribe: Jeff Carlin

## 8.1. *What questions about dark matter and galaxy formation are addressed by an LSST census of dwarfs?*

In this section, we briefly discuss the motivation for finding and characterizing dwarf galaxies beyond the Milky Way (and, in fact, beyond the Local Group). This section is by no means a complete summary of the science questions addressed by such a search, but rather is meant to express some examples briefly discussed by the workshop participants.

- Luminosity/mass function around hosts of different mass, environment
- Galaxy evolution around hosts of different mass, environment
- Amount and properties of substructure in halos – can count the dwarfs and the streams to recreate merger history (e.g., Cen A)
- Statistical cosmology via correlation functions of ∼SMC-mass systems

## 8.2. *Techniques for finding dwarfs beyond the Milky Way*

A variety of techniques can be used to detect dwarf galaxies beyond the Milky Way, including directly with LSST (as either resolved or unresolved systems), as well as using LSST to complement searches conducted at other wavelengths.

### 8.2.1. *HI all-sky surveys*

Find, e.g., isolated HI-rich dwarfs, then search for their optical counterparts in LSST images.

### 8.2.2. *Faint, diffuse, unresolved galaxies*

### 8.2.3. *Resolved RGB star maps*

## 8.3. *Outstanding and anticipated issues*

- Detection and structural parameters for partially resolved dwarfs
- Distance estimates for un-/partially-resolved objects
- (test both the above, plus completeness, by injecting artificial dwarfs into the images)

- Follow-up observations?
- Predictions are easier to make for a galaxy of a given size, rather than a certain volume
- Challenge of crowded fields and elevated backgrounds (unresolved emission)

## 9. ADDRESSING DWARF GALAXY PROBLEMS WITH LSST

Moderators: Nicolas Martin, Gurtina Besla; Scribe: Nicolas Garavito-Camargo

**LSST will provide:**

- Depth: Much deeper data with LSST will enable the detection of fainter dwarfs about the MW, Local Volume and out 100 Mpc (LMC SMC type objects)
- Variable stars, such as RR Lyrae, will yield distances (out to $\sim$ 300 kpc)
- Proper motions measurements: Find stars that move similarly in the sky.
- Wide Field: Increase the volume probed

**Theoretical interests:**

1. Number and distribution of dwarfs: Around the MW and MW analogues.
2. Tidal effects: Streams, morphological evolution.
3. Quenching of low mass galaxies. Role of environment
4. DM halos: Mass, structure and kinematics.
5. Hierarchical Evolution: Group infall, dwarf groups in the field

In the following we list how LSST data might be able to provide data to answer the listed theoretical interests along with needed theoretical work to complement the data. We define dwarf galaxies as having stellar masses less than $M* < 5 \times 10^9$ $M_\odot$. We break down the science interests in terms of 3 dwarf stellar mass bins. The lowest mass bin ($M* < 10^5$ $M_\odot$) refers to ultra faint dwarfs. Intermediate masses ($10^5$ $M_\odot$ $< M* < 10^8$ $M_\odot$) refers to the classical dwarf spheroidal regime. The highest masses ($10^8$ $M_\odot$ $< M* < 5 \times 10^9$ $M_\odot$) encompasses galaxies like the SMC and LMC.

### 9.1. *Lowest Masses: $M_* < 10^5 M_\odot$, $M_{halo} < 10^9 M_\odot$*

**1. Number and distribution of dwarfs**

- LSST : Number of satellites are there at large distances (100 kpc to $R_{vir}$)?
- Theory : New predictions from hydrodynamic cosmological simulations at the lowest masses around MW analogs.

- Theory : Make more robust predictions starting from the prior that there is agreement in the mass function for higher mass satellites. What is the corresponding prediction for lower mass satellites?

**2. Tidal Effects**

- LSST: Observe the stellar outskirts of dwarfs to search for extended stellar structures, warps, streams and define a tidal radius.
- LSST: constraints on the orbits of dwarfs and globular clusters (maybe via Proper motions)
- Theory: How do the lowest mass dwarfs survive given the tidal field of a MW host.

**3. Quenching**

- LSST: Resolved CMDs to search for recent SF. At this mass scale dwarfs should be quenched.
- Theory: What fraction of satellites at this mass scale are expected to be quenched?

**4. DM Halos**

- LSST: Defining the spatial extent of dwarfs. But will still need spectroscopic follow up.
- Theory: Push predictions for the velocity distribution of the stars in such low mass galaxies.

**5. Hierarchical Evolution**

- LSST: Radial distribution of satellites - is there clustering? e.g. around the Magellanic Clouds.
- Theory: Studies of dwarf group infall and the resulting spatial distribution of teh dwarfs - pushing to low masses.

