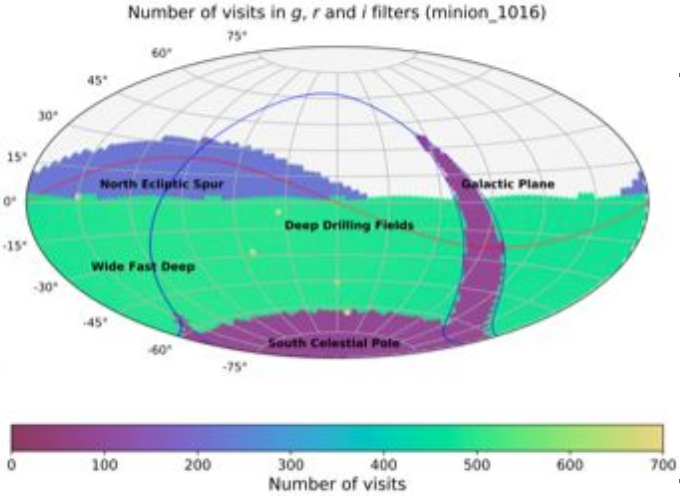
Searching for Dwarf Companions of the Milky Way and Beyond in the LSST Era

Workshop Slides

Session 0: Welcome

LSST is approaching quickly!



Data Production Milestone	Start Date
First on-sky and calibration images with ComCam	May 2020
Sustained observing with ComCam	August 2020
First on-sky and calibration data from Camera+Telescope	February 2021
Sustained scheduler driven observing with Camera+Telescope	April 2021
Start Science Verification mini-Surveys	June 2021

Workshop Goals I.

- Prepare to use LSST for dwarf galaxy detection and science
  - What questions do we want to address with LSST?
  - What techniques will we wish to apply?
  - What demands might we place on the observing strategy, data management system, and Science Platform for the science to succeed?
  - What resources beyond LSST will we want to bring to bear?

LSST Links

https://www.lsst.org/scientists/keynumbers

https://github.com/LSSTScienceCollaborations/ObservingStrategy

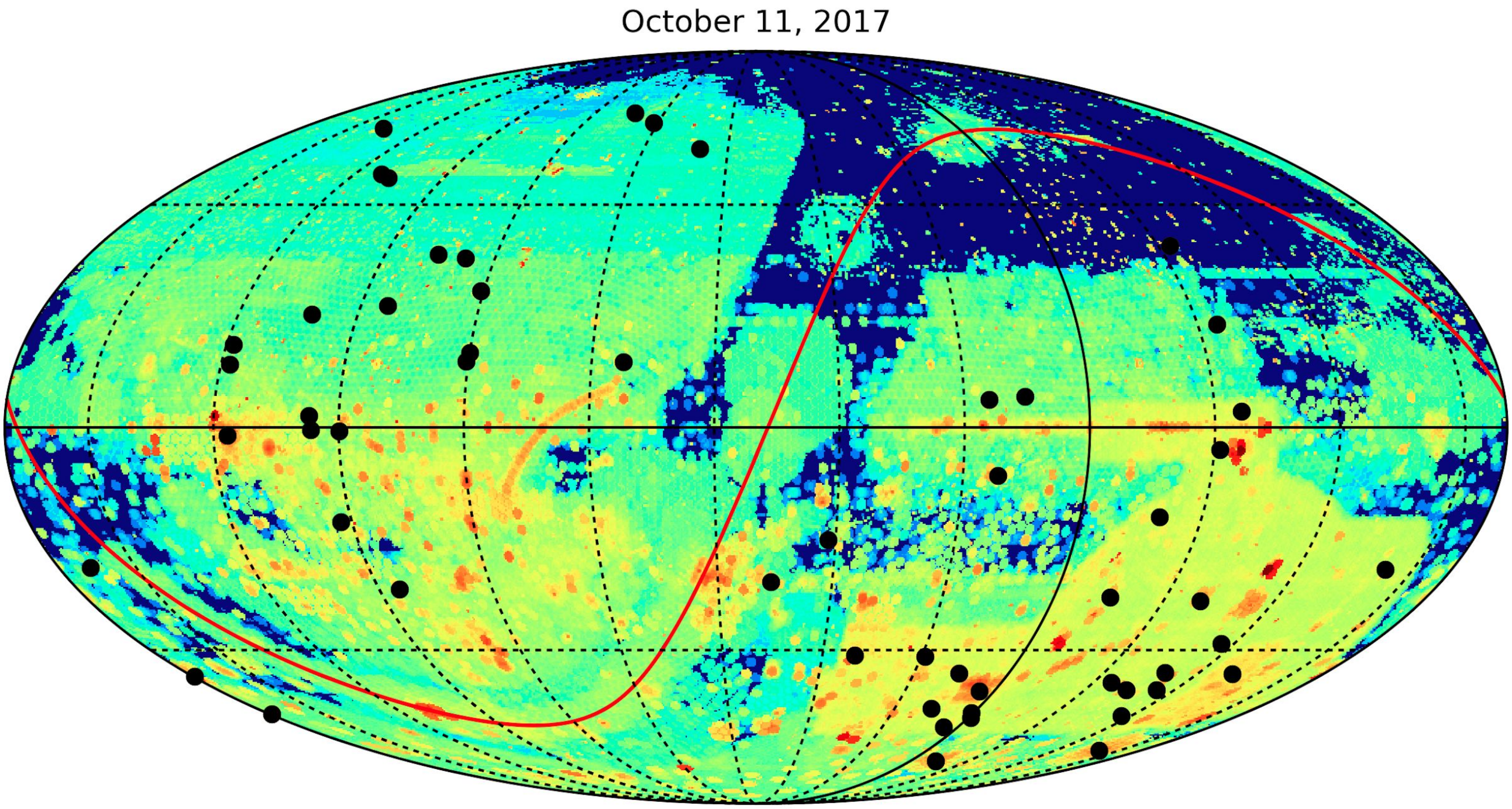
http://ls.st/dpdd

https://milkyway.science.lsst.org

Workshop Goals II.

- Can we extend the analysis of our existing data to get a head start on LSST dwarf galaxy science?
  - Many valuable existing datasets
  - New platforms being built to exploit them (e.g. NOAO Data Lab)

On-sky exposures with DECam and Mosaic imagers



Workshop Format

- Lots of discussion!
- Moderators and Scribes
  - notes go here: https://goo.gl/gFKVtT
- Two Unconference sessions
  - Submit ideas here! https://goo.gl/fusw3W

We value shared responsibility, honesty, and respect in our discussion. From LSST DSFP Principles of Engagement:

- Raise all voices
- No feigning surprise
- No “well-actually’s”
- No “-isms”

Local Volume Stellar Systems Naming Conventions

Collecting responses here:

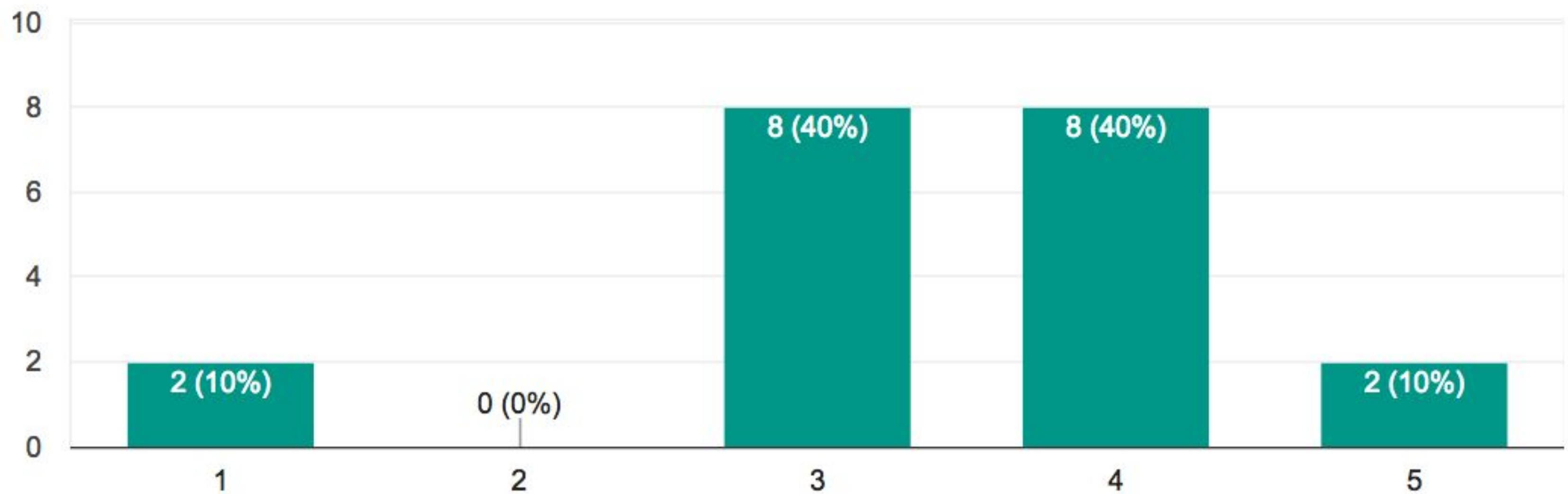
https://docs.google.com/forms/d/e/1FAIpQLSdnWNdrQLRDeOlfEQzloVfbSFp4KzT5Imet5snWr9Mq5-mdWQ/viewform?usp=sf_link

Local Volume Stellar Systems Naming Conventions

Collected (anonymous) responses:
https://docs.google.com/forms/d/1FOTUc54miv7hZEv-SmgFwe77At0Jmi2IThqekYkYt9k/edit#responses

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

20 responses

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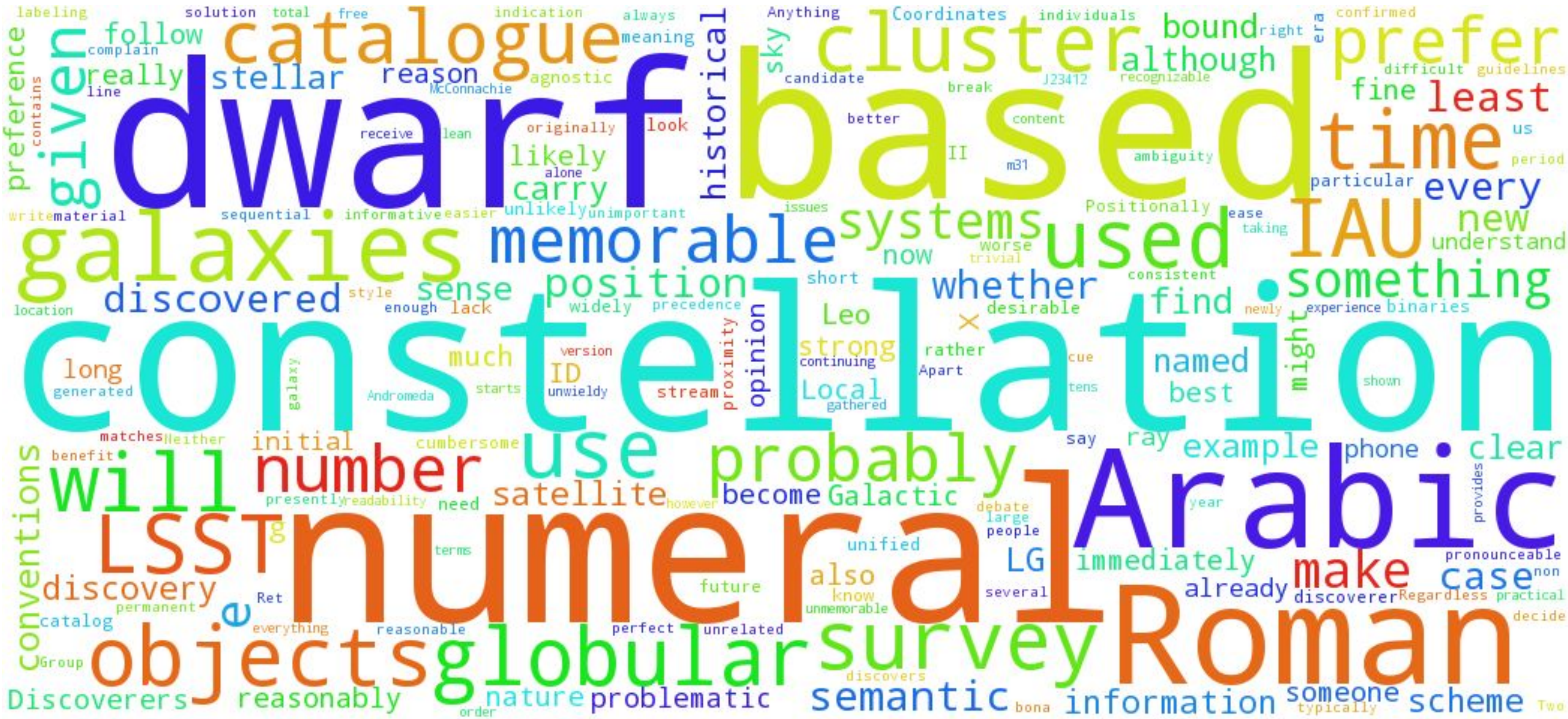
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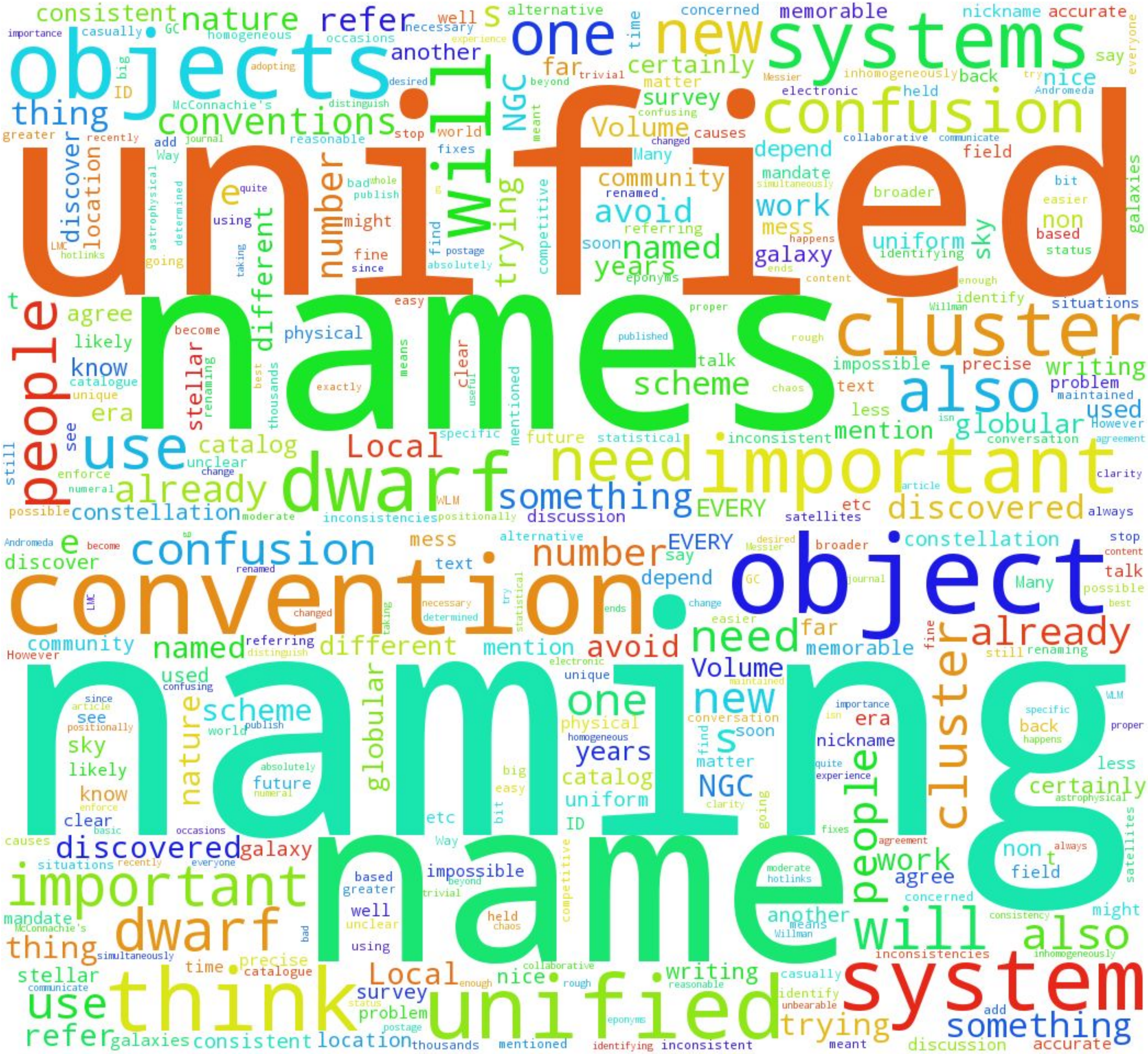
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Workshop output

- Workshop slides and notes
  - To upload files for sharing, we have a shared Google Drive folder: https://drive.google.com/open?id=0BwtoyOxTpGyhcGZldWdLaVhfaGc
- A report to go on arXiv
  - Link to Overleaf document: https://www.overleaf.com/11590236vqzpbqxwwsjp

Logistics

- All sessions in Main Conference Room (MCR)
- Please sign in!
- Lunches served in MCR, but can eat on patio
- Your keycards give you access to most of the doors in the building. Please remember to return them to Maria or drop in the box in reception!
- Dinner ("unbanquet") sign-up sheet for tonight at 7 PM https://goo.gl/4odLhZ
- Remember to fill out the reimbursement forms and return to Jane Price (jprice@noao.edu)

Session 1: Why will dwarf galaxies be important in the LSST era?

What will be the big theoretical questions around dwarfs in the LSST era?

Session Goal: *What scientific questions should we be asking in the next decade?*

We will come back to individual topics throughout the remainder of the workshop… the goal in this session is to **identify the science drivers** that motivate technical development in preparation for LSST (and other near-future projects)

Dwarf galaxies: revisiting basic questions

How many ways are there to form dwarf galaxies? Different dwarfs in different larger-scale environments e.g. groups, clusters, field...

What distinguishes dwarf galaxy/star cluster? Dark matter content?

Dwarf galaxies as “cosmological” probes

Beginning to see **hierarchy of structure at the scale of dwarfs**. Does this provide a new perspective and/or shape our view on the “missing satellites problem”? Any solution would need to be viable at multiple scales, or invoke multiple mechanisms operating at different scales

New ideas to constrain the **nature of dark matter** using dwarfs: indirect detection, central densities, demographics of the population, tracers of the Milky Way (host galaxy) potential, MACHO constraints

How do studies of dwarf galaxies compare to other astrophysical probes of dark matter — will dwarf galaxies continue to be exciting / **competitive** in the 2020s from a dark matter substructure perspective?

If we do live in a “vanilla” CDM Universe, what will we continue to learn about **galaxy formation physics and epoch of reionization** from dwarfs found in the next decade?

From a theory perspective, will we need **spectroscopy** for all the dwarfs that we find with LSST? Which targets are most interesting?

How do the dwarfs that exist today relate to disrupted satellites now seen as stellar streams and velocity / metallicity **structure of the outer halo** that will also be measured with LSST, Gaia, WFIRST, spectroscopy surveys, etc.

What are the current and fundamental **limits in theoretical modeling**, e.g., hydro sims? Are there physical inputs (e.g., sub-grid physics) that still need significant development?

How large of an observed volume is needed to be “statistically representative” in a cosmological sense? Is there a Local Volume analog of **cosmic variance**?

Dwarf galaxies as probes of gastrophysics and feedback

Stellar feedback to erase cusps leaves signatures in the stars left behind.

Deep CMDs as function of radius to constrain SFH

Massive star IMF constrained through spectroscopy - elemental abundances in low-mass stars that formed from gas pre-enriched by the SNe/massive stars

Chemical elemental abundance distribution constrains chemical evolution

Low-mass IMF constrained by star-counts

LSST - proper motions to refine membership? [more of a technical question?]

Maps of star counts to limit black hole

Star clusters of dwarfs - constrain mode of star formation at early times plus dynamics/dynamical friction

Session 2: Recent dwarf galaxy searches

Session 2

Goals of this Session

Guest Speakers: **Alex Drlica-Wagner**

1. Review of recent dwarf galaxy searches – successes and challenges.
2. What progress will be made by start of LSST?
3. What will be the observational obstacles in the LSST era?

Session 2

Overview of Search Techniques

Guest Speakers: **Alex Drlica-Wagner**

- If you see your name, consider yourself on the hook!
- Please feel free to add your name, figures, or slides!
- **WARNING:** I will keep time mercilessly!