9.2. *Intermediate masses:* $10^5\ M_\odot < M_* < 10^8 M_\odot$, $10^9\ M_\odot < M_{halo} < 10^{10}\ M_\odot$

**1. Number and distribution of dwarfs**

- LSST: Number and distribution of dwarfs in the outskirts of the local group.
- Theory: Defining Splashback radii for Local Group analogs in cosmological simulations. Where do we expect the turn-around radius for satellite orbits to be?

**2. Tidal Effects**

- LSST: Detect stellar streams in the outer halo (i.e. apocenters of streams may help find radial streams.)
- LSST: Stream structure: width, density variations.
- Theory: Expected stream frequency at large radii given the merger history of the MW.

**3. Quenching**

- LSST: Can we find quenched dwarfs in the field at this mass scale? Or in proximity to other dwarfs?
- LSST: Variations in CGM properties reflected in the properties of the dwarfs e.g. SAGA survey (Bluer satellites than the MW).
- Theory: Quenched fraction as a function of environment, pushing to low mass hosts.

**4. DM Halos**

- LSST: Density profiles of dwarfs using Globular clusters.
- LSST: Stellar extents of dwarfs
- Theory: Push predictions of the velocity field/density profile of the stellar distribution in classical dwarfs.
- Theory: Any differences in stream structure given initial dark matter distribution?

**5. Hierarchical Evolution**

- LSST: Searching for such dwarfs as companions to higher mass dwarfs.

### 9.3. *Highest masses:* $10^8\ M_\odot < M_* < 5\times10^9\ M_\odot$, $5\times10^{10}\ M_\odot < M_{halo} < 3\times10^{11}\ M_\odot$ *(e.g. LMC, SMC)*

**1. Number and Distribution of Dwarfs**

- LSST: Complete number of dwarfs in this mass scale (SMC types) in the Local Volume/beyond.
- Theory: Create galaxy count expectations for similar volumes at this mass scale.

**2. Tidal Effects**

- LSST: Extents of stellar disks and perturbations in the outskirts and Cepheids / RR Lyrae ages .

- LSST: Existence of stellar streams in dwarf pairs/groups at this mass scale.

**3. Quenching**

- LSST: Quenched fraction in the field.
- Theory: Expected quench fraction of massive dwarfs in the field (LMC mass scale), where self-quenching may operate (core/cusp feedback solutions peak at this mass scale).

**4. DM Halos**

- LSST: Extended old stellar populations
- Theory: What is origin of extended old stellar populations (feedback, companions, angular momentum).

**5. Hierarchical Evolution**

- LSST & Theory: Does the major merger sequence proceed as in more massive galaxies at this mass scale?
- LSST & Theory: Luminosity function of satellites in LMC type hosts
- LSST & Theory: Evidence for stellar haloes around such massive dwarfs?

## 10. ONGOING AND FUTURE SURVEYS AND THEIR RELATIONSHIP TO LSST

Moderators: Robyn Sanderson, Josh Simon; Scribes: Dongwon Kim, Peter Behroozi

LSST Observing Strategy:

Cadence - full depth coverage on small area vs. rolling coverage?

Which areas a priority? LMC/SMC? RRLs?

Proper motions may help. Theoretical reasons to expect interesting dwarf populations at low latitudes (tidal forces, angular momentum).

Time vs. limiting magnitude plot - 1 year to get w/in 1 mag of 10 year depth.

Wide field preferred for some cases (e.g., weak lensing), but high airmass also a concern.

Might be ways to find more time to go to wider areas (greater efficiency, longer snap intervals).

LSST imaging to low latitudes

Down to what latitude can we find dwarfs? How much to push for low-b galactic searches? Confusion limits a concern. Also concerns w/ signal / noise for dwarf searches (mock tests).

Dongwon: LSST deep imaging would result in confusion at low latitudes. Handling this problem would require good PSF information. Finding dwarfs at such low latitudes would remain as a difficult task within LSST data.

Josh Simon - Mock dwarfs tests are required to see whether or not it is feasible to find dwarfs at low latitudes.

Sanderson - Finding dwarfs at low latitudes is important as they would provide valuable information about understanding tidal interaction.

Sanderson, Vivas - Going down at least to 10 deg is required not only for dwarf galaxy search but also for Milky Way science in general.

Follow-up strategies:

LSST mostly gives candidates

Medium-res spectroscopy: Sat LF, DM in dwarfs, subhalo MF

Proper motions also for: Mass of MW, accretion history of stellar halo

Tests for proper motions accessible with LSST. Removing foregrounds may be more successful than detecting proper motion of dwarfs.

Spectroscopic follow up

What is the community strategy for pursuing the massively multiplexed spectroscopic facility that will be needed for LSST follow-up?

Is there enough spectroscopic capacity to follow up all of the expected dwarfs?

J.Simon - NO!!!

3 yrs of time on 8m telescope for full follow-up of LSST candidates ! Either have to come up with clever ways to reduce this or start organizing now to build a facility. Broad agreement on the need for spectroscopic follow-up from other subfields. Private money needed? Retrofitting existing telescopes more feasible politically/financially?

Upcoming multi-objects spectroscopic surveys based on Hawaii (e.g. MSE) will cover the half of the coverage of LSST.

More international community-wide facilities are needed so that everybody can join.

Andrew - What if three ELTs split the task?

Josh Simon - GMT is the only one that provides sufficiently wide-field of view for dwarf galaxy science.

Future tools, databases, computing resources

What do observers need from theorists?

Bechtol - Is there a theoretical 3D model for MW halo stars proper motions that LSST will see?

Session summary:

Need for spectroscopic followup a major problem to solve.

Coverage area - the wider the better, at least to b=10? Synergy w/ other research areas?

Confusion / modeling / computation limit for lower latitudes.

## 11. UNCONFERENCE

Moderator: ————, Scribe: ————

Distance estimation

Surface brightness fluctuation as distance method for dwarfs; Annika searched literature, and hasnt been active in past decades

Group in Utah Valley did SBF Coma cluster distance, using 12 galaxies; Done in Virgo

Problem with dwarfs is that number of stars is very low; Usually done in massive galaxies where are in Poisson limit for bright giants

Similar to problem w/ TRGB distances (cant use if dont have the stars)

What's the alternative?

SBF may not get to much more distance than can do w/ TRGB

Jeff is skeptical - Partially resolved dwarfs will be the real challenge - But helps to have rough distance, doesnt need to be very precise

Are already using SBF by eye - SBF uses more of the stellar population, e.g. Draco has well-defined giant branch, even if TRGB is hard to see

Could maybe do a statistical method with stacking - What's density profile of fainter ones relative to bright neighbors?

Distance by association

BG subtraction and looking for overdensities

Group in Korea using wide field SN search imagers, looking for MV- -10 dwarfs in Local Volume

If moving into statistical regime, maybe dont need individual distances - Still better to have them of course - Should also think of what to do in different mass ranges - Can do simulations now before LSST survey!

Dont know what mass scale is if don't know distance

2-point statistics, 1 halo term

Dream of getting galaxy-galaxy weak lensing with very good photo-z's

What will it take to reach a "blind", "statistical" algorithm for dwarf galaxy populations?

Alex: Automated techniques can be used with simulations in ways that can't be done with current searches (which have humans in the loop). Is it an objective of the field to move towards machine-only searches? Or are we just trying to find all the dwarfs that we can?

Nicolas: numbers are such that think its get whatever possible - Lots of edge cases of contaminants - Up to a few thousand, can still do it with humans in loop

Heidi: two separate topics: can we have human-blind algorithm, and can we have statistically sound method? Think humans can still be involved?

Vasily: want to be able to find everything, but also want to find automated method

Nicolas M: Arent we already doing both? - But usually only keep the things you trust, and separate list of untrustworthy ones

Alex: Some searches have systematic artifacts with high significance, that are obviously not dwarfs. These transitiion to low-level contaminants where the true nature is unclear.

For cluster searches, what are biases? - 3-sigma sources, some will be real - Nobody follows the garbage - Need to keep pushing - How about stacking the garbage?

Also strong biases in how do spectroscopic followup - Only follow up best candidates - How do we include the additional systematic bias in what we decide to follow up?

LSST synergies with other instruments and surveys

Question for LSST: will there be cross-matches? A technical resource limitation? - Simon: there will be cross-matches for calibration purposes, e.g. *Gaia* for astrometry

Will LSST catalog include *Gaia* IDs? - No, not in DPDD. Could request it.

Whats saturation limit for LSST? 16-17.

*Gaia* goes to 20, spectra are uncertain at this point, and then low-resolution SEDs to full *Gaia* depth

If are going to have to do the cross-match, return the IDs!

Also want to make it easy for individuals to do cross-matches

At deeper level, are there discussions of joint processing of LSST with other surveys, e.g. *Euclid*. - Still preliminary. Driver is weak lensing

Big range in potential sophistication, from combining at catalog level, to simultaneous fitting at pixel level. For WL science case, strong interest at pixel level. Would require MOU to go beyond scope of DM processing.