- Search Techniques and Current Status
  - Catalog-based searches:
    - SDSS: **Vasily B., Beth W.**
    - Pan-STARRS: **Nicolas M.**
    - DES: **Keith B., Sergey K.**
    - VST ATLAS: **Gabriel T.**
    - HSC: **Masashi C., Alex DW**
    - Other Surveys: **Dongwon K., Jeff C., Nicolas M.**
  - Variable star searches:
    - DES: **Kathy V., Beth W.(?)**
  - Image-based searches:
    - **David S., Jeff C., D. Zaritsky, Annika P. (?), C. Mihos (?)**
- Progress before LSST
  - **Alex DW, Everyone?** (Victims have not been chosen yet…)
- Future Challenges for LSST
  - **Keith B., Everyone?** (Victims have not been chosen yet…)

SDSS Searches

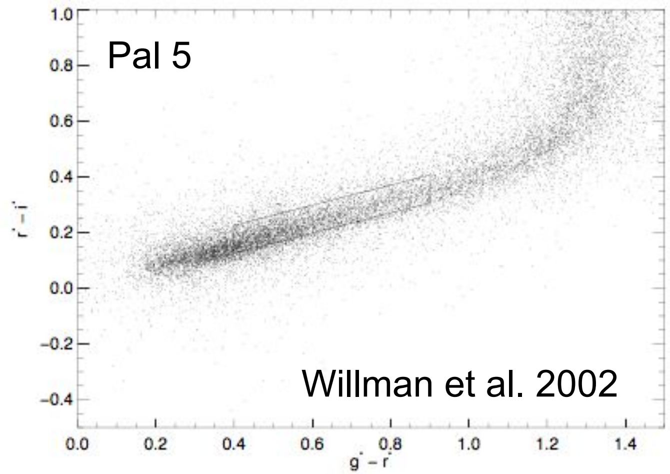
Guest Speakers: **Vasily Belokurov, Beth Willman**

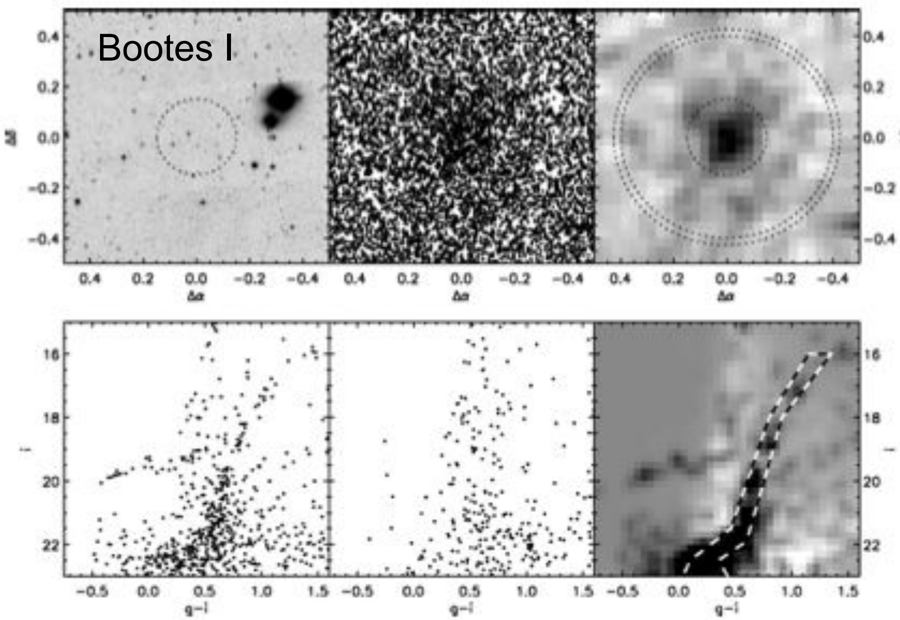
Techniques:

- **RGB color selection (g-r vs. r-i) with spatial convolution (a la Willman et al. 2002).**
- **Blue color cuts (g-r < 0.4) followed by spatial windowing (a la Belokurov et al. 2006).**
- **Isochrone based selections (a la Walsh et al. 2009)**

Questions:

- **What was the biggest change from DR2 to DR5 (just area)?**
- **Is there anything left to find in SDSS?**
- **If we were to reconstruct SDSS, what would make it a better dwarf-finding machine?**





Belokurov et al. 2006

Session 2

SDSS Searches

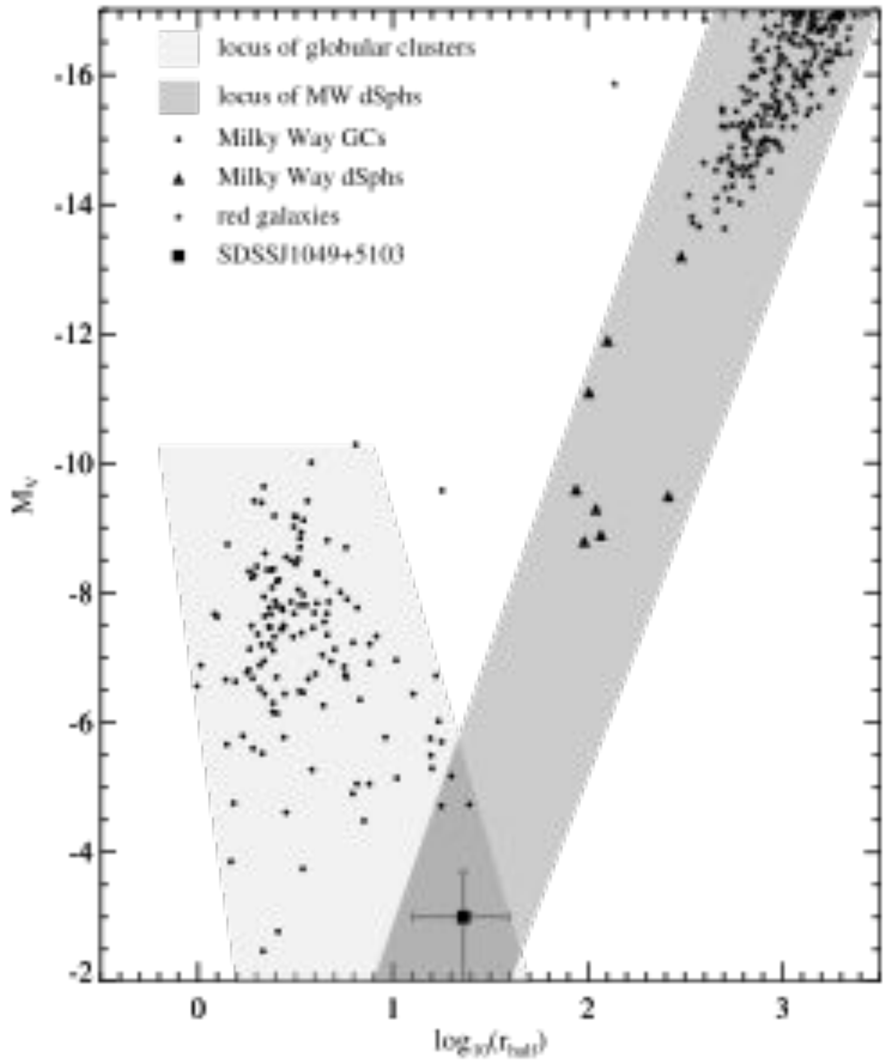
Guest Speakers: **Vasily Belokurov, Beth Willman**

The now (in)famous size-luminosity plot for separating dwarf galaxies from globular clusters (Willman et al. 2005, Belokurov et al. 2007).

Even in the SDSS era dwarfs and globular clusters were not uniquely separable (and matters have just gotten worse).

How useful is this plot going to be in the LSST era?

Willman et al. 2005

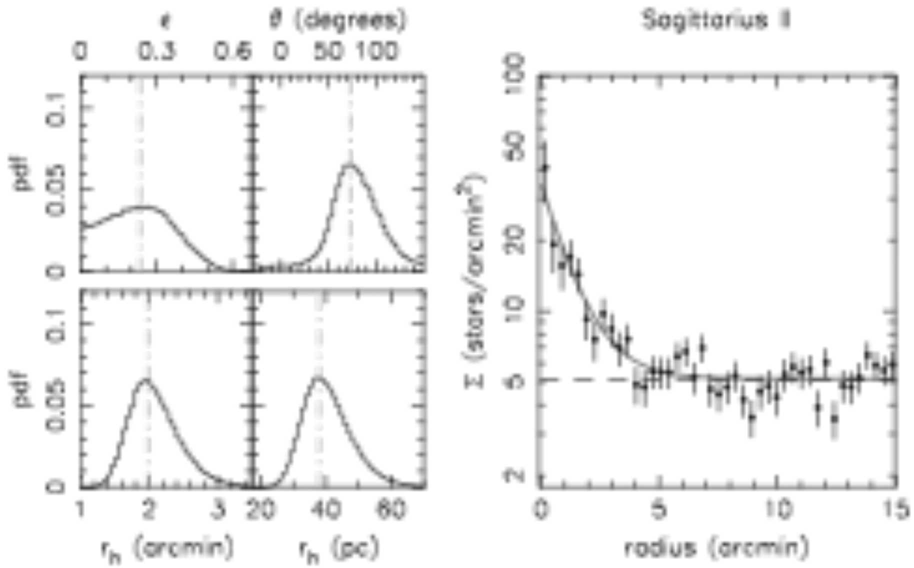


Pan-STARRS1 Searches

Guest Speakers: **Nicolas Martin (Ben Laevens)**

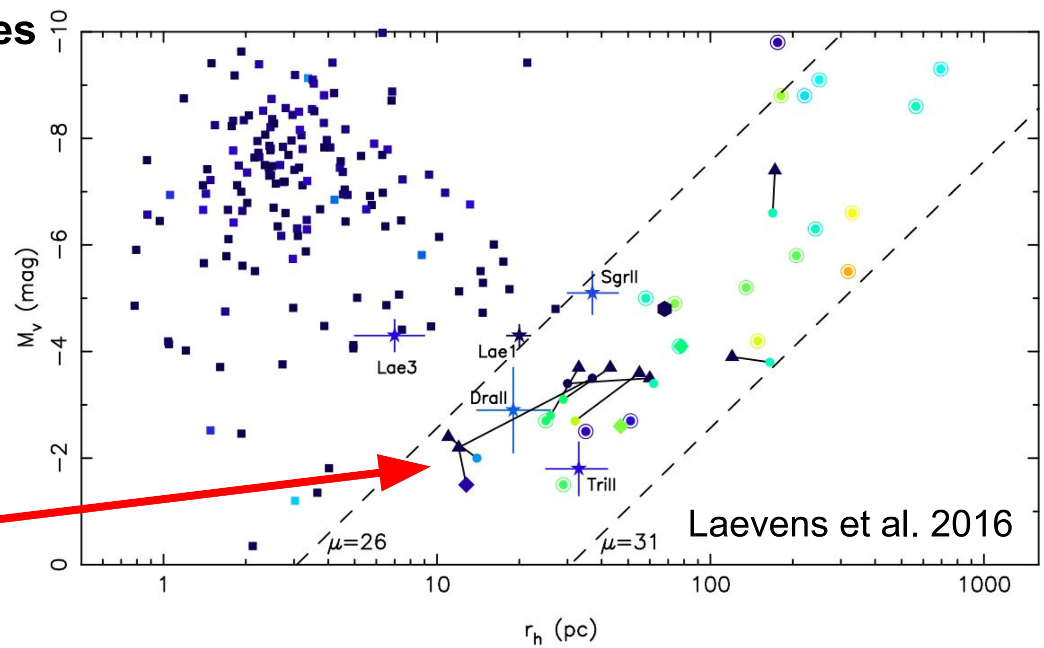
Techniques:

- **Build isochrone mask in r-i vs i and convolve with Gaussian kernels (signal and background)**
- **MCMC parameter fitting has become the standard way to measure dwarf properties.**



Questions:

- **How well do Pan-STARRS searches recover SDSS satellites?**
- **How well do these techniques perform near the Galactic plane?**
- **Is there anything left to find in Pan-STARRS?**



Additional Questions...

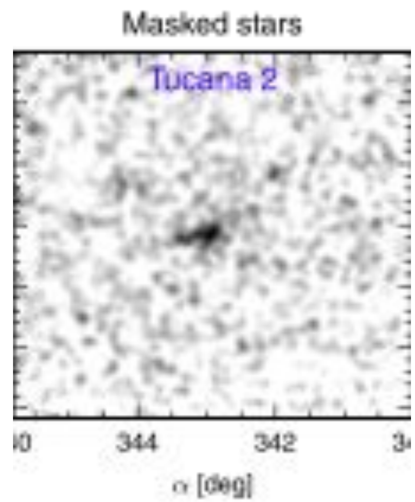
- **How well are different measurements techniques cross-calibrated?**
- **Is this important?**

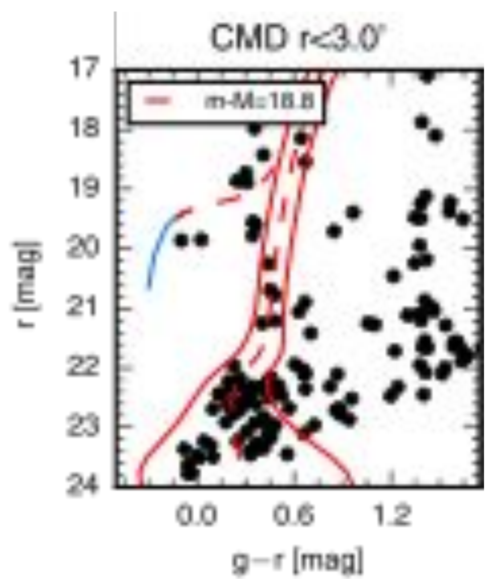
Session 2

DES Searches

Guest Speakers: **Keith Bechtol**

Koposov et al. 2015



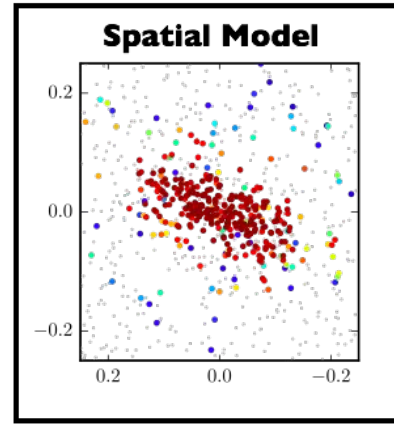


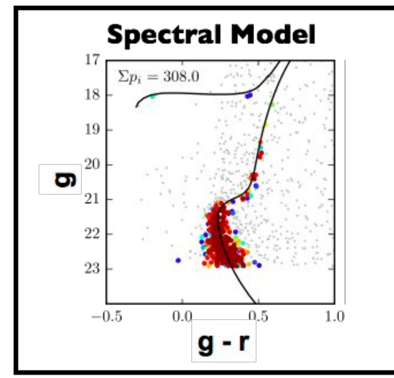
Techniques:

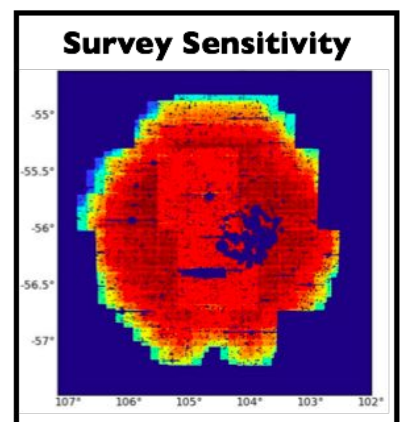
- **Isochrone mask using g-r vs g; spatial convolution by two Gaussians**
- **Maximum-likelihood grid search combining isochrone model with spatial kernel**

Questions:

- **DES goes deeper than SDSS or Pan-STARRS; has this presented a problem yet?**
- **How does the precision cosmology emphasis of DES help/hurt dwarf galaxy searches?**
- **Is there anything left to find in DES?**



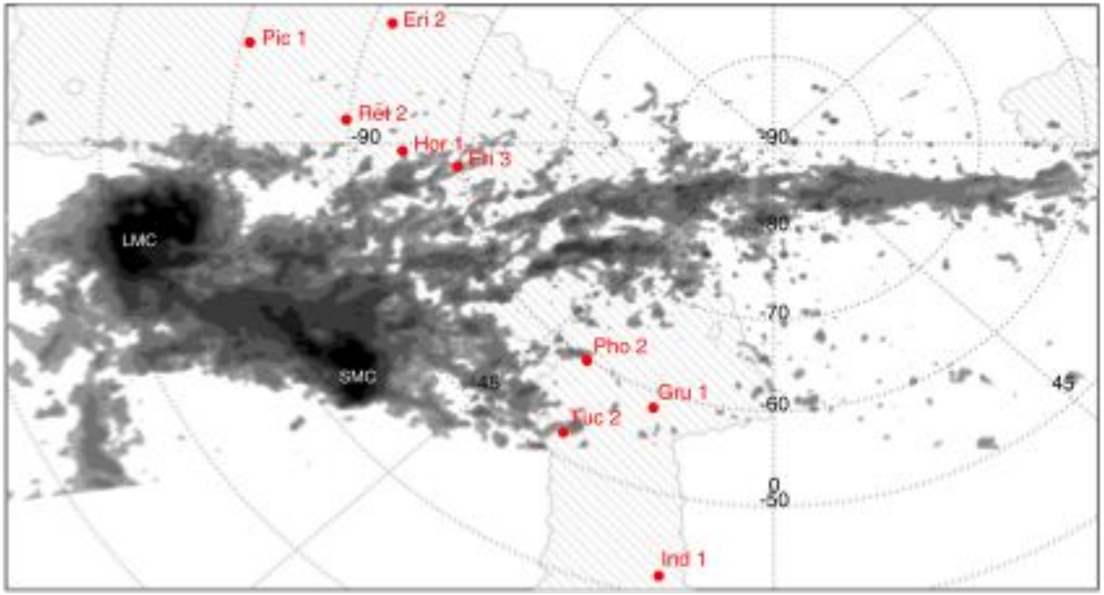


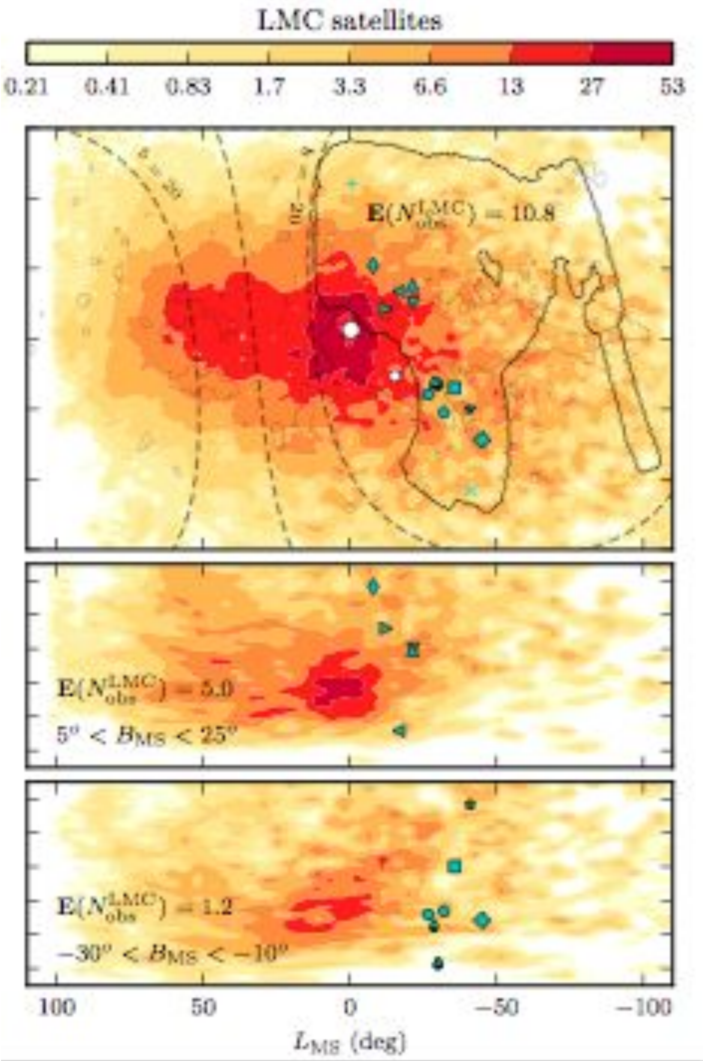


Session 2

DES Searches

Guest Speakers: **Sergey Koposov**





Questions

- **How much do we believe the Magellanic bias for the DES satellites?**
- **How much does a Magellanic origin of the DES satellites influence interpretations from the previous session?**

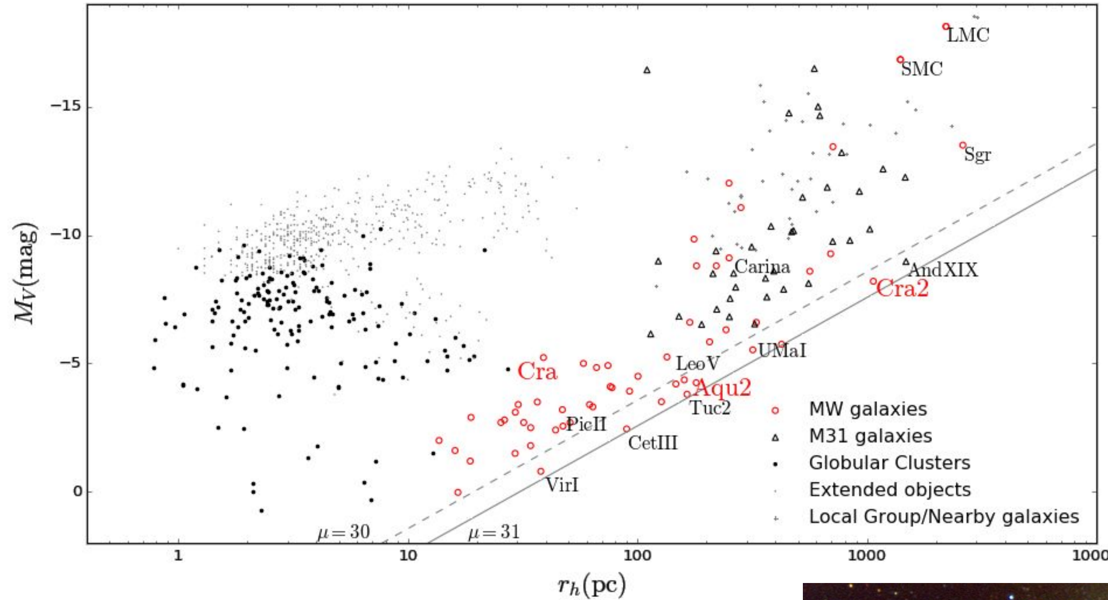
Session 2

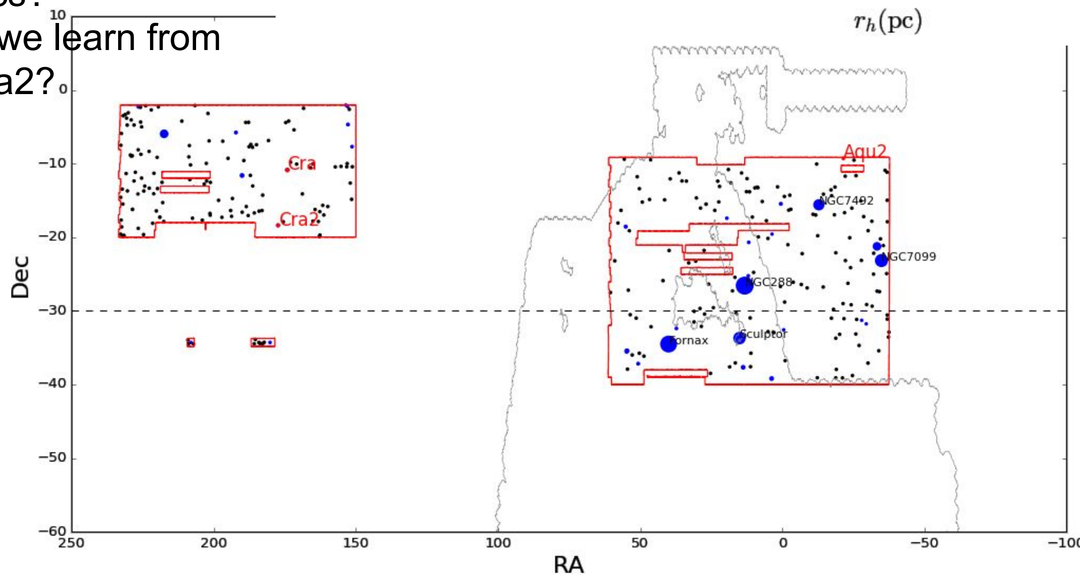
VST ATLAS Searches

Guest Speakers: **Gabriel Torrealba**

Techniques
- Isochrone masking in g and r
- Spatial convolution
- Use large kernels and BHBs
- Modelling of all candidates

Questions
- Are we taking advantage of all the available info?
- How to best combine different statistics?
- How much can we learn from oddballs like Cra2?