Some data rights questions, political questions: Will user-generated cross-matches be able to be shared? Within Science Collabs, yes. Would live on Science Platform. Data rights issues to consider, don't want people exposing all of LSST catalog. Sci Collabs aren't required to make public their own internal data products.

## 12. DISCUSSION/FINAL THOUGHTS

Moderator:Dan Weisz; Scribe: Helio Perrotoni

The use of Power Spectrum may attract attention from other areas.

Most of the galaxies in the local group will not be detectable at any reasonable redshift. Local is the only way to see structures on small scales. The Ly-alpha forest might be used to detect structures on small scales (overdensities of order 10). Probing closer to the linear regime. There is completely different physics in Ly-alpha forest than in dwarf galaxies. There are dark matter effects that can be seen over long time scales. Strong lensing is pushing to $10^7$ solar mass range. We sometimes find dwarf galaxies because we are testing a prediction, and sometimes because we just find something serendipitously.

What can suppress power at small scales? There is a list on the slides.

Accretion of dwarf onto the MW,M31..;

Reionization:

Baryonic Physics/Gastrophysics:

Dark Matter physics;

Quenching;

Halo occupation/ stellar-halo mass relation;

Uncertain mass of host galaxy:

limit of galaxy formation

There are no galaxies fainter than M=-10 at low redshift? Where should the luminosity function be truncated.

There might be tidal dwarfs that don't have halos.

List of things that is implicit in the cooperation between theorists and observers to the understanding of the local scenario of formation and evolution. Documenting how one obtains a number for each of the quantities listed is important because theorists are becoming able to "observe" simulations and want to see the intermediate products from which the numbers are taken. Also the theorists need to provide projections for observers to use for comparison. Maybe we could discuss velocity dispersion instead of halo masses. Theorists should forecast in terms of observable quantities.

We need to have well-posed questions.

Technical challenges on slide. Is it important to distinguish between dwarf galaxies and clusters? Distance-dependent data quality will have to be considered when comparing observations and theory.

Observers need to be more pedantic about selection functions and methods, and share data more.

The imminent need to solve the problem of obtaining spectroscopic follow-up.

Space-based instruments are aging. There is an urgent need to figure out how we will follow up the LSST observations. Also, there is no model for funding LSST data analysis. The competition for NSF funding will be very competitive, and we will be competing with each other.

The NSF responds to proposals. We write white papers as umbrellas, and there is organization to avoid lots of collisions. The science working groups are working in that direction. NSF will review proposals that simulate LSST data, so it is time to start organizing these collaborations. It is unclear how panels will rank these proposals.

Since there is no proprietary period, it might be good to organize the data analysis so people are not doing the same things and stepping on each others toes. We would like to streamline the analysis so that space-based observations can be obtained before the satellites age out. It is difficult to get accurate photometry from the ground even with adaptive optics. HST might have more time available when JWST comes online, possibly. Near-field cosmology still has much useful work to do on HST.

Are there two regimes? The early LSST data will reach 25th magnitude quickly and many discoveries could be made in time to get space-based observations. Then there are discoveries that will need the full depth that will be achieved later.

The DOE is not interested in mapping dark matter, but only in understanding what it is. Indirect detection, direct detection and collider searches. They might want to do astrophysical probes instead of indirect detection. This is potentially another source of funding (currently DESC). There are DOE people interested in this type of science. It is difficult to get 100s of millions of dollars (like the large spectroscopic telescope). What is the well-posed dark matter question that we could pitch to the DOE? Looking for cutoffs is a probe of particle properties. $10^7$ halos might not have dwarf galaxies, but we could go after gaps in streams. The self-interacting dark matter effects in cores are blurred by baryons. Gaps could be made by GCs, disk, molecular clouds, etc. could play a role. We need to make sure we can make a clear measurement of dark matter to go after DOE funding. Dwarf galaxies are one aspect of what LSST can do for dark matter direct detection experiments (need information about local dark matter).

Halo masses of $10^7$ and $10^8$ can be characterized by lensing, so there are other groups that are probing dark matter at small scale. There is dwarf galaxy organization as well as LSST/Dark Matter to discuss similar issues. There are ties to large redshift galaxies and dark matter, etc. But we should have representatives at other conferences.

## 13. RECOMMENDATIONS TO LSST

Scribe: Steve ridgway

Throughout the workshop, the promised performance of LSST was a constant motivator and reference point. In several domains, it became apparent that the LSST survey could deliver even greater value to dwarf galaxy science if certain 2nd order adjustments were made in the observing plan (with respect to nominal survey parameters of typical, recent benchmark survey schedule simulations). In some cases these adjustments are similar or identical to survey changes proposed for other science. Here, we present a list of recommendations and summarize the motivation for each.

### 13.1. *Increased u-band Depth*

Improved sensitivity in *u*-band would aid significantly in reducing background galaxy contamination to mitigate confusion with the stellar constituents of diffuse dwarf galaxies. The improved sensitivity could be achieved with a longer integration time (e.g. 2× would be very valuable) while maintaining the planned number of visits in

$u$. Increased $u$ exposure time is already under consideration by the project for other reasons.

### 13.2. *Macroscopic dithering*

A critical step in pixel-based dwarf galaxy searches is the removal of spurious image content, such as secondary reflections, scattering and detector artifacts. Dithering is essential to support identification and mitigation of such effects. Dithering should be in both translation and rotation, and should generously explore the full field of view of the camera. Detector-scale dithering is widely assumed for the LSST survey. FOV-scale dithering is less discussed, but has similar promise, and deserves study.

### 13.3. *Coverage of the entire accessible sky*

The distribution of Milky Way dwarf galaxies across the sky is not uniform, and cannot yet be modeled with confidence. Increased sky coverage is an absolute positive value for dwarf galaxy research. It is not necessary for this extended coverage to include the full wide-fast-deep cadence. A lesser depth, of order 26.5, would provide most of the LSST advantage. It is important that the visits be timed to support proper motion measurements, for discrimination of foreground and stream member stars. It is also important to provide a sufficient time series to confidently identify RR Lyr stars, for their diagnostic power. Thus a limited coverage over an extended sky area should be planned with some care to provide appropriate cadences. We note that many other science areas also would benefit directly from increased total sky coverage, even with reduced cadence.

- Coverage should be extended to the celestial pole. The Magellanic Clouds are known to participate in a complex and very extended association of dwarf galaxies - extending sky coverage to the pole is essential to fully characterize this distribution.

- Coverage should be extended closer to the Galactic plane. Due to the known inhomogeneous distribution of dwarfs, it is not possible to evaluate the completeness of dwarf counts without better coverage near the plane. Tidal effects and formation histories will also impact the near-plane population. LSST coverage should extend down to a Galactic latitude of at least $|b| = 10$ degrees. Modeling could provide a more secure rationale for filter selection and latitude limit (possibly longitude dependent). Precursor studies (i.e., DECam Galactic bulge and plane surveys) will help inform the ability of current search techniques to operate in these crowded conditions.

- Coverage should be extended further north. The study of Milky Way dwarf galaxies is an all-sky problem. Improving the overlap of the LSST survey with northern surveys will significantly improved vital completeness corrections in the merging of heterogeneous datasets.

### 13.4. *Source-subtraction is an essential processing stage*

In pixel-based searches for dwarf galaxies, all known sources are removed from an image field (mostly stars and distant galaxies - i.e. point sources and near-point sources), in order to reveal low-level, extended sources. These extended sources typically consist of stars that are individually near to or below the detection limit.

- The best performance will be achieved by correcting for scattered light and performing source-subtraction on individual images. LSST does not currently plan to provide this as a survey product. We note that source-subtracted single images will be valuable, even if only offered for a subset of the images, e.g. for the best-seeing images. If this service is not provided by LSST, then it is important to support pixel access for subsequent reprocessing.

- A stacked subtracted image combines the power of image cleaning and the suppression of artifacts by averaging. If this data product is not offered by LSST, then it will be essential to support data archive access for secondary processing in the community.

### 13.5. *Request to LSST for Special Survey Simulations*

The suggested changes to the LSST baseline survey can be compactly summarized with a short list of requested schedule simulations, incorporating adjustments. The changes could be implemented in various combinations and all together.

$2\times$ $u$-band exposure time

Increased survey sky coverage: 1) with WFD candence, 2) with $0.1\times$WFD cadence (tuned to deliver proper motions and RR Lyr classifications)

Extension to south celestial pole

Extension to Galactic latitude $b = \pm 10°$

Extension to $+20°$ declination

## 14. CONCLUSION

LSST is anticipated to produce an incredibly powerful dataset for mapping the outer halo of the Milky Way and extending our census of dwarf galaxies throughout the Local Volume. Over two days of intensive workshop discussion, a few key themes emerged.