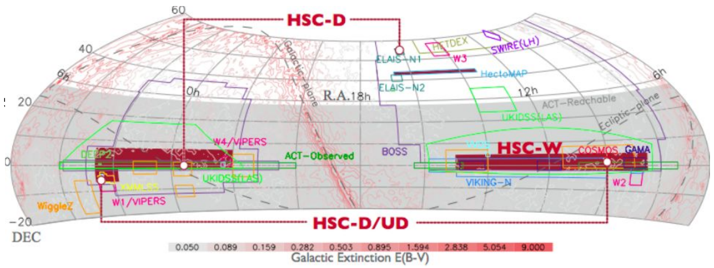


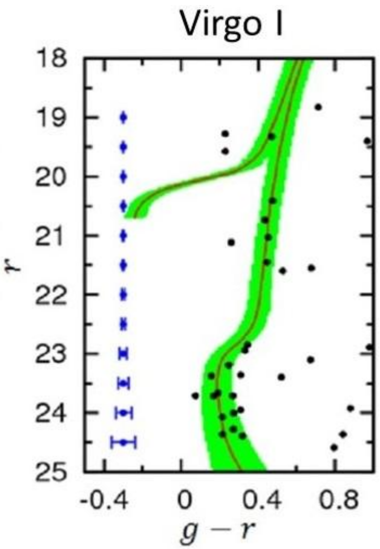
Session 2

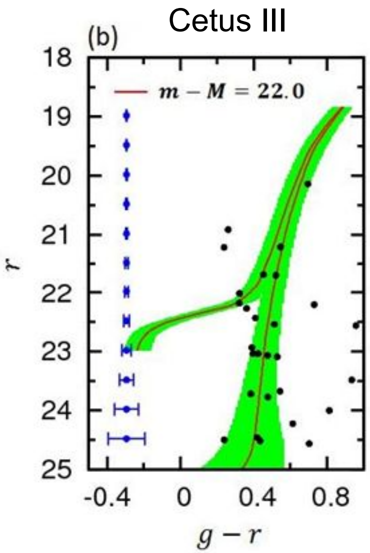
HSC Searches

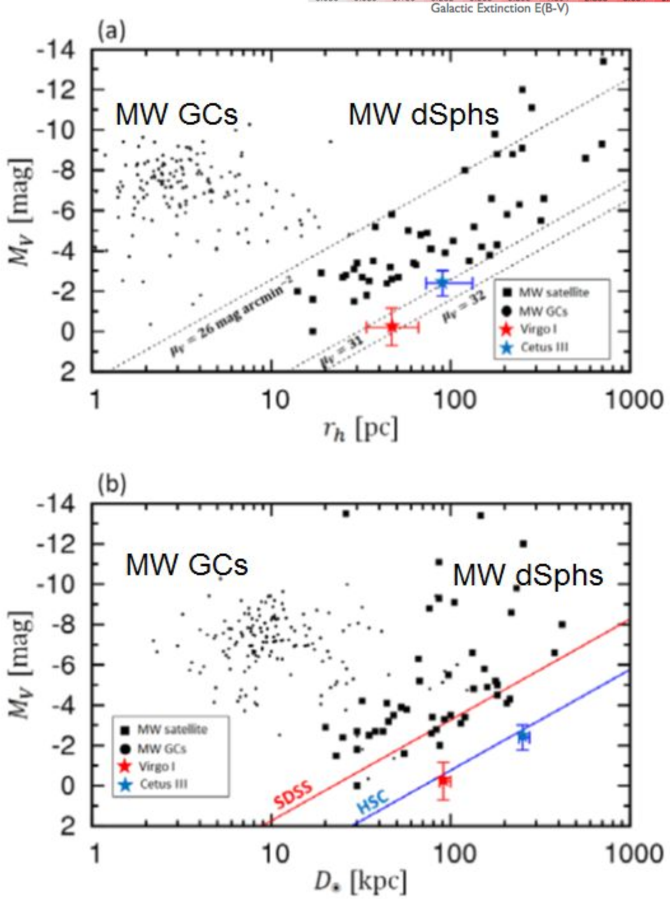
Guest Speakers: **Masashi Chiba (Alex DW)**

HSC Subaru Strategic Program with Wide, Deep, and Ultra-deep layers,
5 bands (g,r,i,z,y) --- dSphs search from the data of the Wide layer
over ~ 300 deg^2 released so far (goal: 1,400 deg^2)









	Virgo I	Cetus III
Coordinates	: $(\alpha, \delta) = (180^\circ.04, -0^\circ.68)$	: $(\alpha, \delta) = (31^\circ.331, -4^\circ.270)$
Absolute magnitude :	$M_V = -0.33$ mag	: $M_V = -2.45$ mag
Heliocentric distance :	$D = 87^{+13}_{-8}$ kpc	: $D = 251^{+24}_{-11}$ kpc
Half light radius :	$r_h = 38^{+12}_{-11}$ pc	: $r_h = 90^{+42}_{-17}$ pc

Selection method:
(1) select point-source images (remove galaxy images)
(2) select star candidates from the g-r vs r-i diagram
(3) set an isochrone filter in a CMD g-r vs r (13Gyr, [M/H]=-2.2)
(4) search for an overdensity passing the isochrone filter
(5) examine its statistical significance

Homma, MC, et al. 2016, ApJ, 832, 21
Homma, MC, et al. 2017, PASJ, in press arXiv:1704.05977

Other Searches

Guest Speakers: **Dongwon Kim**

- Found 5 objects from 3 different data sets between 2014 and 2016:
(1) Sloan Digital Sky Survey (SDSS) DR 8: **Kim 1 & Pegasus III**
(2) Dark Energy Survey (DES) DR 1 - public data: **Horologium II**
(3) SMS Survey (PI: Jerjen, ANU) ~1,200 sq degrees, using DECam: **Kim 2 & 3**

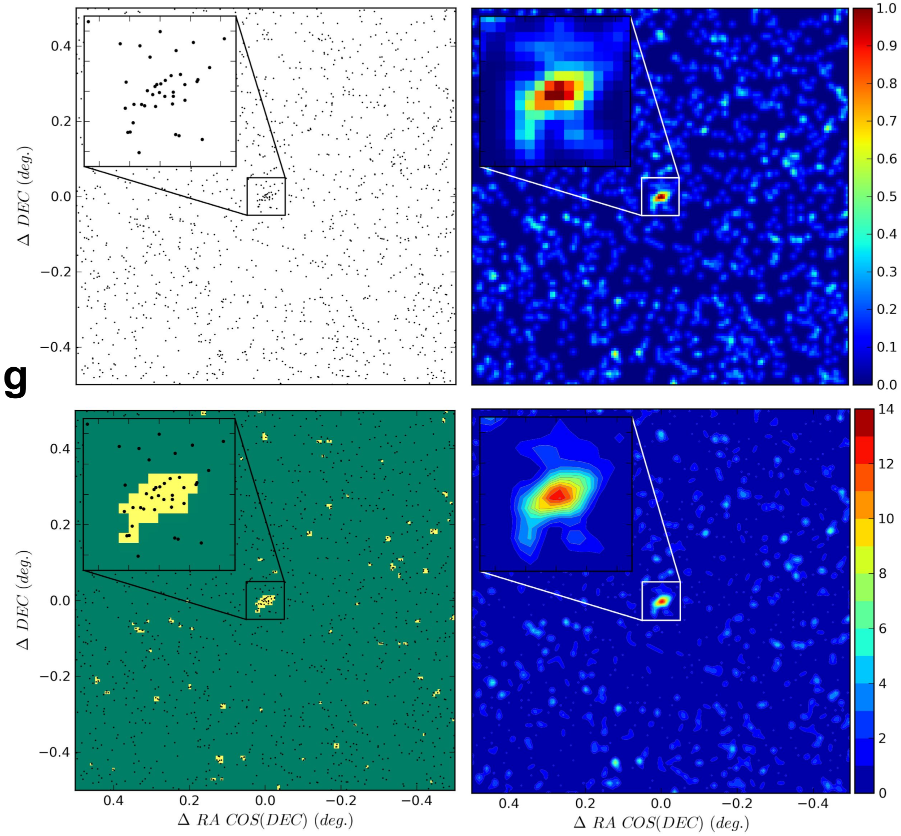
Techniques:

- **Isochrone mask using g-r vs r .**
- **Construct a 2D density map using the selected stars.**
- **Convolve with a Gaussian kernel.**
- **Examine significance of clusters.**

Questions:

- **Majority of discovery papers published before 2014 include deep follow-up imaging data, while many of recent papers don't. What determines whether or not follow-up imaging is a requirement? Is there a clear criteria for this?**
- **Would the current criteria be still valid/helpful/useful in LSST era?**

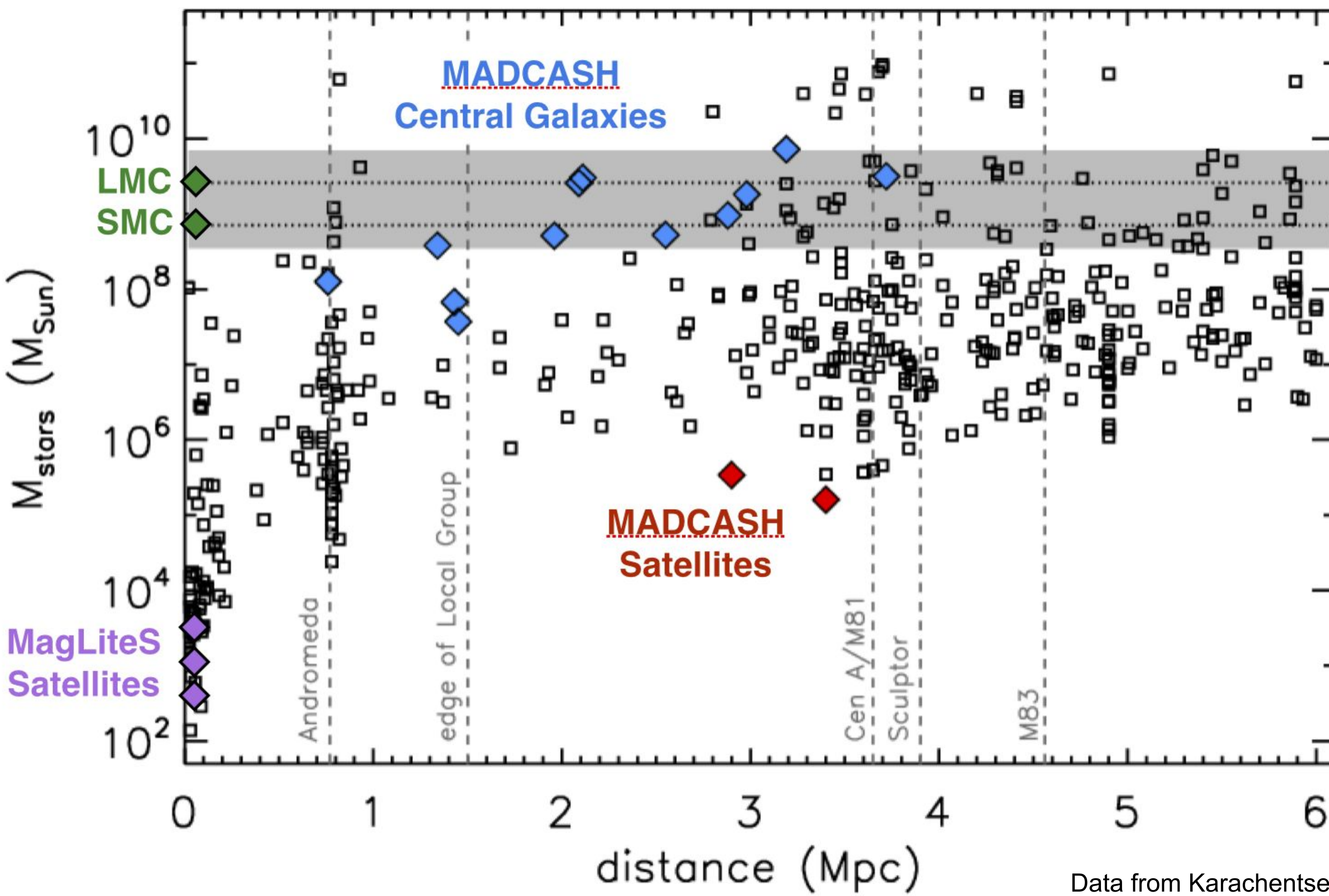
Kim & Jerjen 2015



Session 2

Other Surveys: MADCASH

Guest Speakers: **Jeff Carlin**



Data from Karachentsev et al. 2013, AJ, 145, 101 (https://relay.sao.ru/lv/lvgdb/)

Session 2

Other Surveys: PAndAS

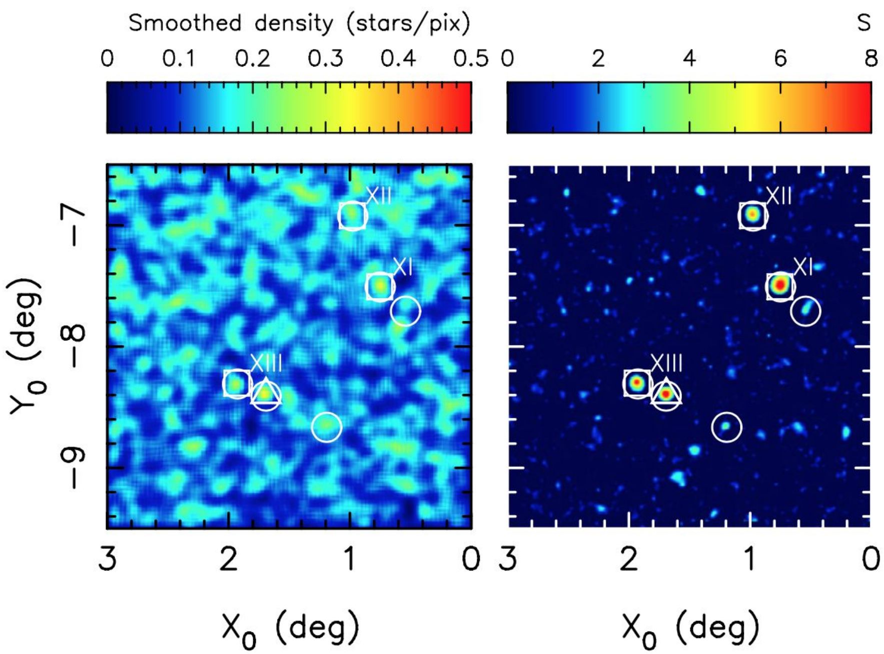
Guest Speakers: **Nicolas Martin**

Technique:

- **Testing the likelihood of family of spatial + CMD dwarf galaxy models and comparing it to model w/o dwarf galaxy**
- **Every 0.5 arcminute in survey**
- **Building contamination model from surroundings**

Questions:

- **Is this applicable over 20,000 deg2?**
- **More parameters than most other techniques (rh, N*, distance, age, [Fe/H])**
- **Sensitive to localized overdensities (streams,...) but isn't the case for all techniques?**



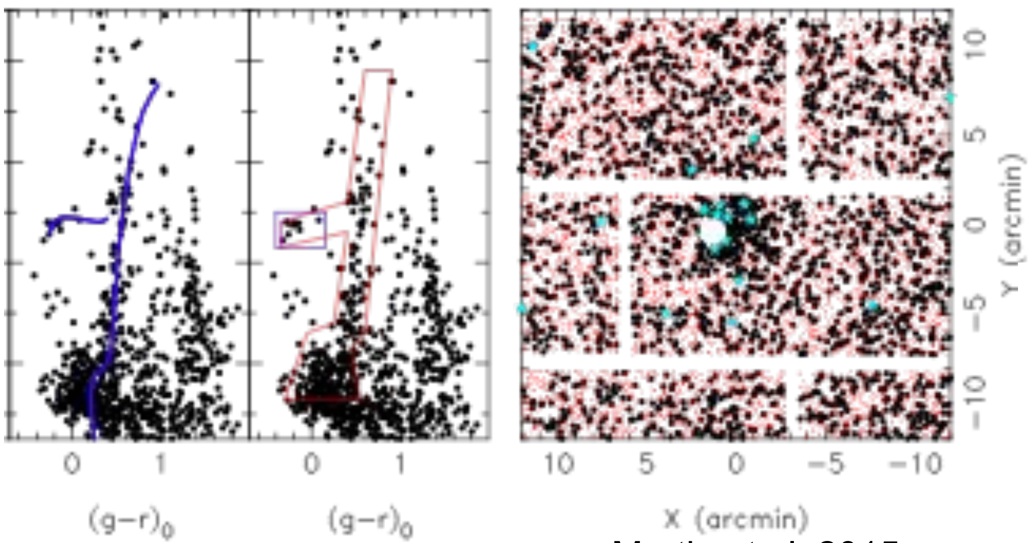
Martin et al. (2013)

Session 2

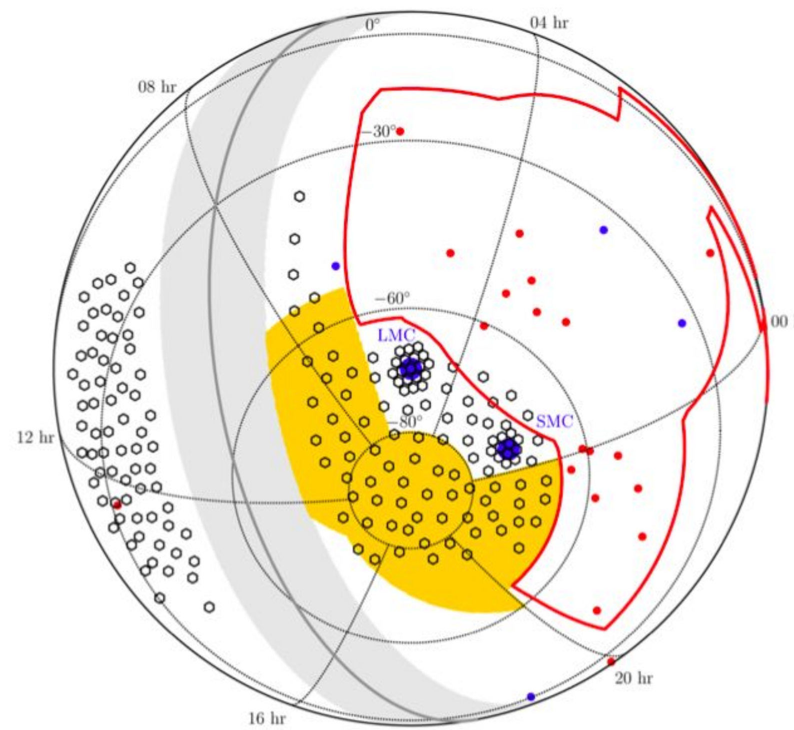
Other Surveys: SMASH & MagLiteS

Guest Speakers: **Knut Olsen, Keith Bechtol**

Hydra II



Martin et al. 2015



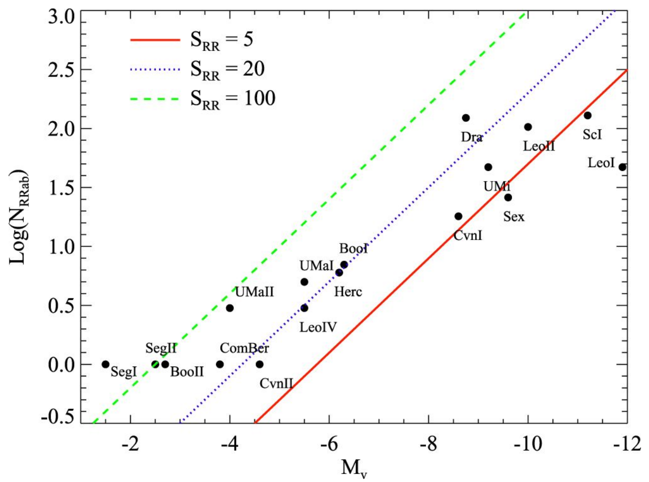
Session 2

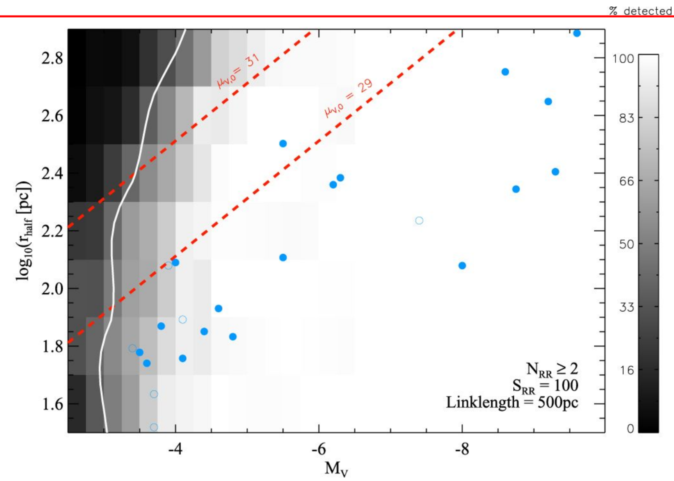
Variable Star Searches

Guest Speakers: **Kathy Vivas**, (Beth Willman, Jeff Carlin)

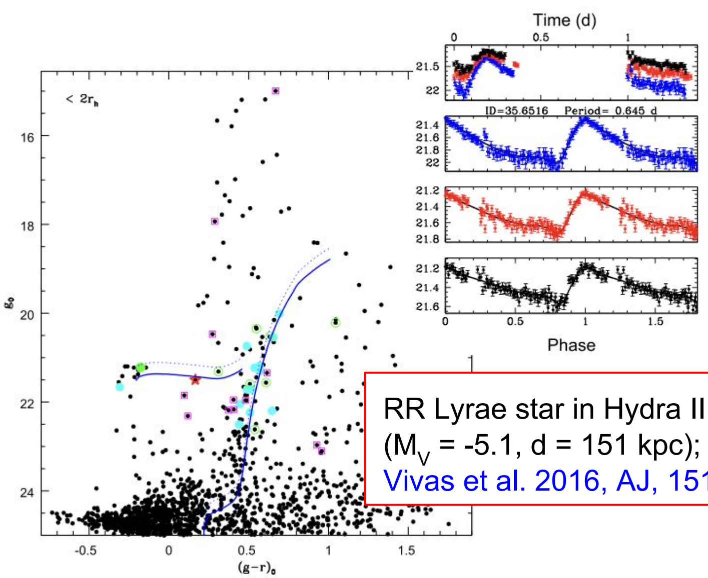
All Milky Way dwarfs that have been searched have at least one detected RR Lyrae star.

Dwarfs with at least 2 RR Lyrae stars beyond d=100 kpc can be detected unambiguously to extremely low surface brightness.