- Until recently, studies of the least luminous galaxies have been largely limited to the immediate vicinity of the Milky Way. Discovery and follow-up papers have typically featured single or a handful of stellar systems at a time, and we still often refer to individual dwarfs by name. However, there is growing theoretical interest and observational capability to study dwarf galaxies as a *statistical population* extending beyond the Milky Way. Workshop discussion topics included detailed studies of the detection efficiency for Milky Way satellite galaxies, satellite populations of galaxies out to several Mpc, and automated detection of dwarfs out to tens of Mpc by their diffuse light. In the LSST era, we anticipate comparing statistical observables to theoretical predictions, such as correlation functions of individually resolved Milky Way halo stars, angular clustering statistics of Local Volume dwarfs, and structure along stellar streams. LSST will be the first unbiased (statistically representative??) survey with sensitivity to dwarfs in all environments, ranging from galaxy clusters to isolated field systems.

- The term "dwarf galaxy" encompasses several orders of magnitude in both stellar mass and halo mass, ranging from the extreme lower threshold of galaxy formation, to analogs of the Magellanic Clouds. Different physical processes operate over this large range of scales, such that the ensemble of dwarfs around the Milky Way and beyond will enable studies of reionization, chemical enrichment by the first stars, and the relative influence of local environment / internal feedback on galaxy formation.

- Dwarf galaxies continue to be *competitive probes of small scale structure* predicted in the Cold Dark Matter paradigm. Ultra-faint Milky Way satellites inhabit the smallest collapsed dark matter halos that can be currently studied in detail, and thus offer a promising avenue to constrain dark matter self-interactions.

- The anticipated richness of LSST data products, including precision 6-band photometry, lightcurves with hundreds of individual flux measurements, milliarcsecond proper motions, and sensitivity to low-surface brightness features, motivates development of novel data analysis methods.

We also identified several challenges to be confronted in the next decade.

- As with current Milky Way satellite searches, the detection thresholds to discover new stellar systems in LSST data might be set by *systematic uncertainties*. For example, LSST imaging will reach depths at which the number of unresolved background galaxies vastly exceeds the number of foreground stars. We recommend that multiple strategies to approach star-galaxy confusion using morphological, color, and temporal information be investigated. Also, LSST will image the Galactic plane where crowding of disk stars and high interstellar dust extinction have severely limited our search sensitivity.

- What can we learn from Local Volume dwarfs that are only partially resolved into individual stars, or *detected solely as diffuse light*? In this case, distance estimation directly from the LSST data is probably not possible, and therefore the luminosity, size, and other key physical parameters have large degeneracies. The number of diffuse-light dwarfs detected by LSST is likely to greatly exceed the available space-based imaging capabilities. This is an example of where forward modeling may be needed to compare incomplete observational information to theory.

- A particularly thorny problem is *associating visible stellar populations to dark matter halos* predicted by theory. Kinematic measurements of member stars probe only the innermost regions of the halo, and determining membership for individual stars is problematic. In addition, some fraction of satellites may not be in dynamic equilibrium due to tidal effects from larger neighbor galaxies. Orbital histories derived from systemic proper motions may help to identify the most dynamically stable systems.

- Workshop participants reiterated a pressing need for *spectroscopic follow-up capabilities* in the LSST era to maximize the scientific output from newly discovered dwarfs. The envisioned instrument is a wide-field multi-object spectrograph on a 8-m class or larger telescope with a spectral resolution X to measure the few km/s velocity dispersions typical of ultra-faint galaxies. (Section 10)

## ACKNOWLEDGEMENTS

This workshop would not have been possible without the financial assistance of the LSST Corporation, under their *LSSTC Enabling Science Grant Program*. This resource was applied primarily to travel expenses, and allowed us to bring together a significant representation of the LSST dwarf galaxy community.

NOAO's Jane Price provided timely and professional support, especially in local arrangements and in organizing catering.

## APPENDIX

## A. NAMING CONVENTIONS FOR LOCAL VOLUME STELLAR SYSTEMS

Moderator and Scribe: Keith Bechtol

As a warm-up exercise before the workshop, we created an anonymous survey to collect thoughts from workshop participants on naming conventions for stellar systems in the Local Volume. Below is a copy of the message to workshop participants announcing the survey:

> We have a discussion topic for all workshop participants that can be viewed as an informal warm-up for the workshop  naming conventions for newly discovered low-luminosity and/or low-surface-brightness stellar systems within the Local Volume.
>
> We anticipate that LSST data will enable the discovery of numerous such stellar systems, perhaps dozens at a time. Based on current trends, the discovery rate in imaging data is likely to outpace our ability to acquire spectroscopic follow-up observations, and therefore, the physical nature (e.g., Galaxy, Defined, Willman & Strader 2012, https://arxiv.org/abs/1203.2608) of many newly discovered systems is likely to be uncertain for extended periods of time. Furthermore, as our search sensitivity extends to larger heliocentric distances, physical associations between newly discovered systems (as satellites and/or members of various galaxy groups) is likely to be ambiguous in some cases. A further challenge for some naming conventions is indexing, since many candidates may be found more or less simultaneously, are later reclassified, and/or found to be spurious.
>
> Unified naming conventions could be useful, both to facilitate communication among Local Volume researchers, and for clarity of presentation to the broader astrophysics community, especially considering the many connected research areas such as galaxy formation, reionization, chemical evolution, dark matter, etc. In recent years, several newly found objects have been given multiple different names by different groups, sometimes hinting at different classifications when compared to traditional naming conventions. To what degree is some naming confusion tolerable and/or inevitable?
>
> A few examples:
>
> (1) The IAU convention (e.g., SDSS J1049+5103, http://adsabs.harvard.edu/abs/2005AJ....129.2692W) has the advantages of being relatively neutral on physical classification and association, but is cumbersome for everyday communication and not easily memorable.
>
> https://www.iau.org/public/themes/naming/#nebulae

One variation is MADCASH J074238+652501-dw (https://arxiv.org/abs/1608.02591), which gives an indication for the physical nature of the object.

(2) Local Group dwarf galaxies have often been named after their resident constellations, indexed with roman numerals. This indexing convention goes back to at least Hodge (1962, http://adsabs.harvard.edu/abs/1962AJ.....67..125H) for Leo II

Meanwhile, globular clusters have commonly been named after individuals or surveys (typically indexed by arabic numerals), though in some cases, the physical nature of the objects has been uncertain.

(3) More recently, low-luminosity stellar systems (both dwarfs and globular clusters) have sometimes been given constellation names indexed with arabic numerals (e.g., Crater 2, https://arxiv.org/abs/1601.07178). This approach would avoid names that look like Super Bowl editions, e.g., Andromeda XXVIII, and is more agnostic on classification.

(4) In some cases, Local Volume dwarfs have been given names that suggest a physical association with a central galaxy or group, and indicate the instrumentation used in the discovery (e.g., Scl-MM-Dw1, http://adsabs.harvard.edu/abs/2014ApJ...793L...7S)

To collect responses from the group, we have created a google form feel free to be as terse or verbose as you like! Well plan to circulate the collected responses a few days before the workshop.

The survey consisted the three questions, listed below. We also include a few representative individual responses to illustrate the range of viewpoints expressed in the survey.

1. How important is it to have unified naming conventions for newly found Local Volume stellar systems?

| Imporantance | Votes |
|---|---|
| 1 (Not Imporant) | 2 |
| 2 | 0 |
| 3 | 8 |
| 4 | 8 |
| 5 (Very Imporant) | 2 |

2. Your explanation for why unified naming conventions are more or less important:

*It is important to talk in the same terms. Science won't change, but discussion is much easier*

---

*I think that there is a fundamental problem that the nature of systems are unknown when they are discovered and published. This means that it is impossible to be 100% accurate when naming new objects, and that if a consistent naming convention is desired, then the names of objects will need to be changed once their physical nature is determined (sometime years later). I think that the renaming of objects causes greater confusion than an inconsistent naming convention.*

---

*Many more ambiguous systems are being discovered and we need a naming convention that is neutral as to the astrophysical status of the system.*

---

*Thus far, I don't think it's vital (though I do find the Roman numeral naming of Andromeda dwarfs convenient and simple). However, in the future, when there will likely be thousands of Local Volume dwarfs/clusters discovered, the chaos will become unbearable. Some clarity about conventions could avoid a lot of possible confusion in the field.*

---

*It's already a mess, and it's not clear that adopting something uniform going forward fixes the mess. It is also unclear that those who discover new systems will adhere to a convention. This isn't to say we can't try for a unified naming system, only that it's of moderate importance.*

---

*Why do we need a unified naming convention? Local Volume stellar systems have been named inhomogeneously for 200+ years and we've done fine. For example, Milky Way globular clusters are named by constellation, catalogue, survey, facility, and/or discoverer(s). Although the naming convention for dwarfs is more unified (most recently, typically by constellation) it is still far from homogeneous – think LMC, SMC, NGC 205, M32, Willman 1, Segue xx, WLM, etc. Implementing a unified naming convention is also not trivial to enforce robustly: do we have one convention for dwarfs and one for globular clusters? (this depends on what's a dwarf and what's a cluster, already impossible in some cases). Where is the "edge" of the Local Volume? (i.e., where does the convention stop?). What happens when, in this competitive field, people publish discoveries simultaneously? (as has happened on several occasions already). Arguably the best option for uniqueness is to name by position and survey – e.g.,* *LSST052334-694522 – but this just ends up assigning names that (from experience) absolutely nobody will use!*

---

*While on the surface a unified naming convention might seem pedantic, I think it is important for reducing confusion, avoiding potential name collision, and allowing for names to be used fluidly in discussions. Names should ideally communicate rough location in the sky, type of system, and be memorable enough to use in conversation.*

---

*I think we'll soon be moving beyond the postage stamp era to the statistical era.*

3. Do you have a preference among naming conventions that have been used thus far? Are there alternative naming conventions that would be preferable?