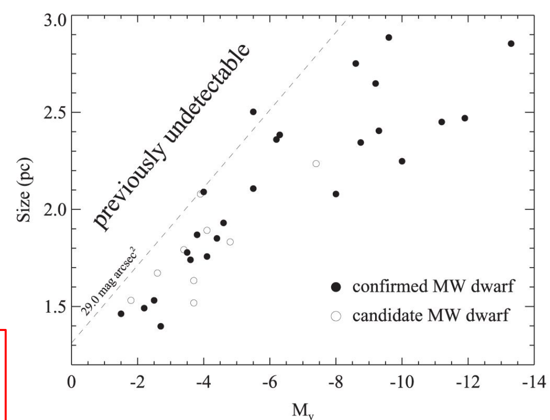


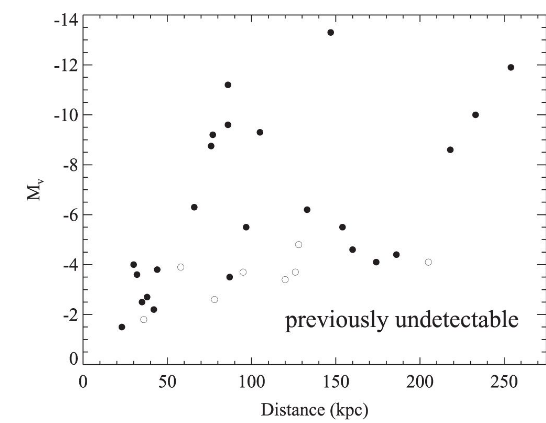


Baker & Willman 2015, AJ, 150, 160



RR Lyrae star in Hydra II UFD (M_V = -5.1, d = 151 kpc);
Vivas et al. 2016, AJ, 151, 118



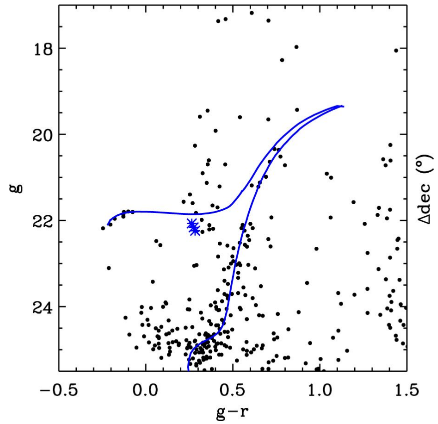


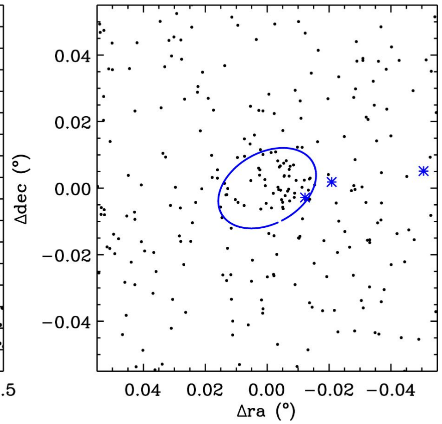
Session 2

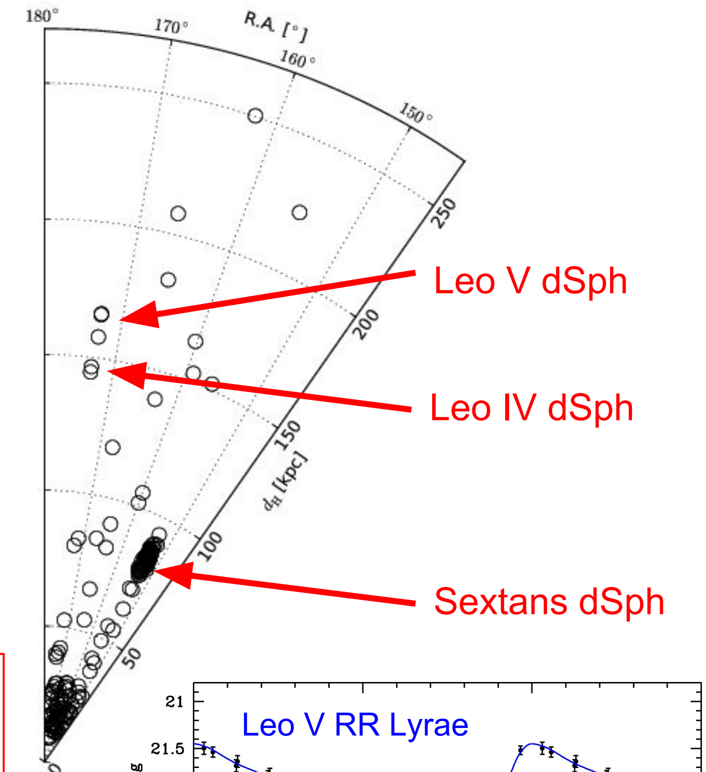
Variable Star Searches

Guest Speakers: **Kathy Vivas**, (Beth Willman, Jeff Carlin)

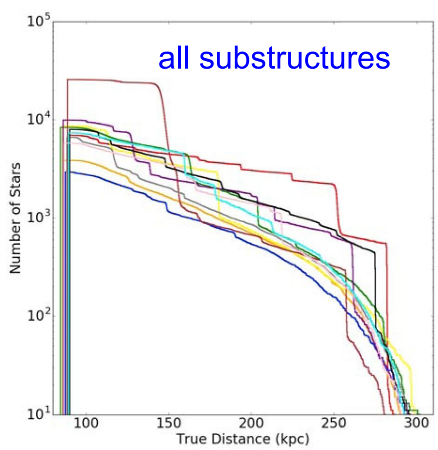
3 RR Lyrae members of Leo V (M_V = -4.4, r_h = 65 pc, d=173 kpc) “serendipitously” found in HiTS (supernova survey) data [Medina et al. 2017, ApJL, 845, 10]

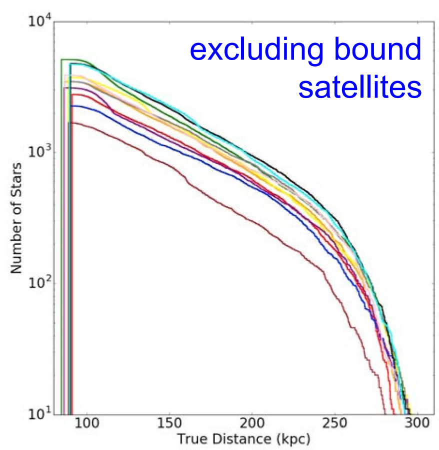


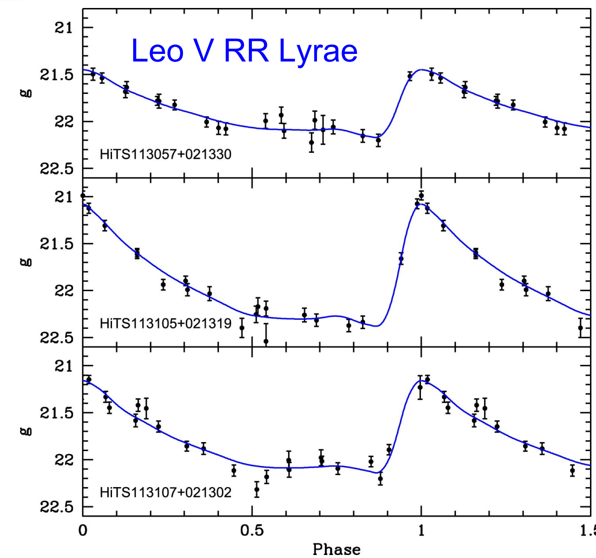




Expect 2000-10000 RR Lyrae between 100 < d < 300 kpc in the MW; half are still in bound satellites. [Sanderson et al. 2017, MNRAS, 470, 5014]





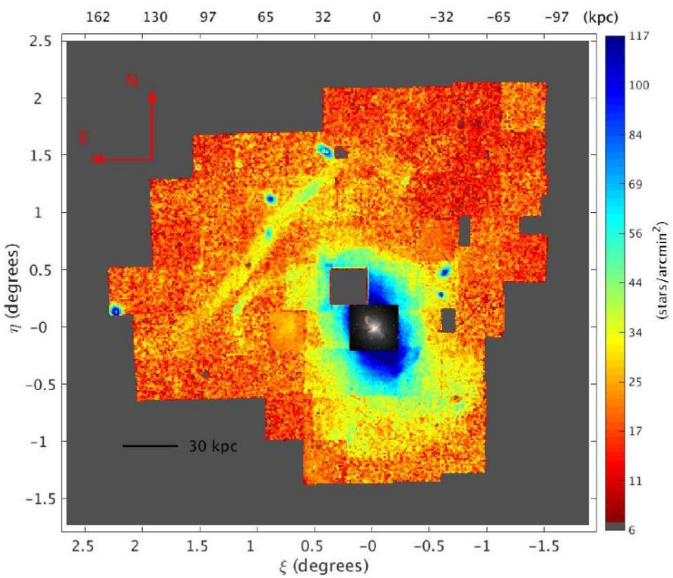


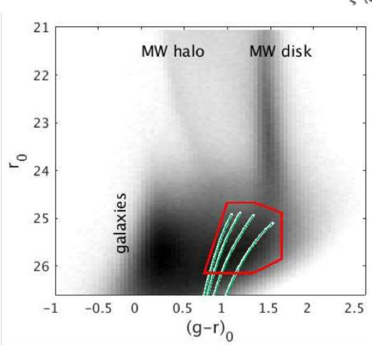
Session 2

Pixel-Based Searches

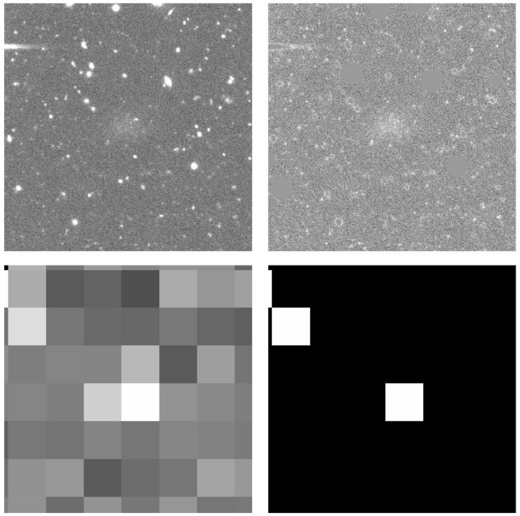
Guest Speakers: **David Sand, Jeff Carlin**

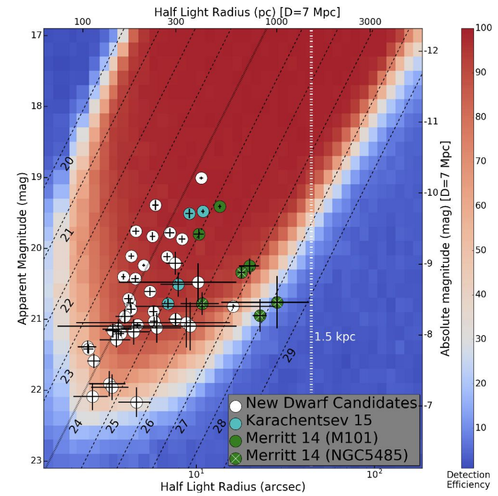
PISCeS: Resolved substructure (streams *and* dwarfs) around Centaurus A (D ~ 3.7 Mpc): [Crnojević et al. 2016, ApJ, 823, 19]

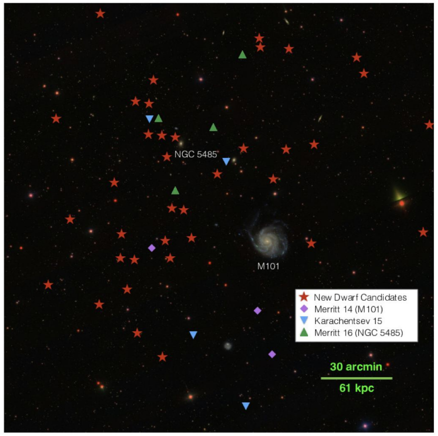




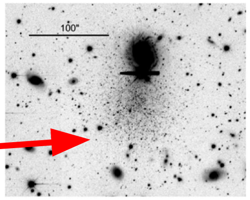
Unresolved dwarfs around M101 (D ~ 7 Mpc). [Bennet et al. 2017, ApJ, *accepted,* arXiv:1710.01728]

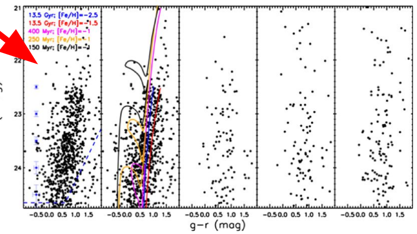






Dwarf galaxy **Antlia B:** (M_V~ -9.7) near NGC 3109: (M_* ~ 0.5 $M_{*,SMC}$, D~1.3 Mpc) [Sand+2015, ApJL, 812, 13]





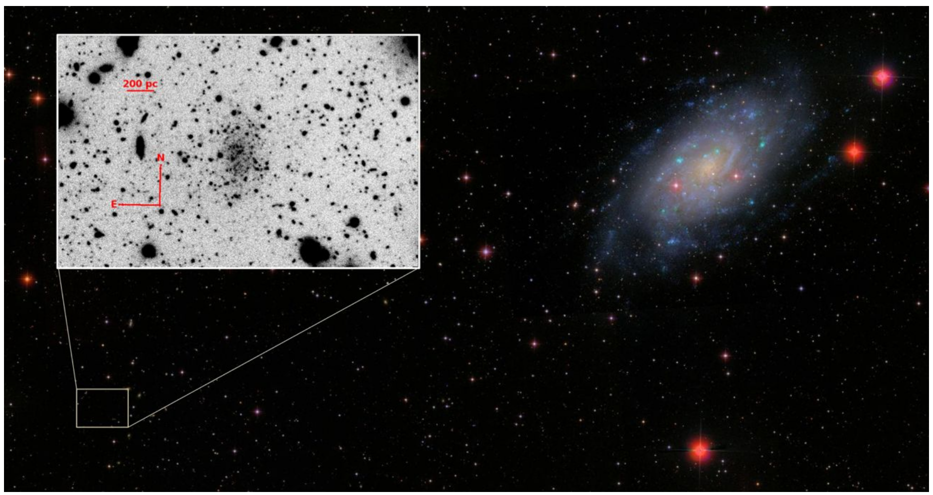
Session 2

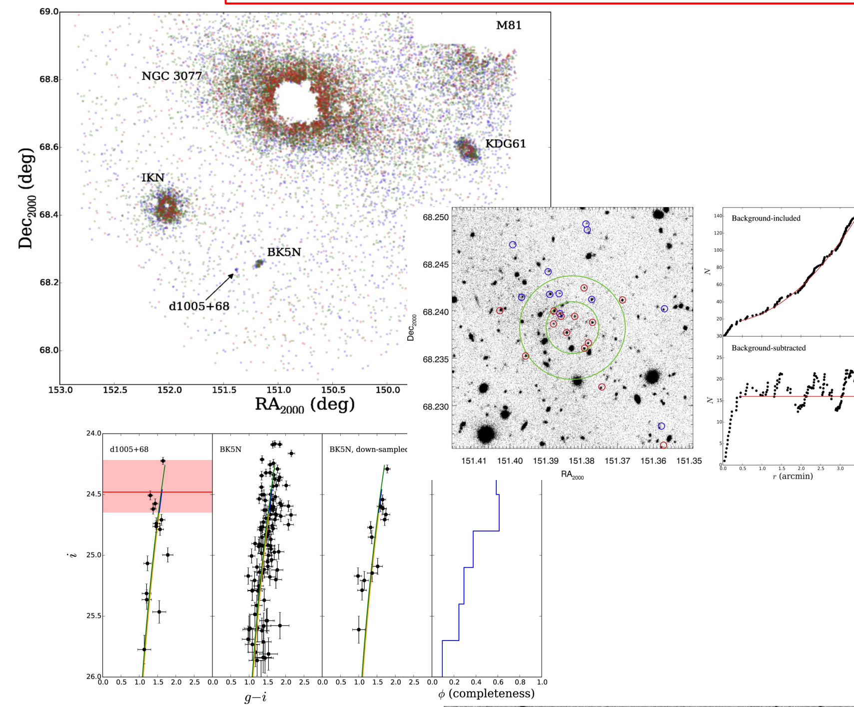
Pixel-Based Searches

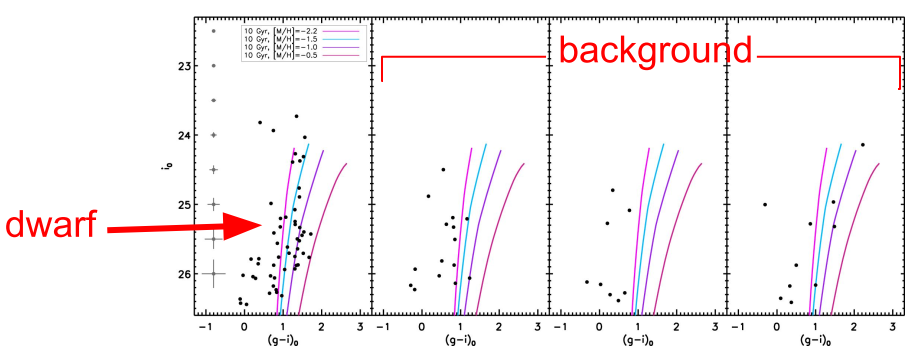
Guest Speakers: **David Sand, Jeff Carlin**

d1005+68 (M_V ~ -7.9) in M81 group (D ~ 3.6 Mpc) [Smercina et al. 2017, ApJL, 843, 6]

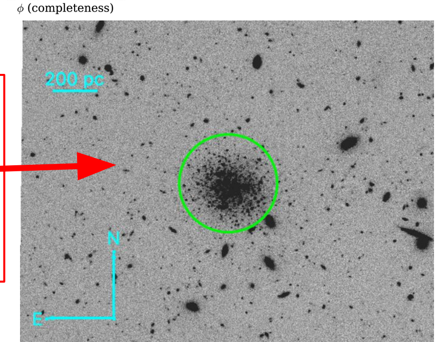
<u>**M**</u><u>agellanic</u> <u>**A**</u><u>nalogs' </u><u>**D**</u><u>warf </u><u>**C**</u><u>ompanions </u><u>**a**</u><u>nd </u><u>**S**</u><u>tellar </u><u>**H**</u><u>alos:</u>
MADCASH J074238+652501-dw: faint (M_V ~ -7.7) dwarf companion of ~2x LMC stellar mass host NGC 2403 (D~3.2 Mpc) [Carlin et al. 2016, ApJL, 828, 50]



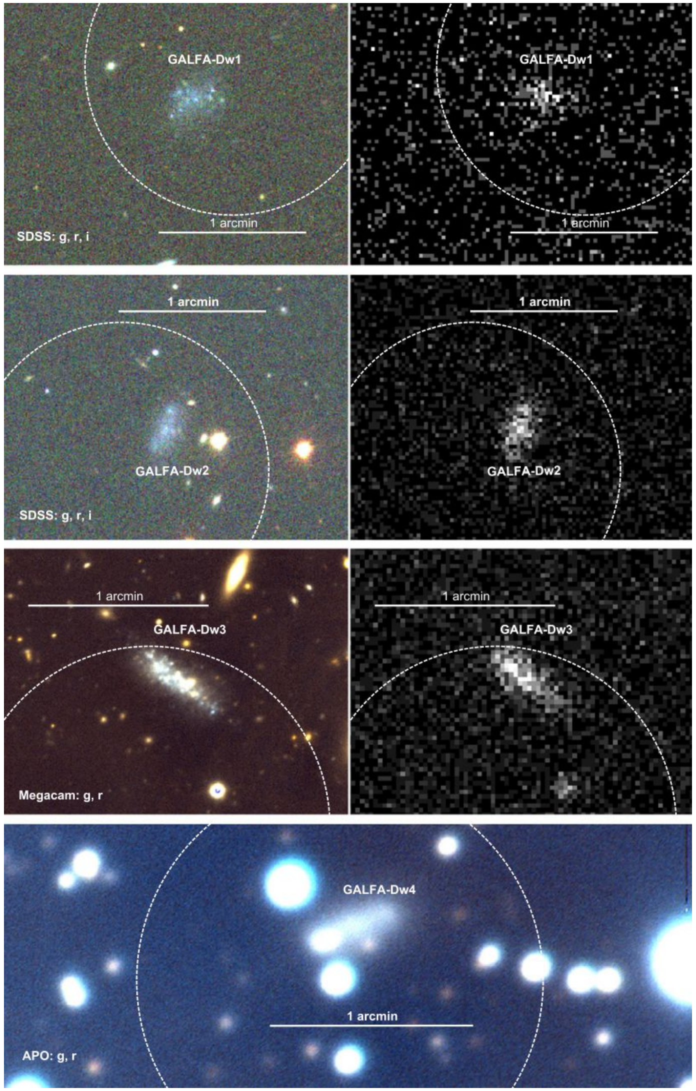


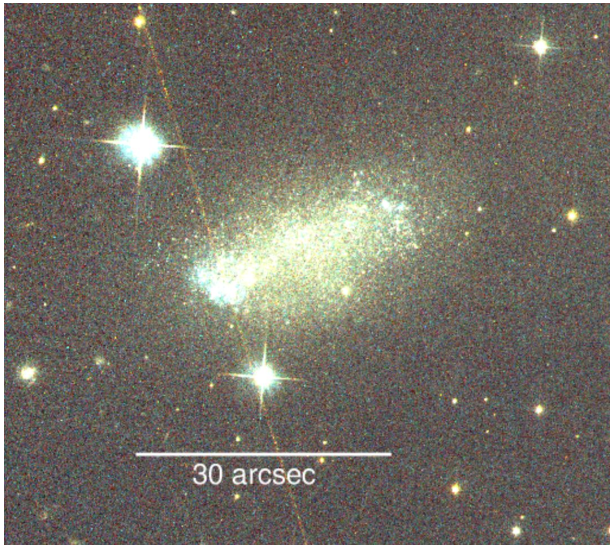


New MADCASH dwarf near NGC 4214 (D ~ 2.9 Mpc, $M_* \sim 0.5\ M_{*,LMC}$)?

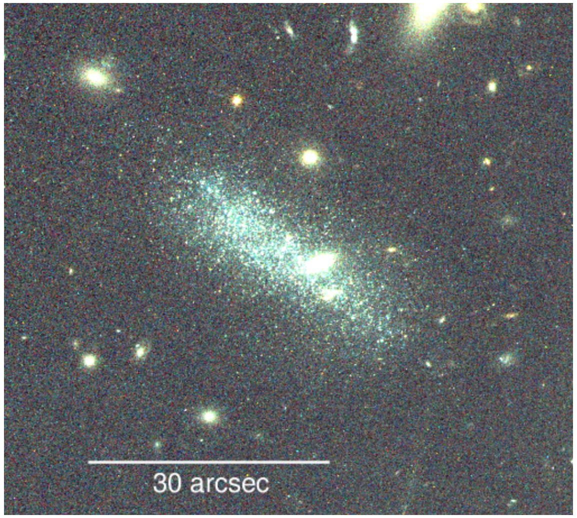


HI-based searches for dwarfs





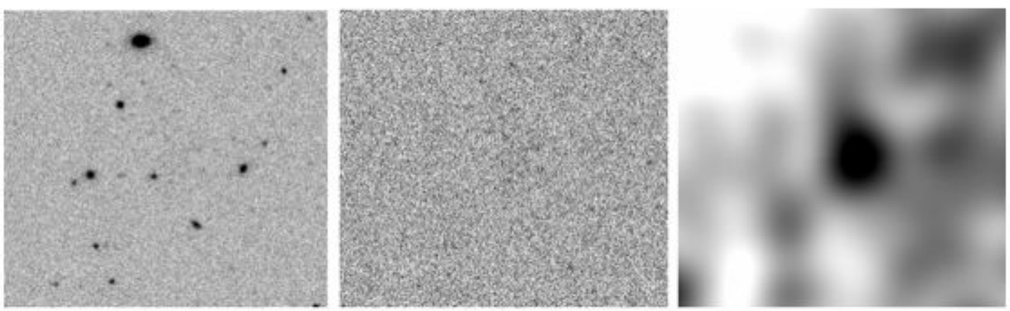
D~3 Mpc

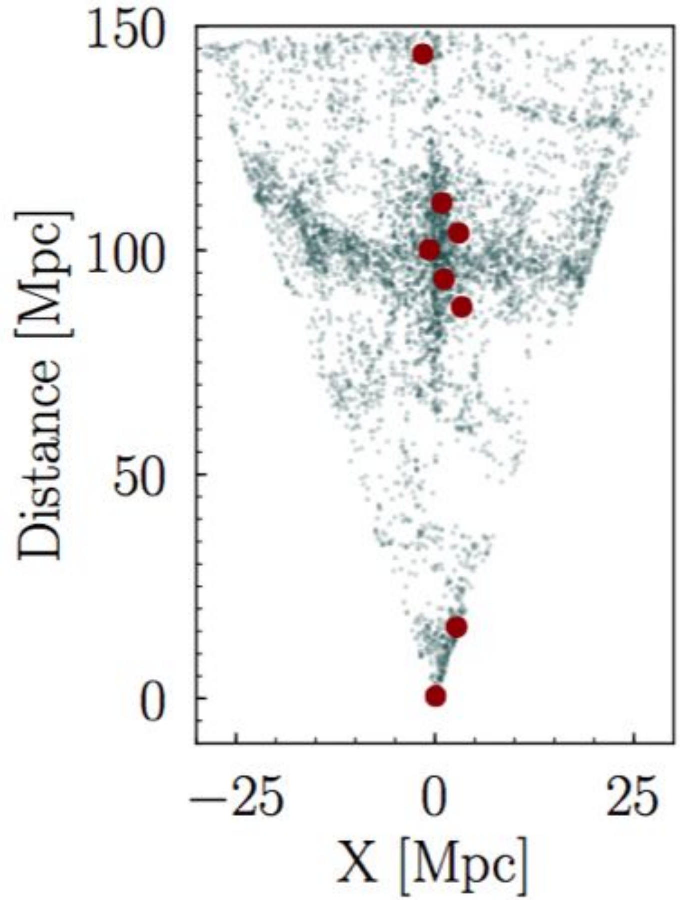


D~8 Mpc

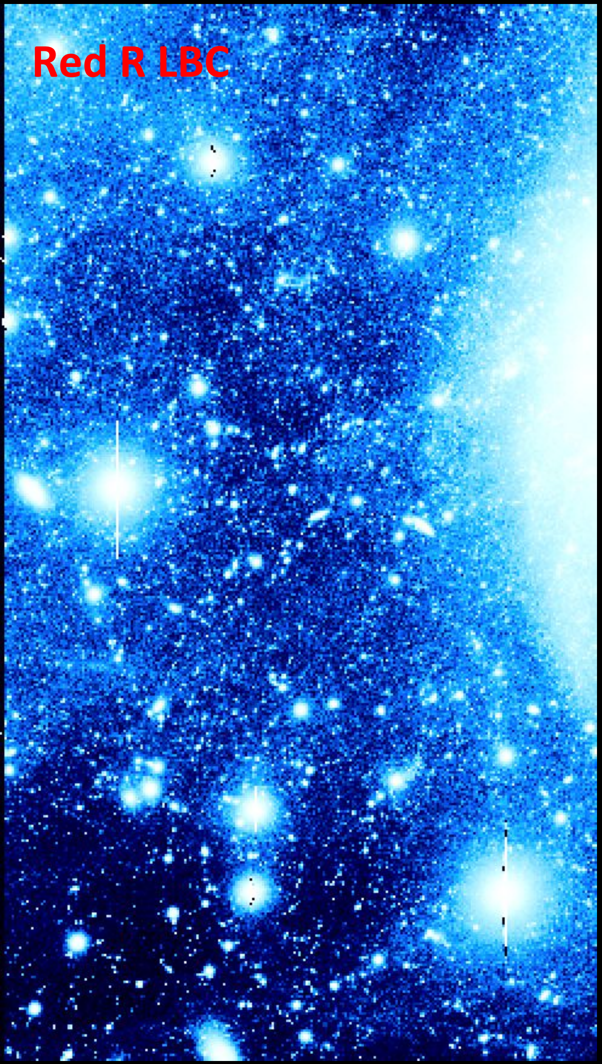
Systematically Measuring Ultra-Diffuse Galaxies (SMUDGES)

Zaritsky (PI), Donnerstein, Kadowaki, Zhang, Dey, ++





Unleashing the power of U*



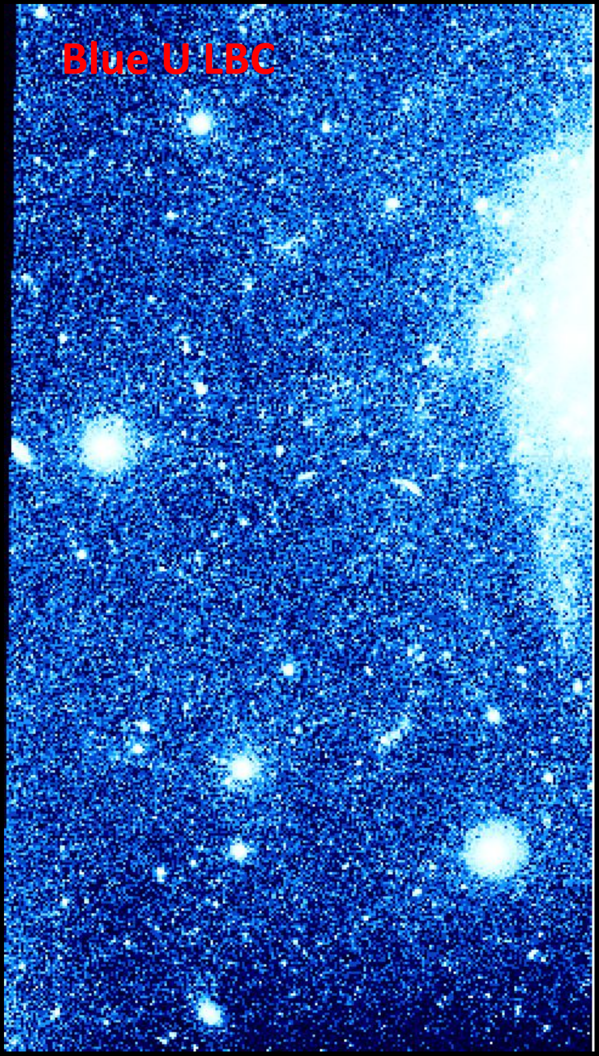
LBT search for close-in-projection satellites of star-forming hosts. (Annika Peter, Anna Nierenberg, Chris Kochanek, Bianca Davis)

Can identify M_V < -8 by eye.

To get lower, need automated detection (gentle nudging of Source Extractor).

R band has 3x the exposure of U, B, or V

We have MANY gnarly backgrounds that are better behaved in U.



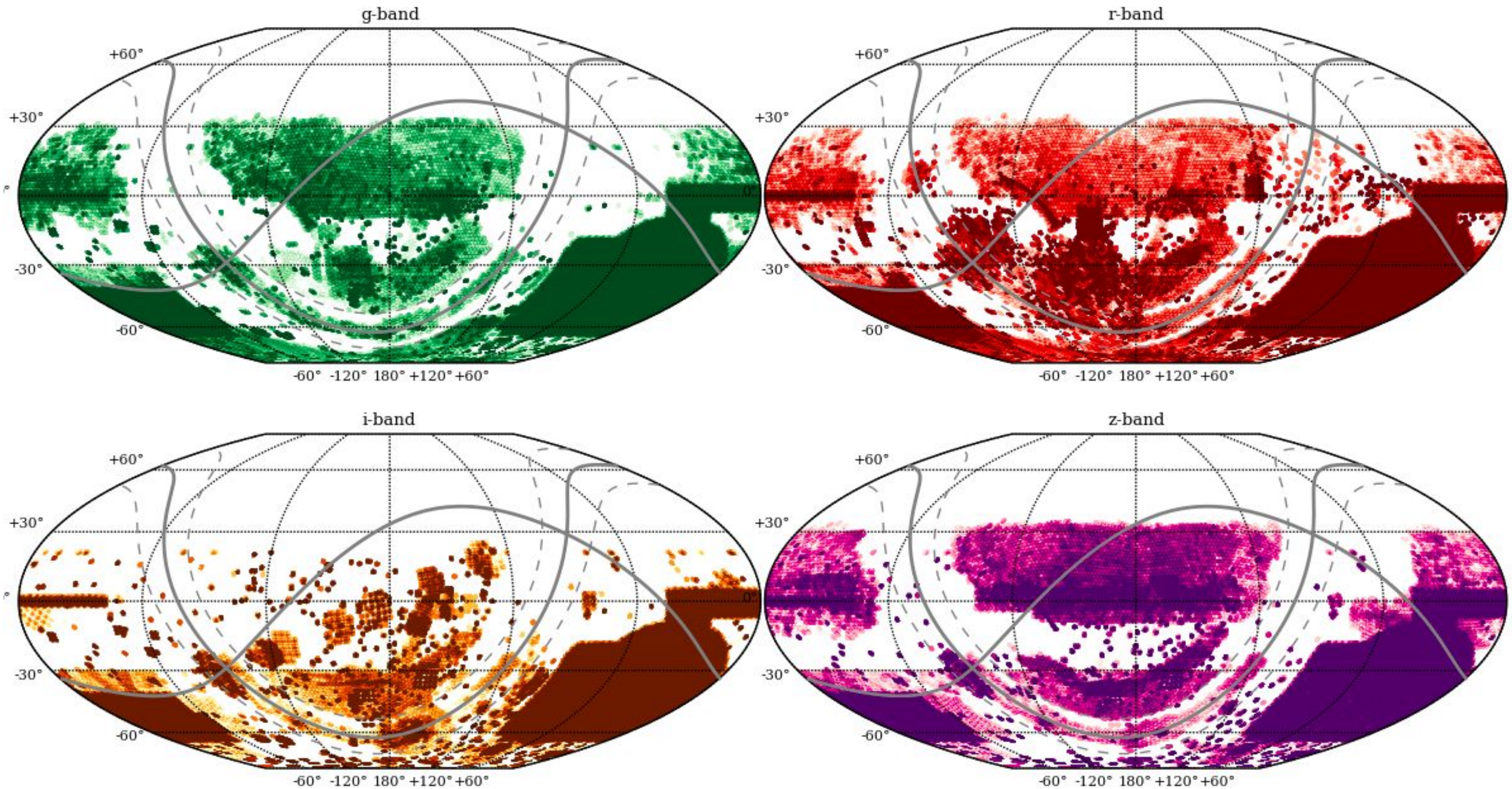
*Pun credit: Alex Drlica-Wagner

Session 2

Progress Before LSST

Guest Speakers: **Alex DW, Everyone?**

Current DECam sky coverage

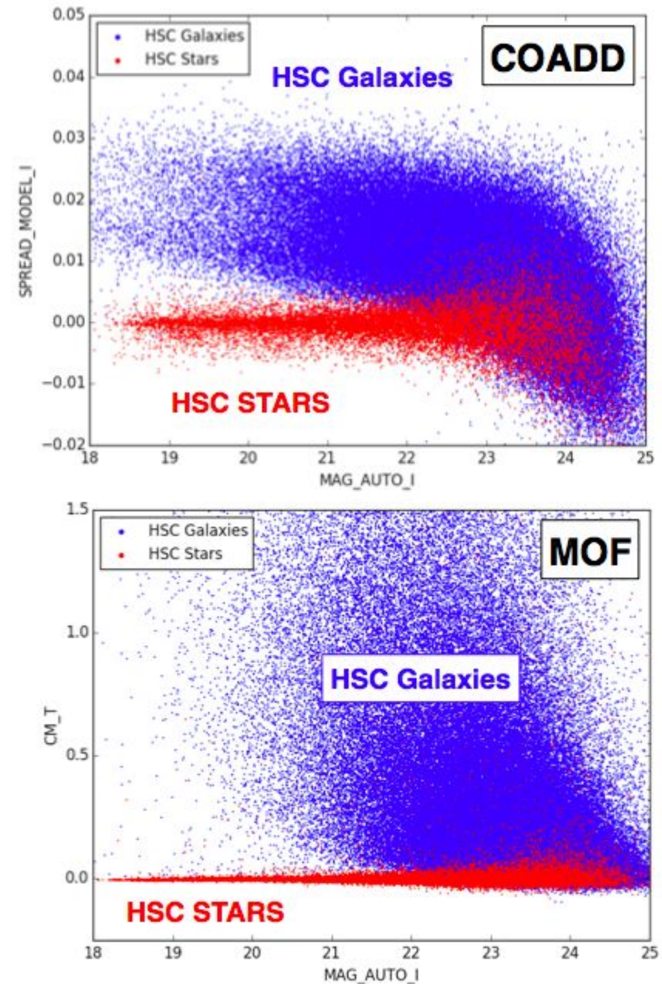


Session 2

Challenges for LSST

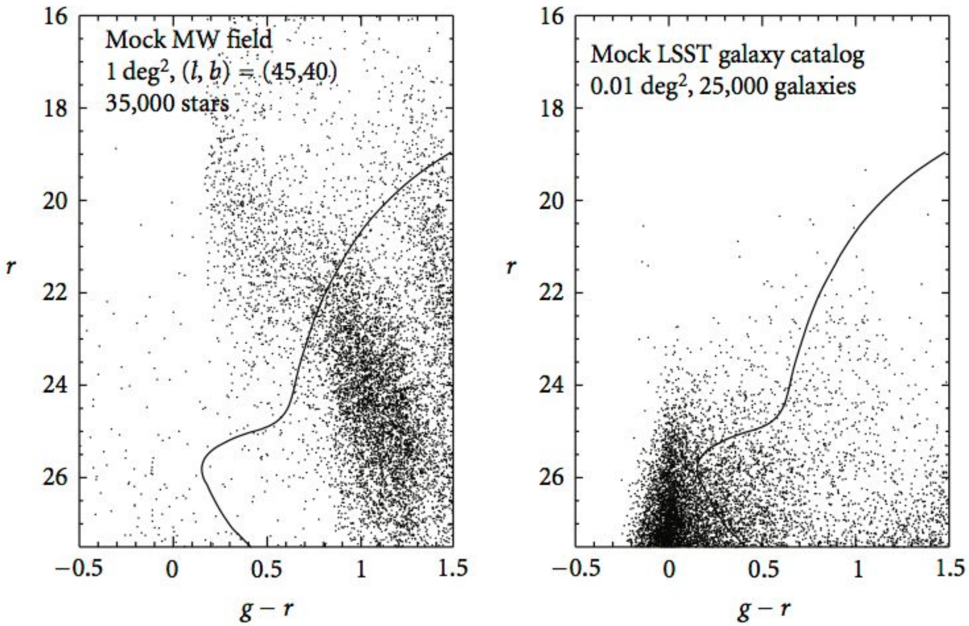
Guest Speakers: **Keith B., Everyone?**

- Star galaxy selection
- Do color based cuts really add much (lessons learned from DES)?



Bechtol (TeVPA 2017)

Willman 2010



Session 3: Expected LSST data products and services

Sorry, no slides for this section - please consult extensive LSST documentation, e.g.
https://www.lsst.org/about/dm/data-products

LSST Data Products - discussion report

Construction is proceeding rapidly

Read the DPDD! http://ls.st/dpdd !

It seems likely that Local Volume science will involve going back to the individual images and performing custom analyses at the pixel level. Perhaps there are specialized image products (e.g., sources removed) that would be valuable.

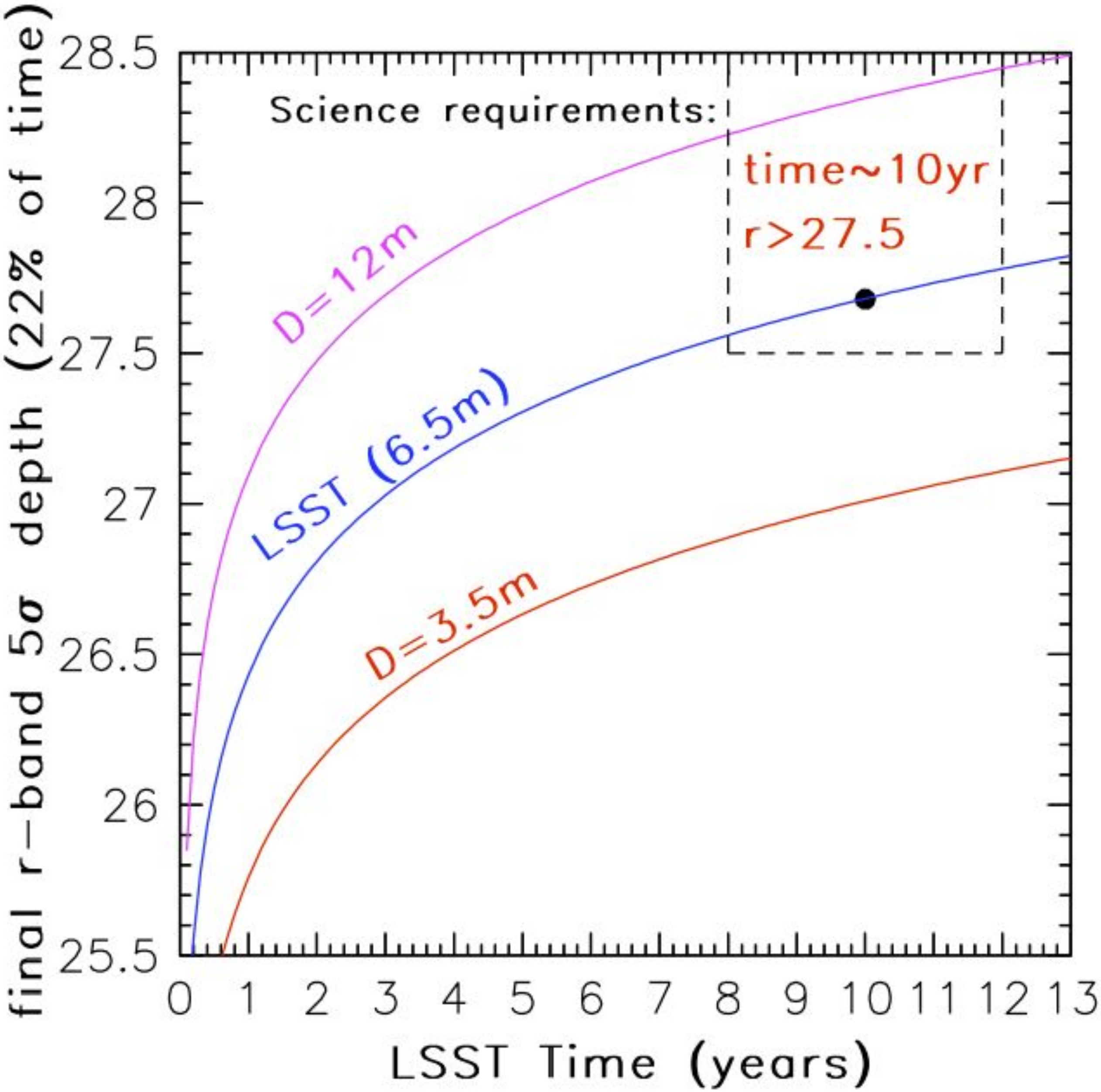
Full res image of the whole sky is 1.7 PB, but maybe could pixelize at coarser level if looking specifically for diffuse light sources. Could ask Project to produce a coadd with sources removed. Instrumental signature removal at the single-visit level.

LSST Science Platform (See http://ls.st/lsp)

Impact of LSST Observing Strategy on Dwarf Galaxy Science

- Does cadence matter for dwarf searches?
  - Will any LSST cadence be good enough for RRL identification and period measurement?
- How will the LSST footprint placement affect dwarf searches?
  - How far north to go?
  - Coverage of SCP and Magellanic Clouds?
- Down to what latitude can we find dwarfs?
  - Should we push for additional low-b observations?

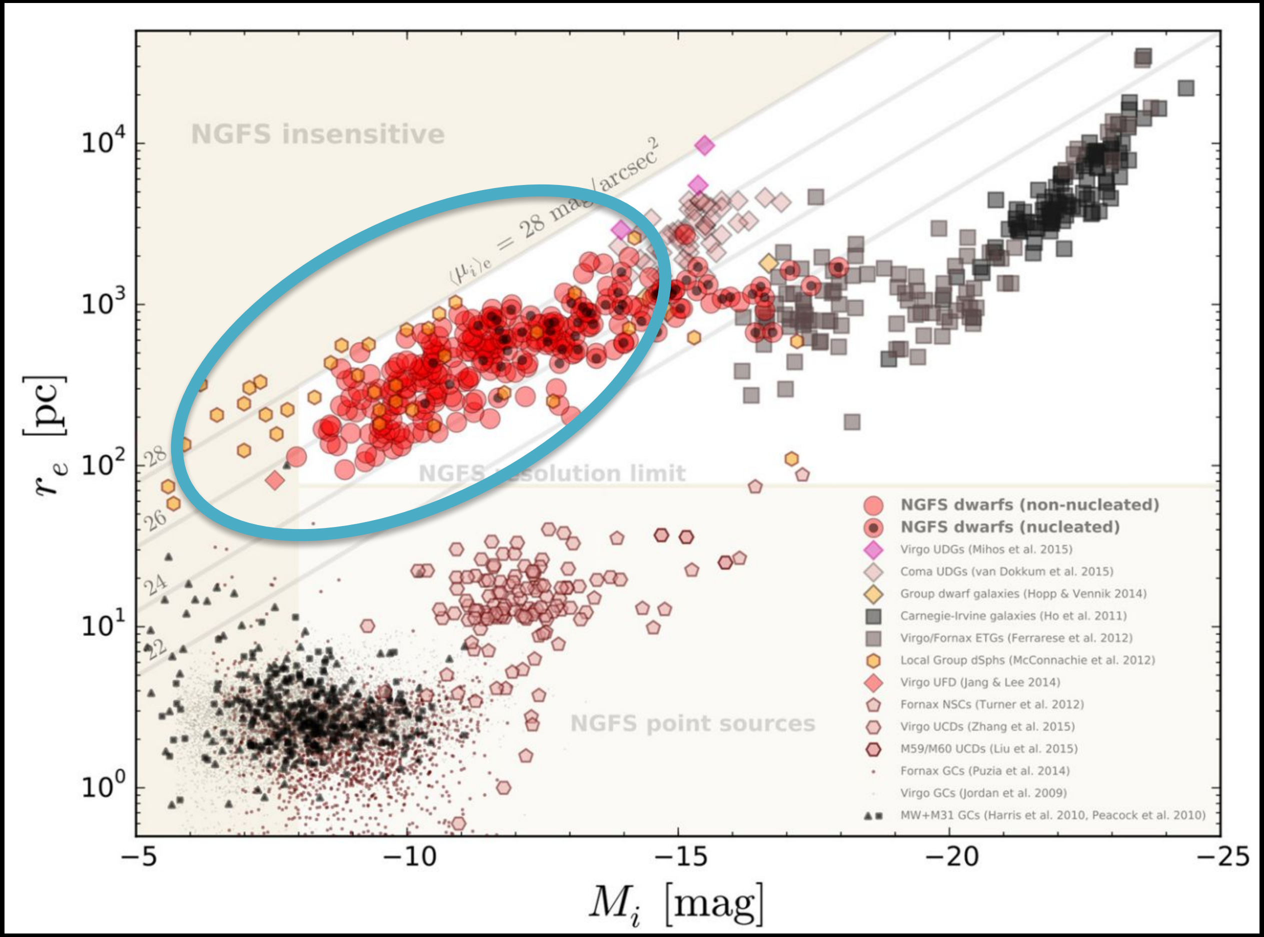
http://decaps.legacysurvey.org/


Science requirements:
time~10yr
r>27.5
D=12m
LSST (6.5m)
D=3.5m
final r−band 5σ depth (22% of time)
LSST Time (years)
28.5
28
27.5
27
26.5
26
25.5
0 1 2 3 4 5 6 7 8 9 10 11 12 13

Session 4: What should we be looking for?

DWARF GALAXY OBSERVABLES IN THE LSST ERA

New era for dwarf searches

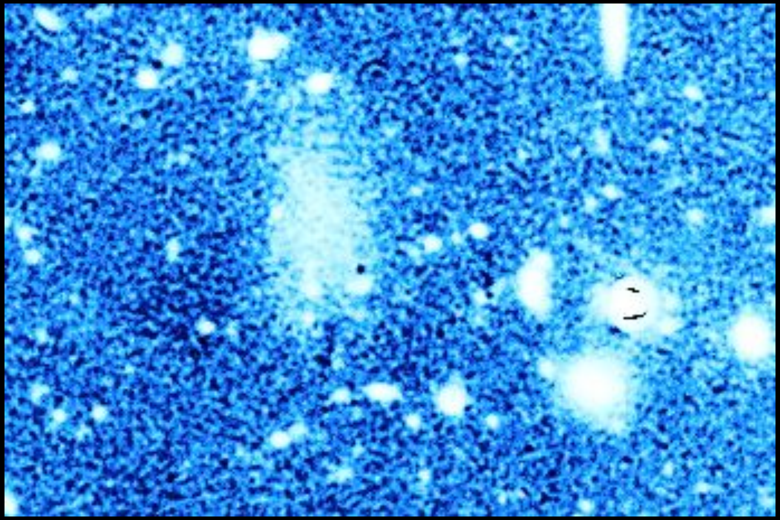


Munoz+ 2015
Fornax
cluster

What do we want to know about dwarfs?

- How many are there (i.e., # density in space)?
- How do their properties depend on environment? (e.g., gas-rich field objects vs. gas-poor satellites)
- What kinds of dark matter halos do they live in?
- Where is the transition from the ultrafaint ancient to classical recently star-forming regime?
- Are ultradiffuse galaxies “normal” dwarfs, or are they “massive failures”?

What do we do when we find a smudge in a survey?



Satellite dwarf candidate in NGC 3344
LBT R band

"glorious name"

Half-light radius
Color
Sersic profile
Clumpy?

Is it in GALEX/Spitzer/WISE/SDSS/radio?