*Constellation naming makes sense, but it can be problematic when the nature of the object is not clear. Arabic numerals, although they might break how names were originally given, are desirable due to ease of readability. This will be more important in the LSST era, where several tens of satellites are expected, and Roman numerals become quickly cumbersome, as Andromeda has shown us.*

---

*Position-based names are widely used in other subfields, for example, Galactic X-ray binaries, and they work fine. My suggestion would be for every object to have a position-based name that starts with the survey name, consistent with IAU guidelines. I also think there should be a Local Group catalog of stellar systems where new objects are added in sequential order of discovery. Once the classification of a new object is reasonably clear (in terms of its distance and whether it's a dwarf), I'm happy for bona fide LG dwarfs to be given constellation names as is presently done. Again, taking a cue from Galactic variables, new transients (e.g., novae or X-ray binaries) are given an initial position-based name, and then, typically at the end of the year, they are given a permanent name that uses the constellation they are in, which is preferentially used in the future. If, as is likely to be the case for some future objects, the ID is very uncertain for a period of time, the initial position-based and/or LG catalog names could be used until enough data is gathered to be reasonably certain of the ID, which might be indefinitely.*

---

*I agree that the IAU convention is cumbersome. I also do not understand any particular reason/benefit for naming systems based on proximity to a (unrelated) constellation. Regardless of the system, arabic numerals are preferable. Likely, ambiguity* *(at least for non-trivial time after discovery) between dwarf galaxies and globulars etc only will get worse in LSST era, so probably better to use type-agnostic names.*

---

*Constellation + number is fine. I prefer a system that provides at least some information on location rather than say a scheme that uses a survey (i.e. LSST 32).*

---

*Every 'candidate' should get an unmemorable phone number. Those that are confirmed galaxies (or clusters) can then receive a more memorable additional name in line with historical conventions.*

---

*Constellation + Roman numeral has historical precedence for galaxies, but constellation + Arabic numeral I think makes more sense as newly discovered systems become large in number. Neither convention is perfect, however.*

---

*No strong preference. The IAU-like convention is the most informative, because from the name alone you already know where to look on the sky. But these names are unwieldy, so it's not ideal. I lean slightly toward Roman numerals in the Roman vs. Arabic debate, but not for any particular/practical reason.*

---

*I prefer something like the constellation labeling, which is short and memorable, contains a coarser version of the same information in the "phone numbers" generated by the IAU convention, and can be made relatively free of interpretation about what an object is. Discoverers (surveys or individuals) can be credited in citations rather than in object names. Perhaps shifting everything to Arabic numerals as opposed to Roman would allow us to be more agnostic about whether something is a galaxy or globular cluster or something else—I anticipate that this will pretty much require follow-up for every LG stellar system that LSST discovers and it's annoying not to know what to call something until someone gets time to do deep spectroscopy. What about naming conventions for stellar streams? That's just a total Wild West right now. I think they should follow whatever is laid out for gravitationally bound objects - after all they all used to be bound systems, and the few cases where we can see a progenitor, the stream is named after that (Sgr, Pal 5). And I wager we find at least a few things in LSST where it won't be clear immediately whether it's bound or not.*

During the workshop itself, we summarized the findings of the anonymous pre-workshop survey, and then opened the floor for discussion. The collection of survey responses evidence a wide range of opinions, and a similarly broad set of arguments were raised during the workshop discussion. Although the majority of workshop participants seem to prefer some form of unified namining convention, there was no consensus on a specific implementation. The arguments made by individual participants also give insight on ways that our field of research is changing, and demonstrate a general sense of optimism for the discovery potential of LSST. As far as problems go, a naming convention challenge is perhaps a good problem to have.

## B. SCIENCE ORGANIZING COMMITTEE

Knut Olsen (NOAO, Chair)

Stephen Ridgway (NOAO, co-Chair)

Keith Bechtol (LSST)

Alex Drlica-Wagner (Fermilab)

Marla Geha (Yale)

Alan McConnachie (DAO)

David Sand (U. Arizona/Steward Obs)

Jay Strader (Michigan State)

Kathy Vivas (CTIO)

Dennis Zaritsky (U. Arizona/Steward Obs)

## REFERENCES