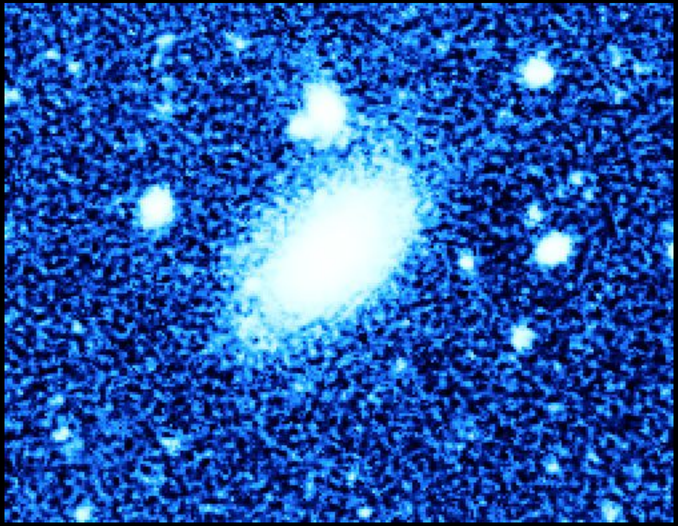
HST follow-up for a TRGB distance & SFH

21 cm follow-up (is there gas?)

Optical spectrum (is it actively star-forming?)

Properties of individual galaxies matter.

Big galaxies in surveys


Random galaxy in LBT R band

“LBT-JXXXX-YYYY”

Sersic index
Half-light radius
Shape
Photo-z

Maybe spectroscopy (probably not in LSST era)

Often not compare w/data in other bands

Many libraries of models to get photometric stellar mass/age

Statistics of objects matter than properties of individual galaxies.

Questions

- What do we need in order to get to the "statistical" era for dwarf searches? What other facilities do we need to get there?
- How do we get distances or accurate photo-z's? Can we use the clumpiness of light?
- What kind of selection effects do we need to be aware of?

1) How can observations inform theory?

Number of dwarf galaxies

- In the Milky Way: beginning to be informative on the nature of dark matter
- Around MW analogs: placing MW in context, exploring possible accretion histories
- In the field: valuable tests both for galaxy formation and dark matter physics

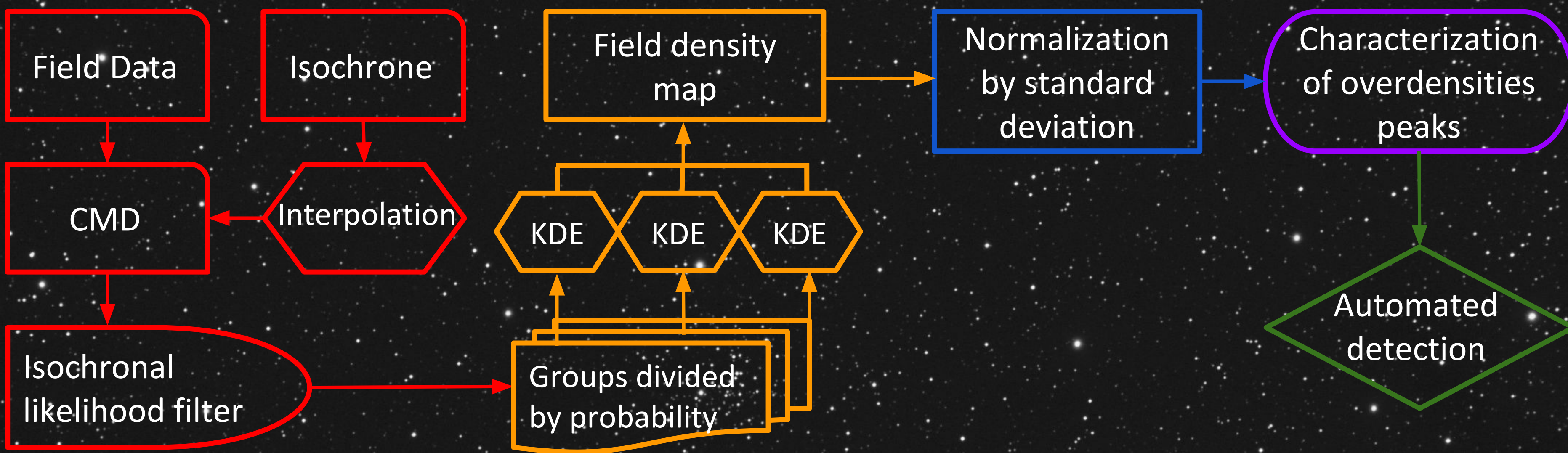
Spatial distribution

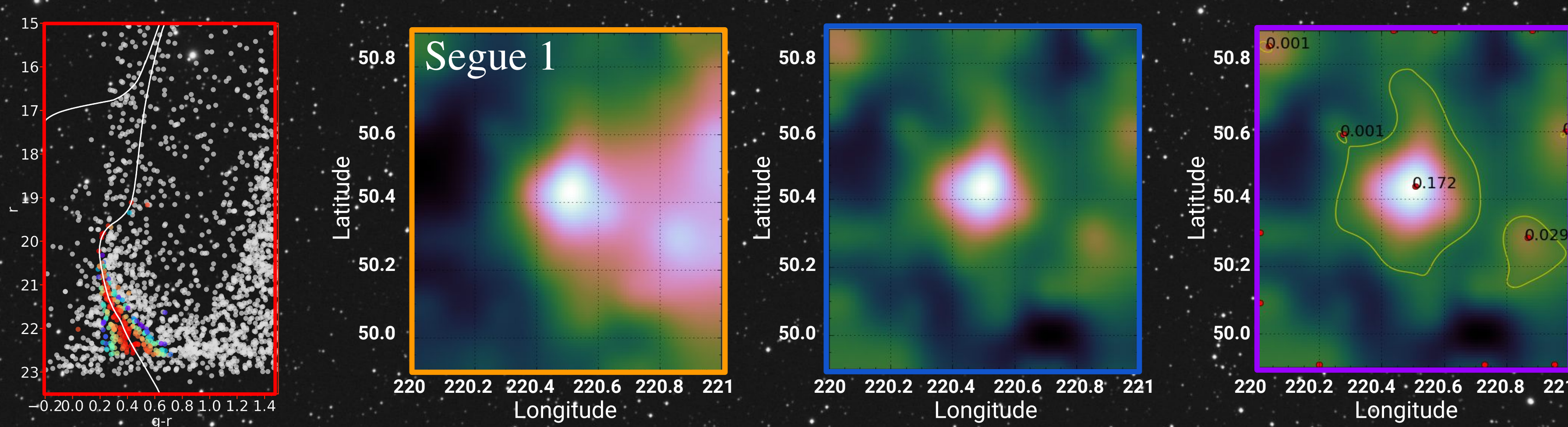
- Individual dwarfs: radial distribution of satellites, clustering in the field
- Star-star correlation functions: circumvents the issue of classifying bound objects
- Stream morphology: handle on the inner profile

Session 5: Catalog-based search techniques

MaGIK Mapping Galaxies using Isochronal Likelihood and KDE

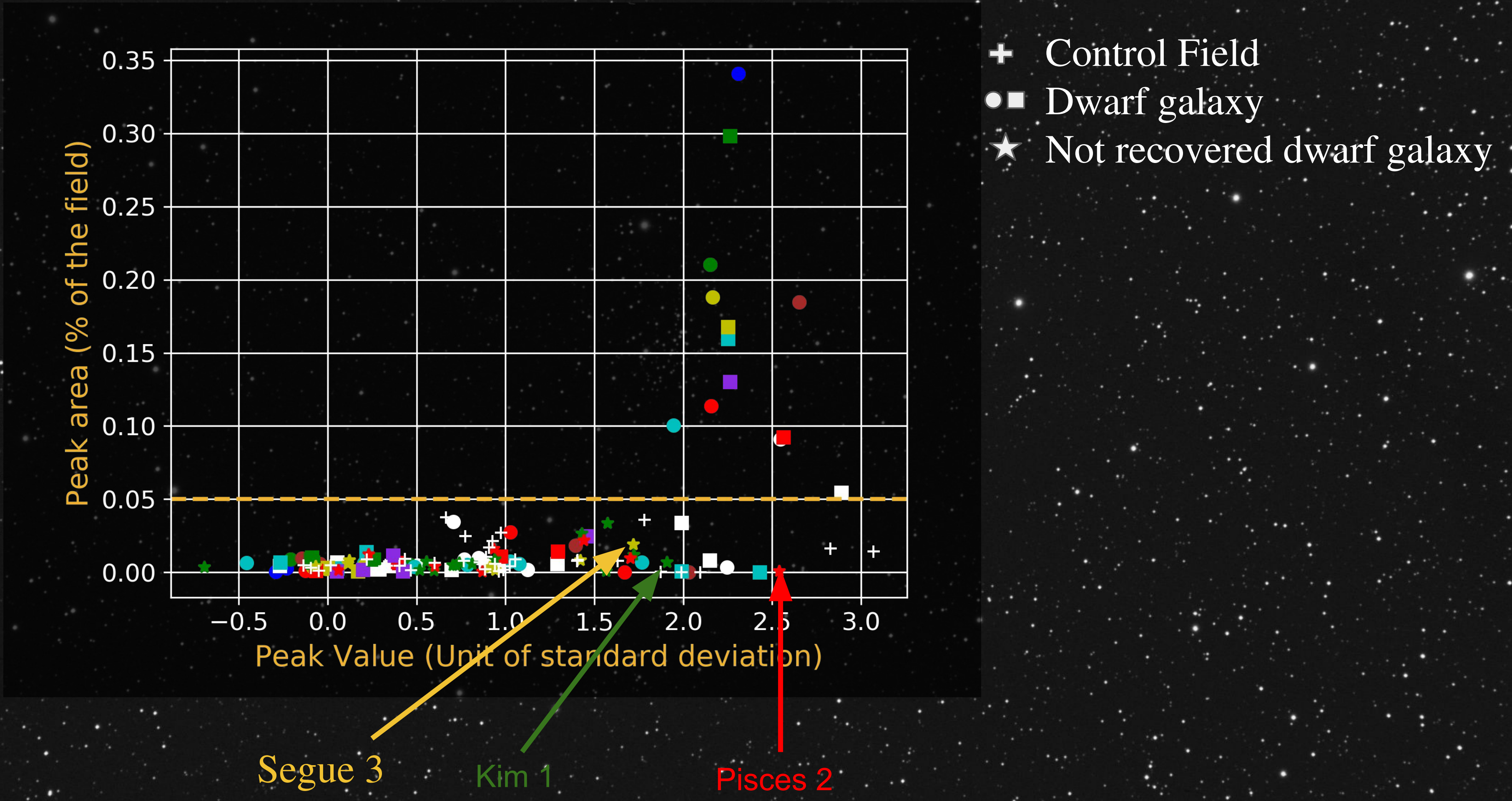
Isochronal Filter Density Map Normalization Characterization





MaGIK Mapping Galaxies using Isochronal Likelihood and KDE

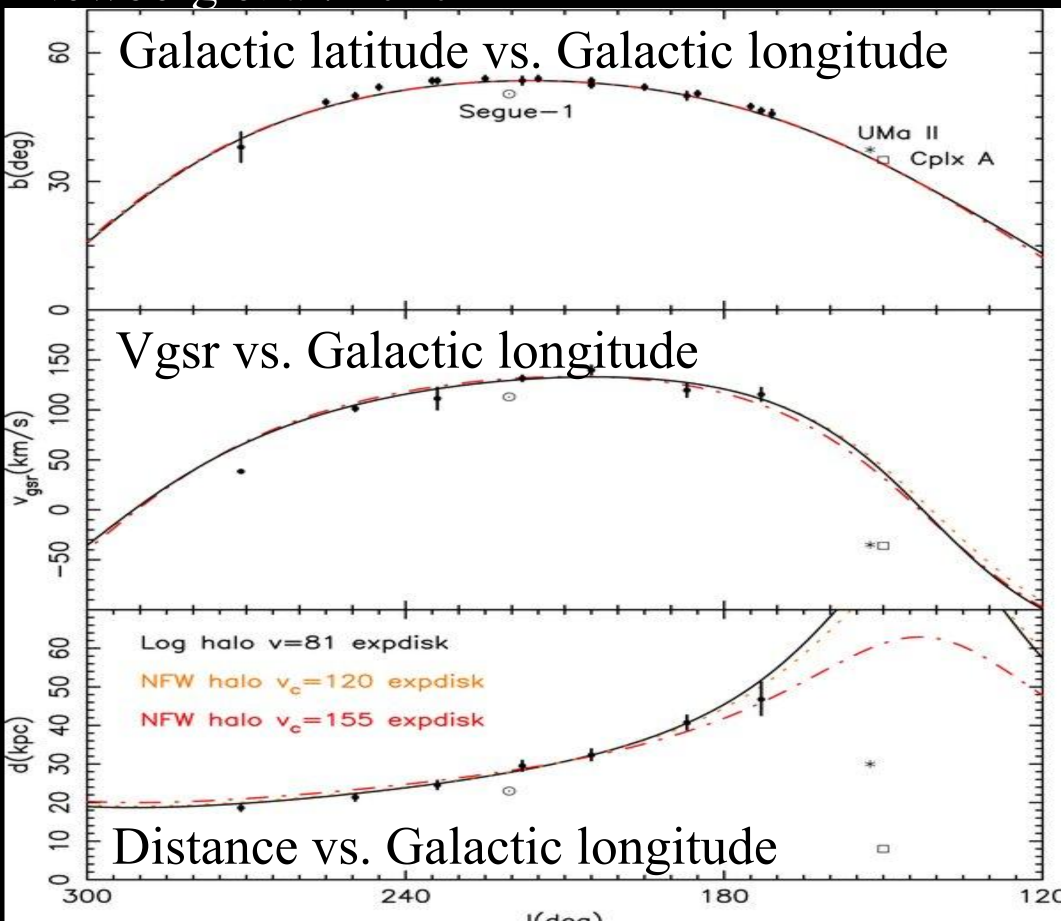
Sample SDSS DR11 (16 dwarf galaxies - recovered 13 dwarf galaxies)



Determining the Properties of Dwarf Galaxy Progenitors from Tidal Streams

Heidi Newberg, Sidd Shelton, Jake Weiss, Matthew Arsenault, Jake Bauer, Travis Desell, Malik Magdon-Ismail, Larry Widrow, Clayton Rayment, Matthew Newby, Jeff Thompson, Benjamin Willett, Adam Susser, Steve Ulin, Joe Souto, Jayshon Adams, …

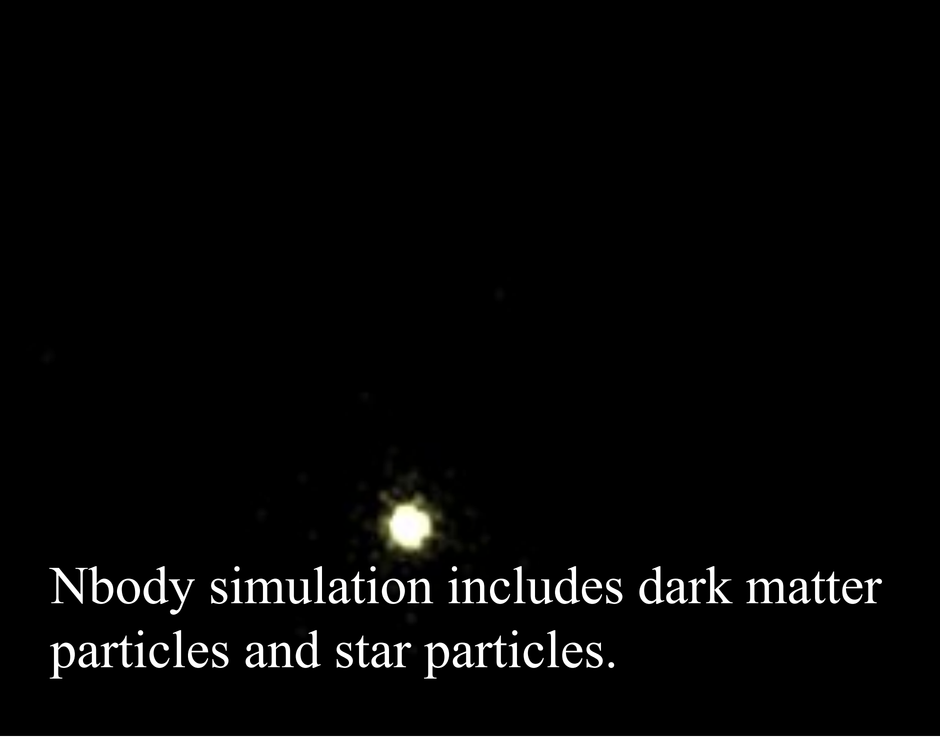
Newberg et al. 2010

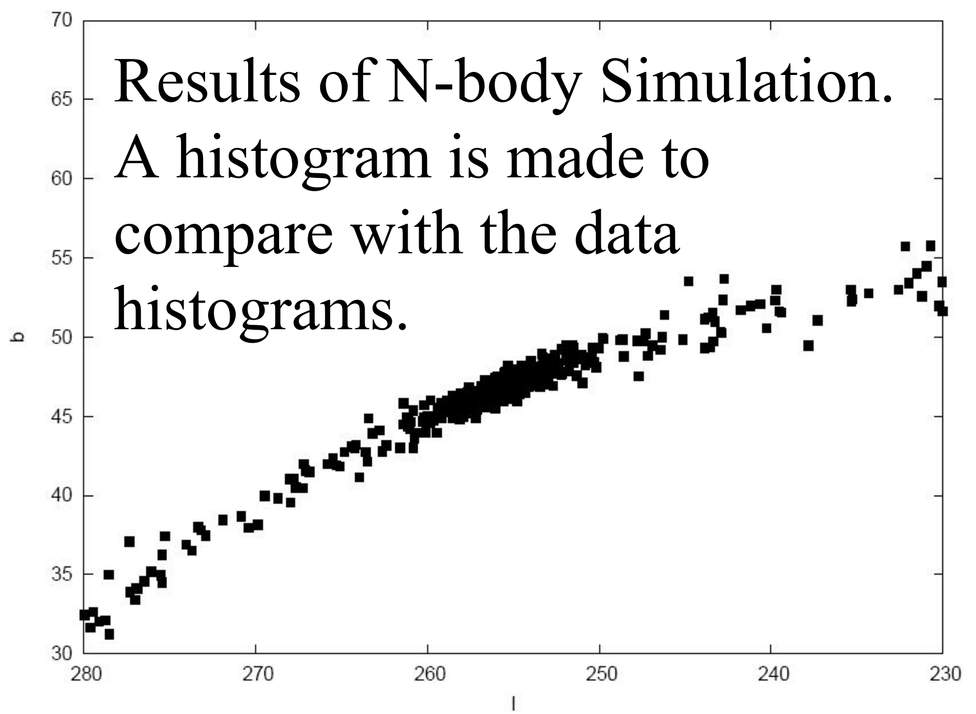


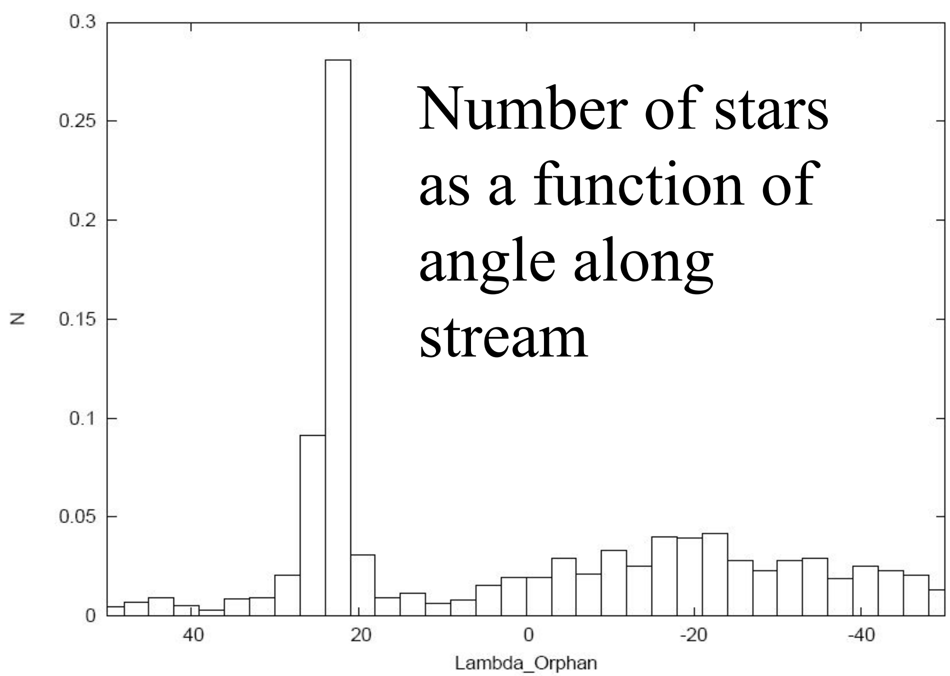
An Orbit Fit to the Orphan Stream

First, assume a reasonable Galactic potential.

The dwarf galaxy orbit can be fit to the angular *position of the stream in the sky* and the average *velocity of the stream stars*, as a function of angle along the stream.







Using the *radial velocity dispersion and density along the stream*, we can determine the mass, radius of the baryons; the mass, radius of the dark matter; and the approximate time the satellite has been disrupting.

If the underlying model is known and the data is high quality, we can *recover the baryon parameters to 10% and the dark matter parameters to less than a factor of a few*.

This requires running many N-body simulations with different parameters to compare with the data, and efficient optimization techniques.

Many tests of sensitivity to the model choices and unknowns need to be done.

9 days running on MW@home; have not yet converged.

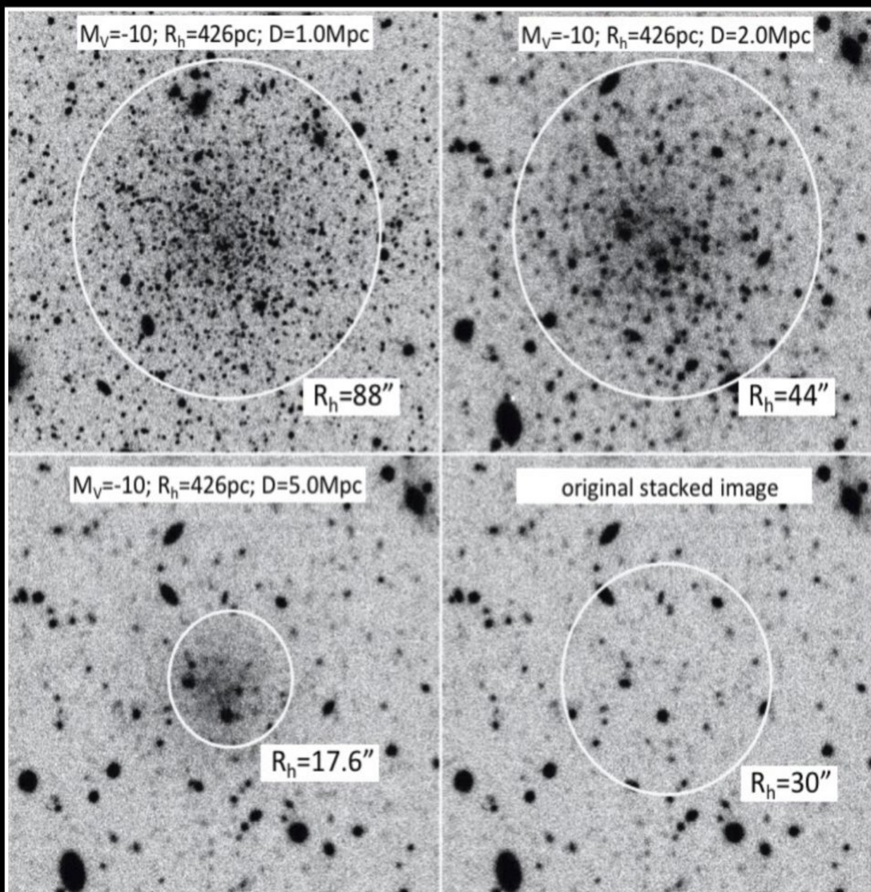
	Search Range	Simulated Value	Particle Swarm
Evolution Time (Gyr)	3-5	3.95	3.96
R_stellar (kpc)	0.1-0.5	0.20	0.21
R_stellar/(R_stellar+R_dark)	0.1-0.5	0.20	0.24
M_stellar(simulation units)	1-50	12.0	12.1
M_stellar/(M_dark_M_stellar)	0 .01-0.95	0.20	0.35

Sidd Shelton

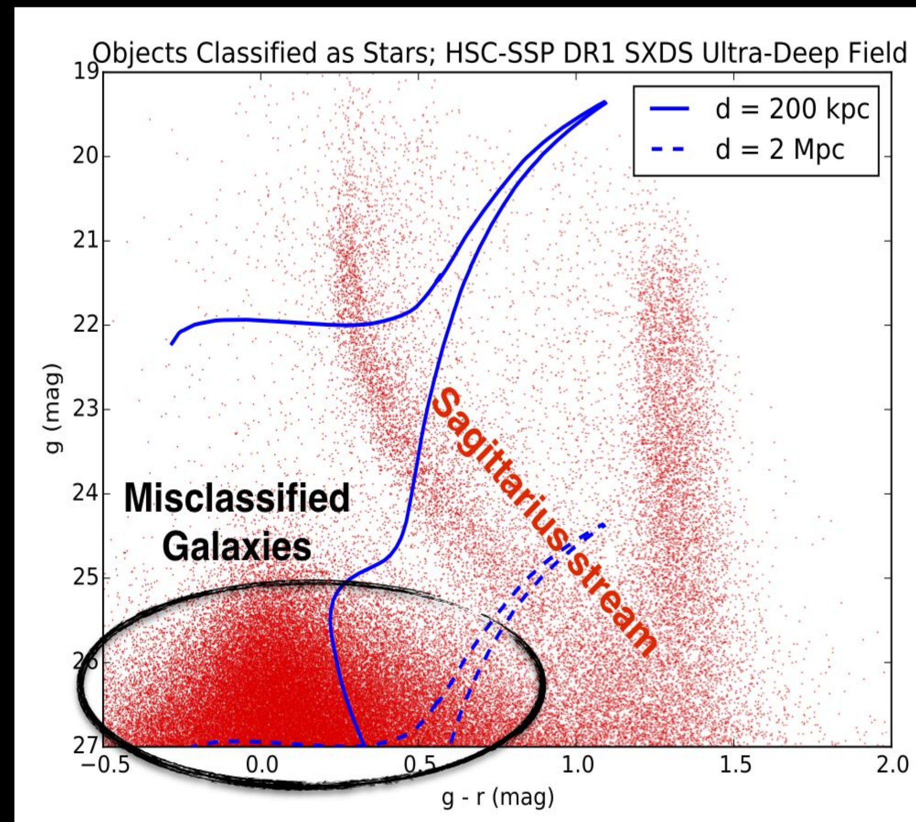
MilkyWay@home

Identifying dwarfs by their diffuse light

Simulations from Beccari et al. 2016



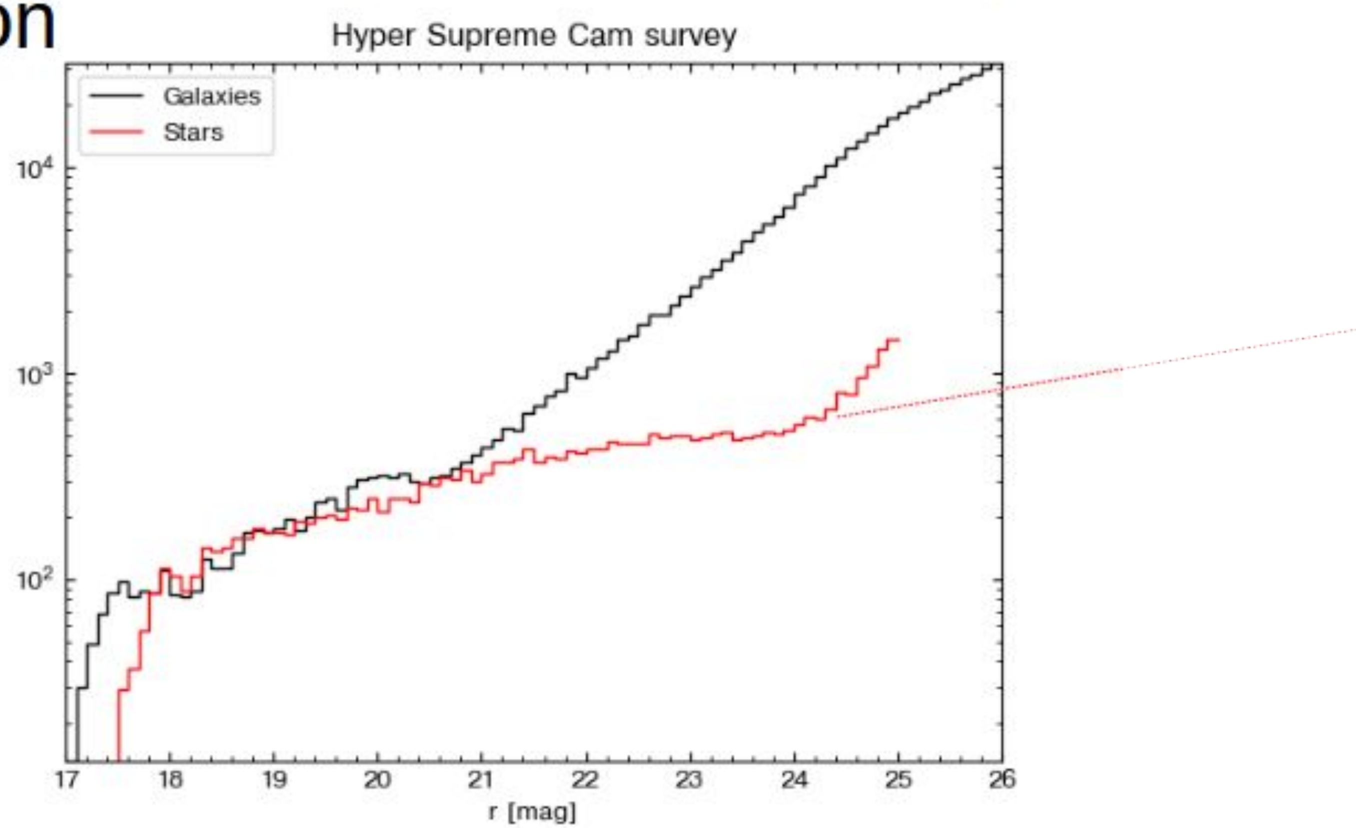
Comparable to LSST Wide-Fast-Deep 10 yr depth (27th mag), 0.6" seeing



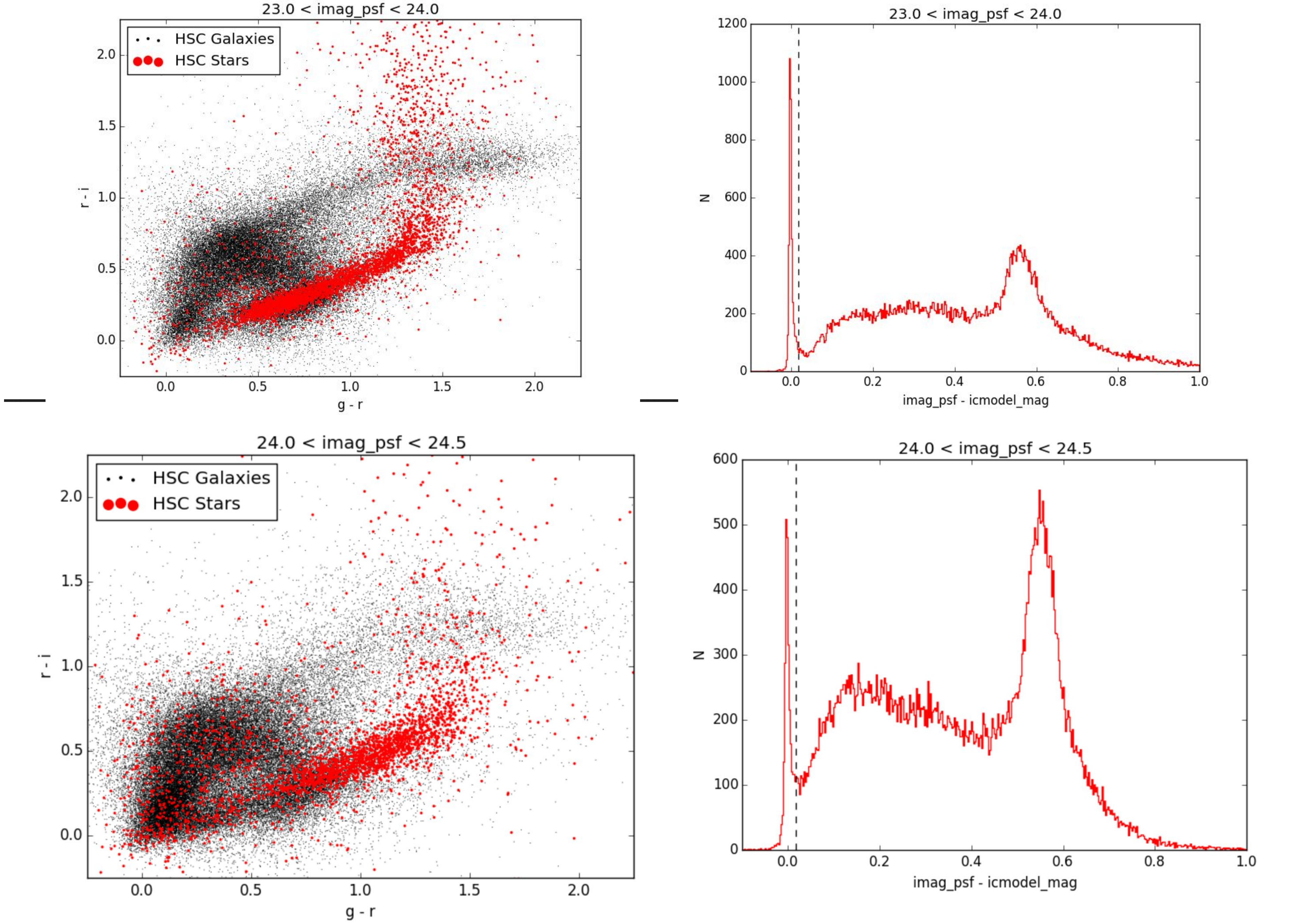
HSC-SSP DR1 SXDS Ultra-Deep Field

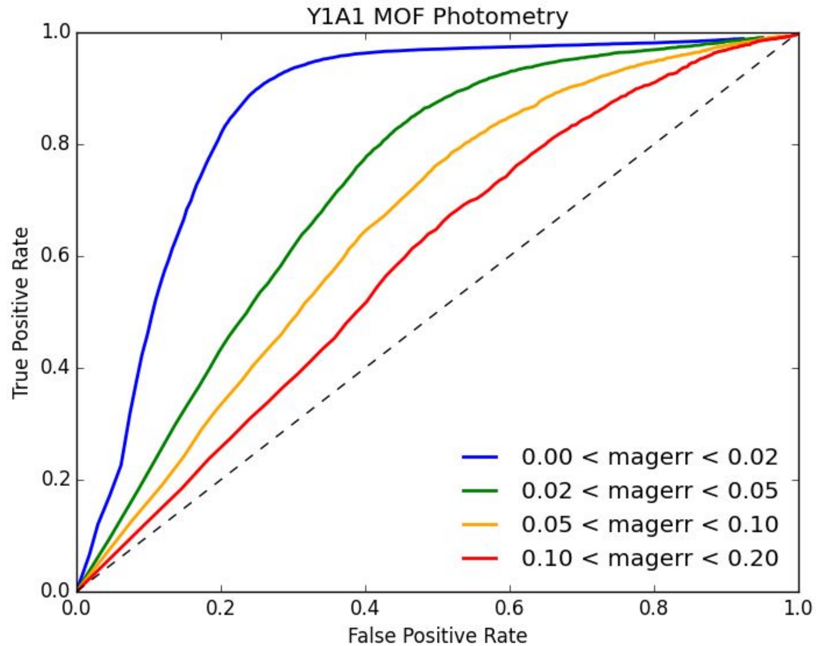
Problems

- Star Galaxy Separation is critical at r>24
- We need efficient (probablistic) star-galaxy separation

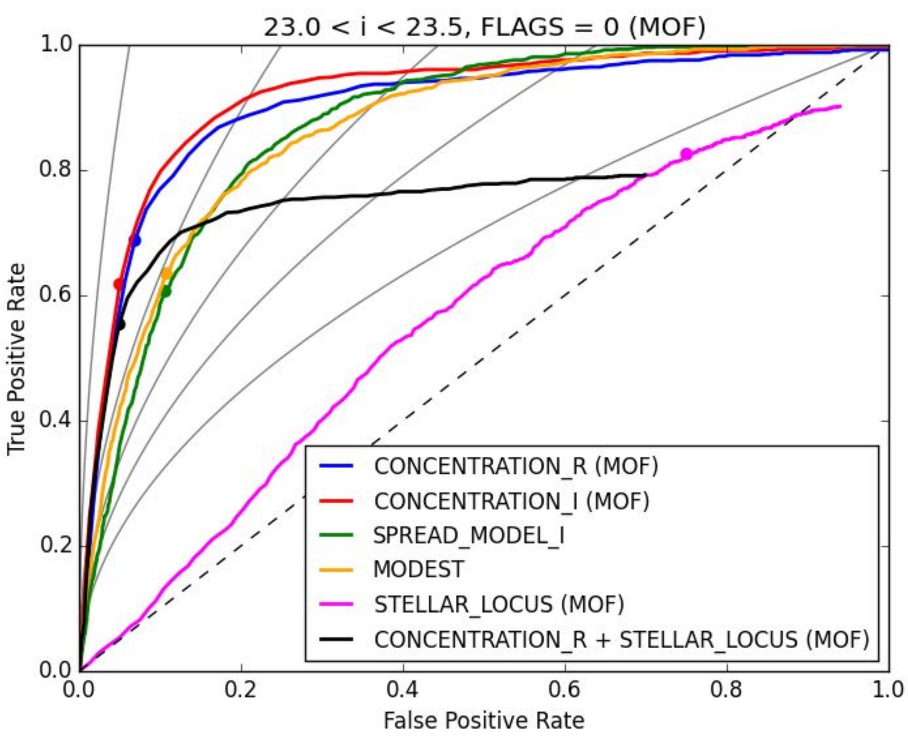


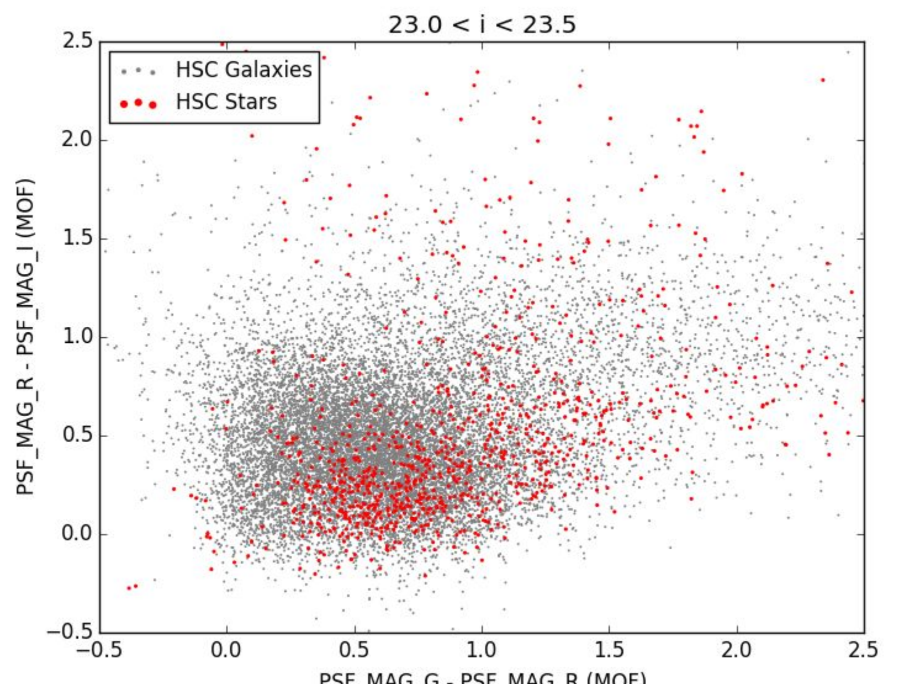
HSC Ultra-Deep Field



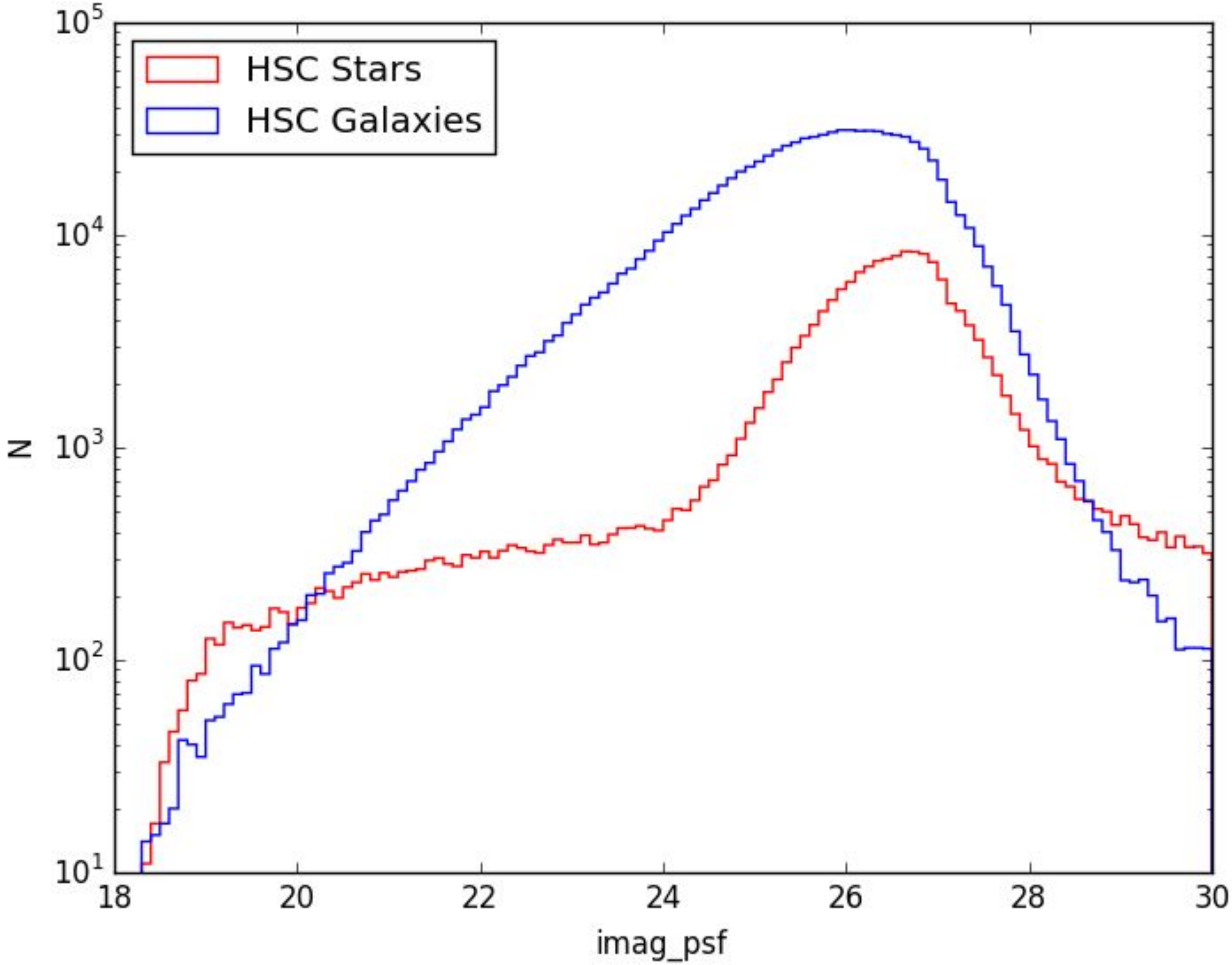


Trying to use color information to improve star-galaxy contamination

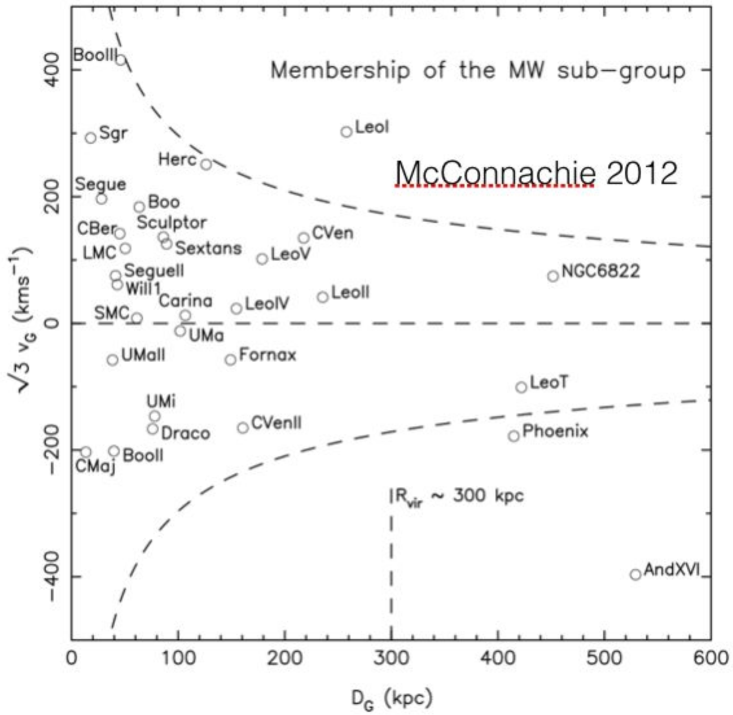




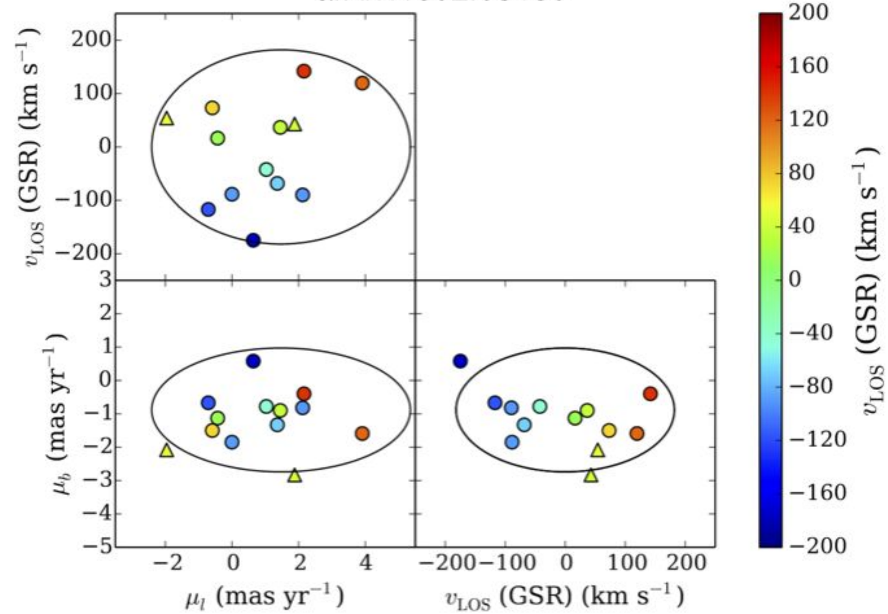
HSC Ultra-Deep Field



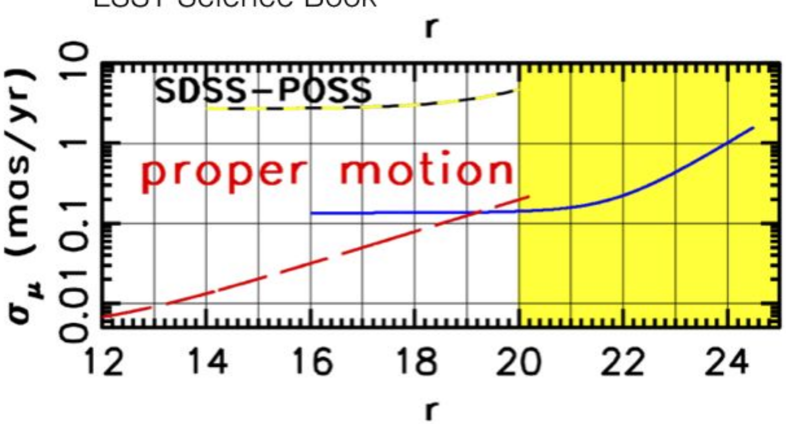
Time Domain: Proper Motions



Cunningham et al. 2016
arXiv:1602.03180



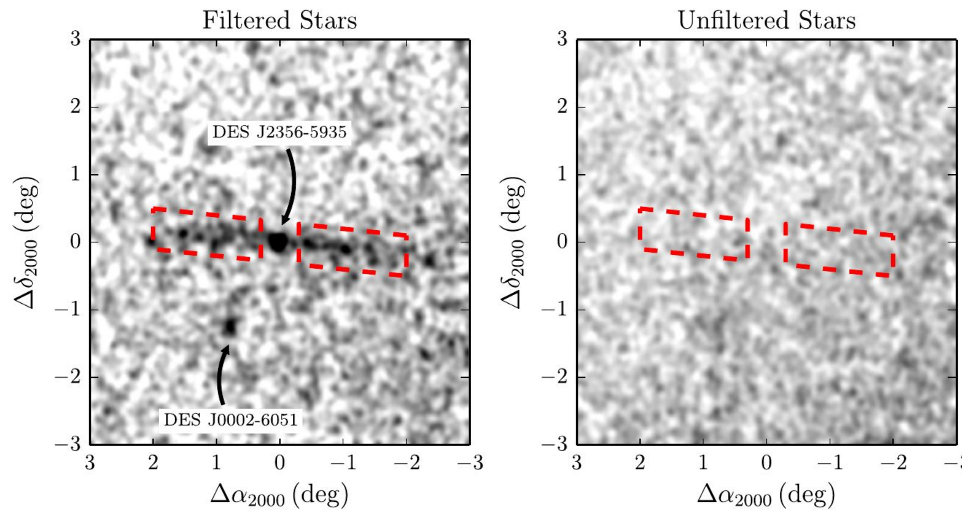
LSST Science Book



First sample of halo stars with measured 3D kinematics outside the solar neighborhood
13 main sequence stars at ~25 kpc

$$\mu\ [\text{mas yr}^{-1}] = 0.21\ v_t\ [\text{km s}^{-1}]\ /\ d\ [\text{kpc}]$$

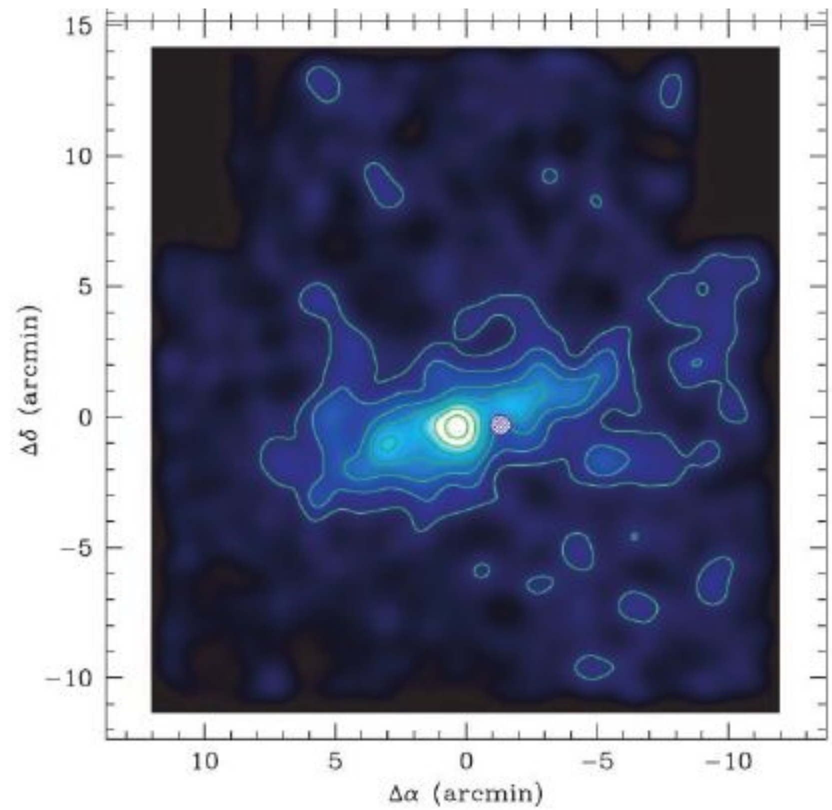
Dwarfs are not circular !



Most algorithms look for circular things

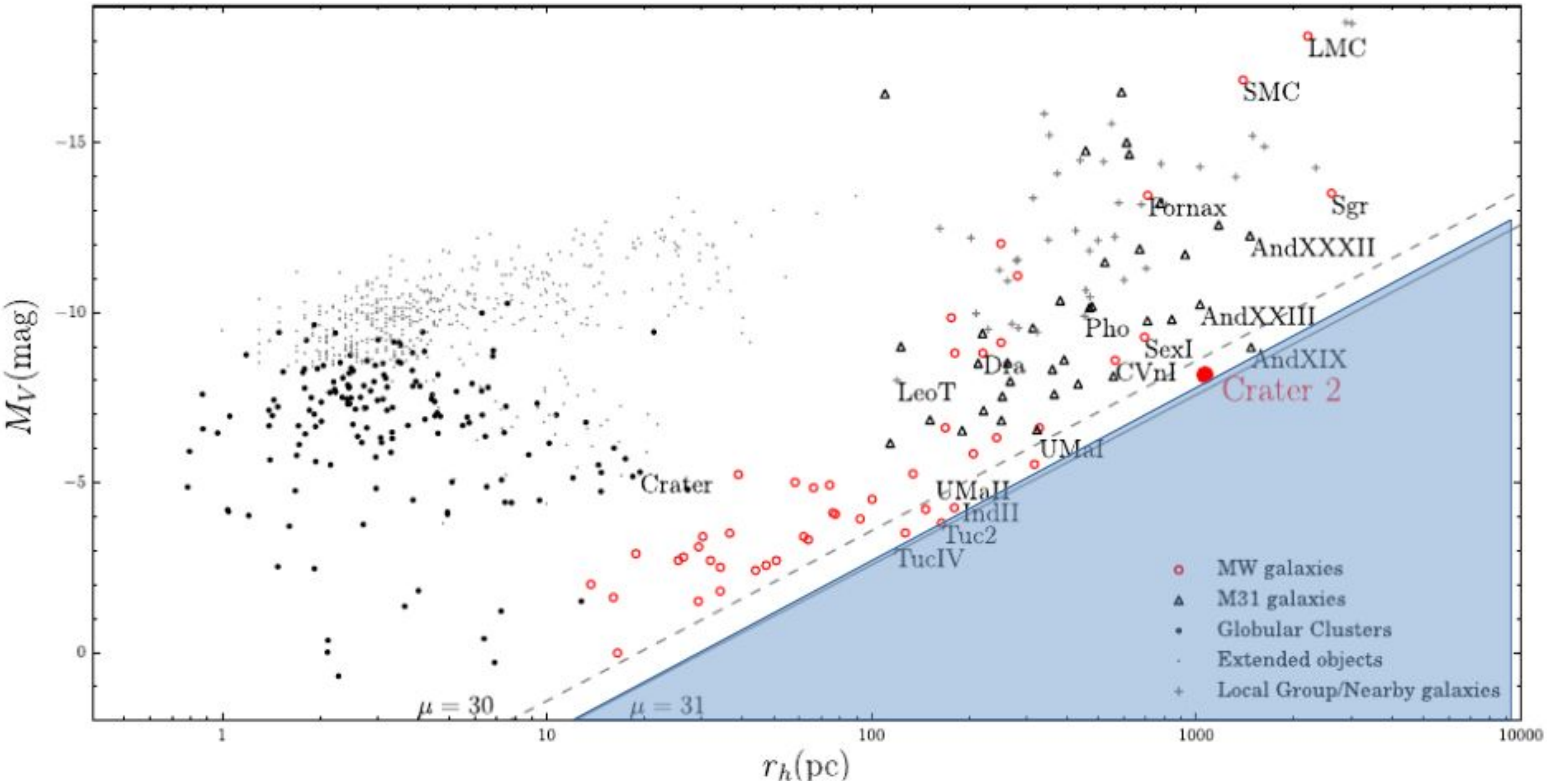
Do we need to run special searches for very elongated objects?

Streams/dwarfs is there boundary ?



Surface brightness limit

We seem to hit the surface brightness limit of 31 ?
Is it a physical limit ?
How do push beyond it ?



Multi tracer searches

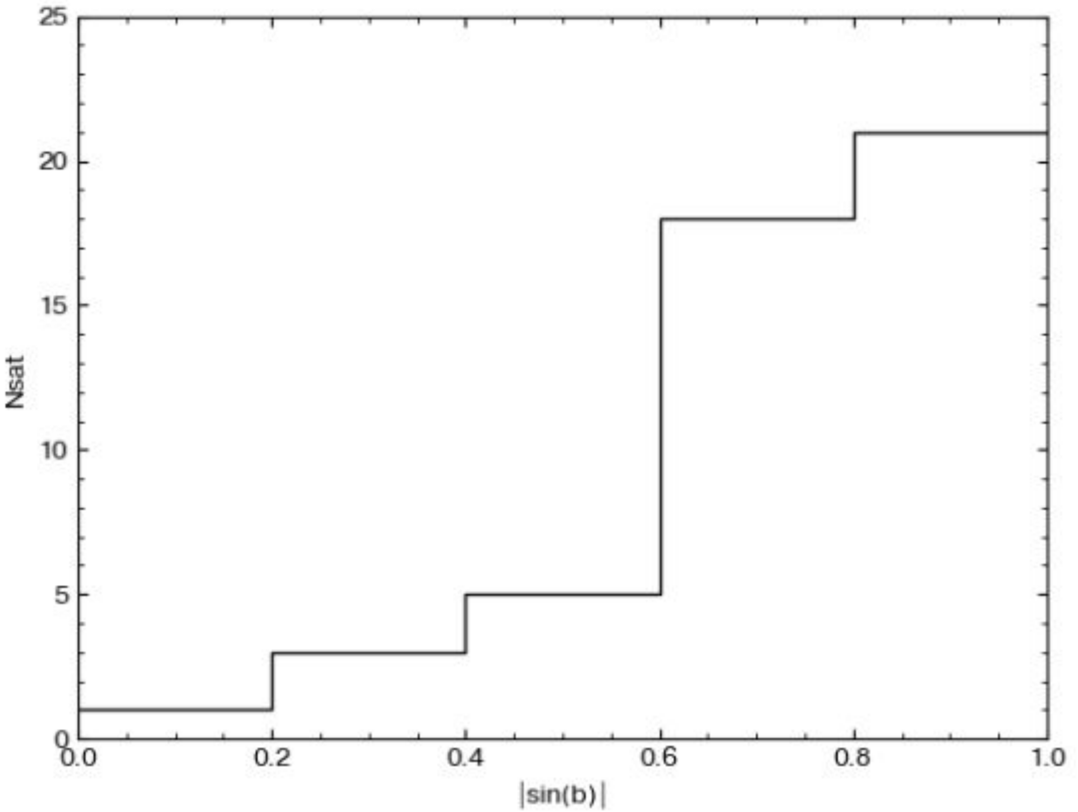
- RR-Lyrae
- Blue Horizontal Branch stars
- Carbon stars
- Metal poor stars
- Problems: very rare tracers

Large number of candidates

- How to deal with them ?
- Machine Learning ?
- Which ones to observe ?
- Finite amount of observing time
- Can we do stacking of dwarf candicates ?

Galactic plane searches

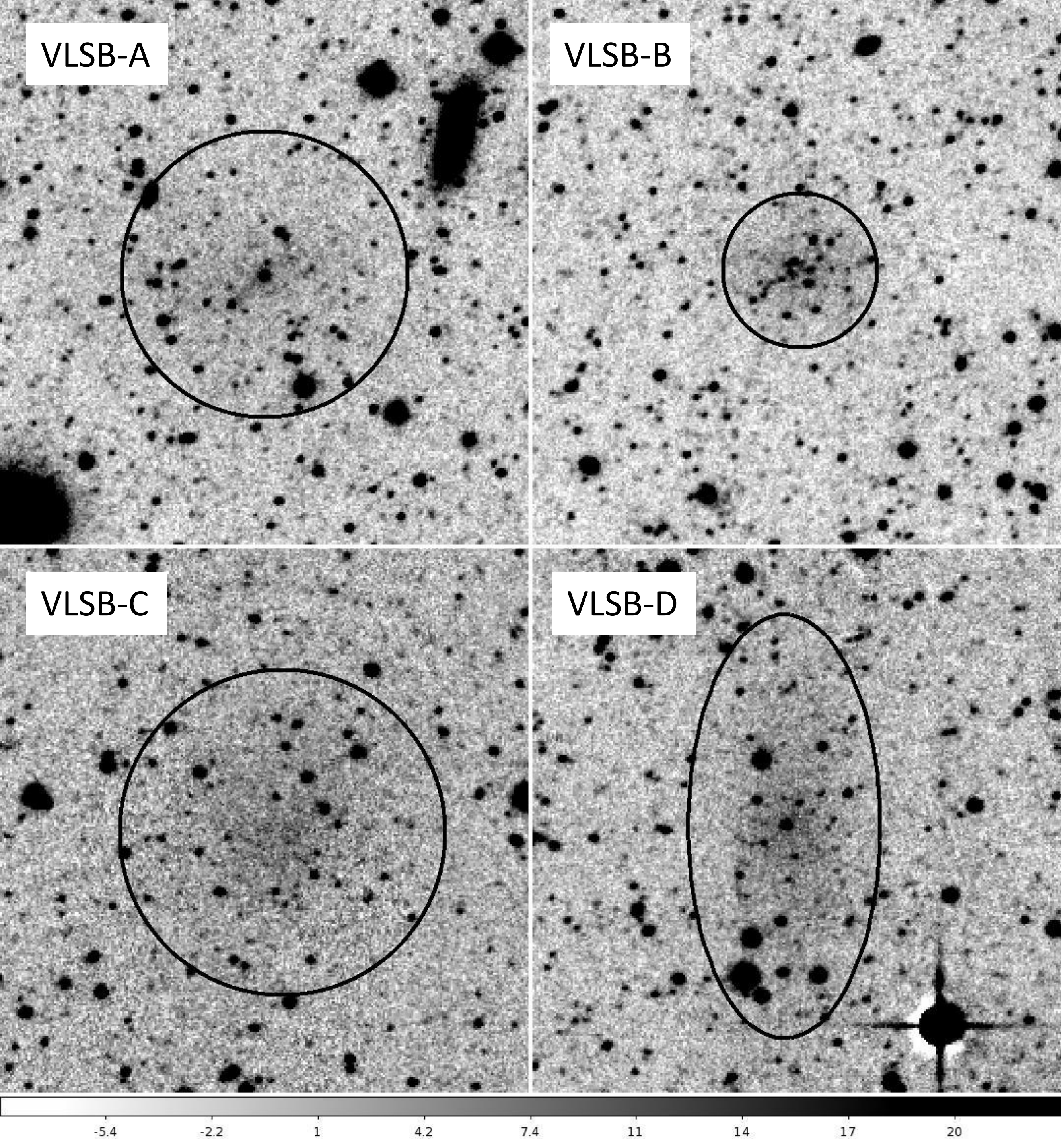
- We are still heavily incomplete
- Do we need to go there ?



Session 6: Pixel-based search techniques

Pixel-based Searches: Hunting Diffuse Galaxies

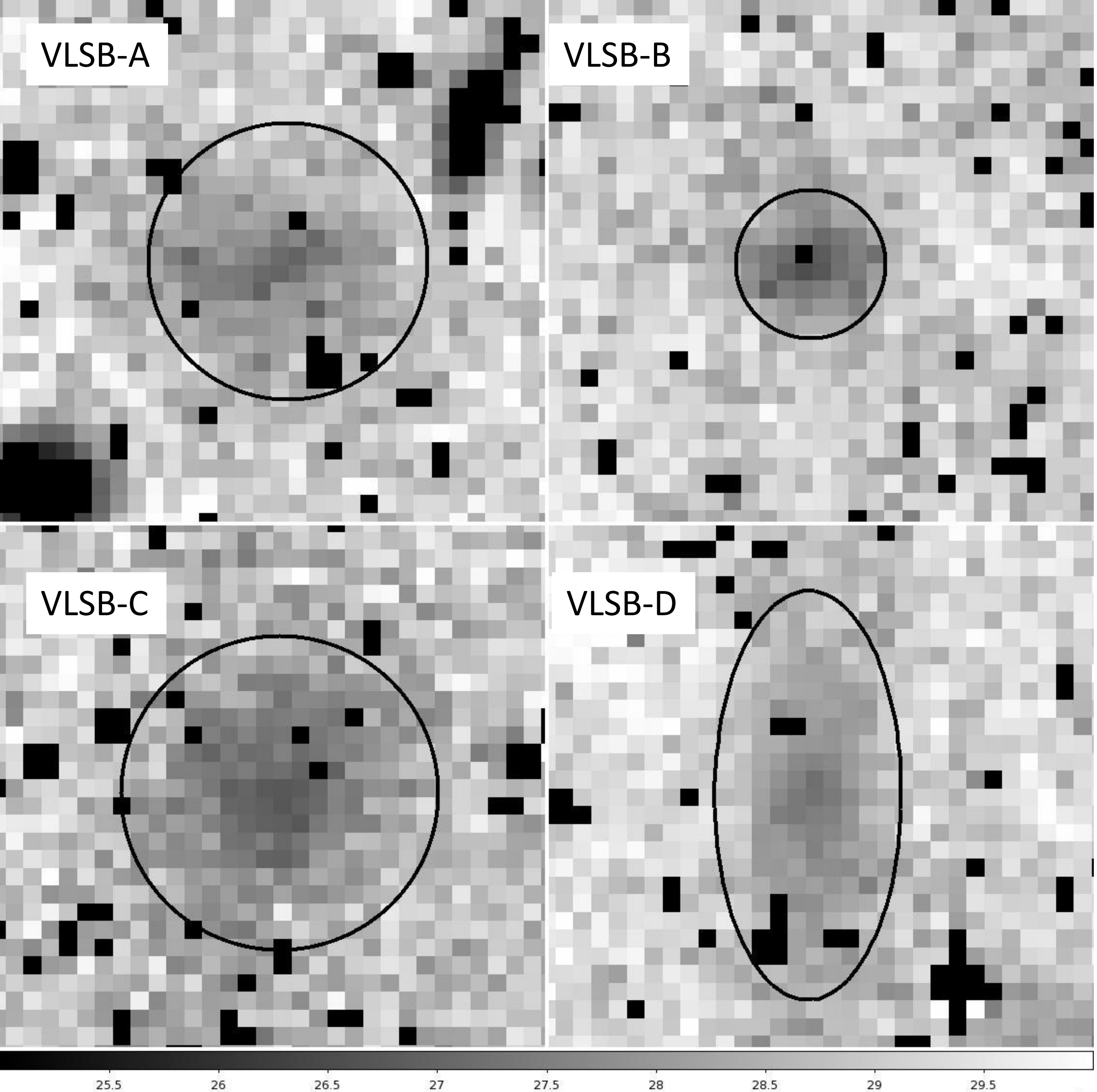
Chris Mihos, Case Western Reserve University



Virgo UDGs
Mihos+ 15, 17

$\mu_{V,0} \sim 27$
$R_{29} \sim 1\text{-}2'$

Schmidt



Virgo UDGs
Mihos+ 15, 17

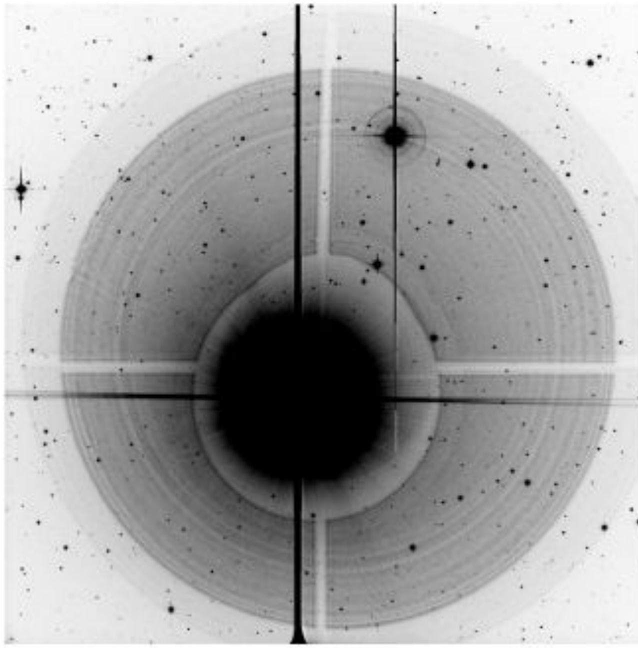
$\mu_{V,0} \sim 27$
$R_{29} \sim 1\text{-}2'$

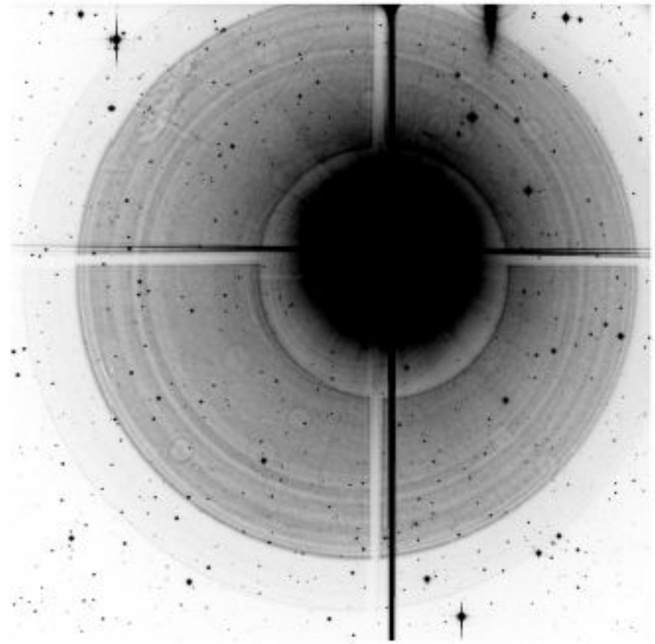
Schmidt Masked/Binned

How do we process data for deep imaging?

Chris Mihos, Case Western Reserve University

All stars imprint reflections onto the image, which move with respect to the optical axis.





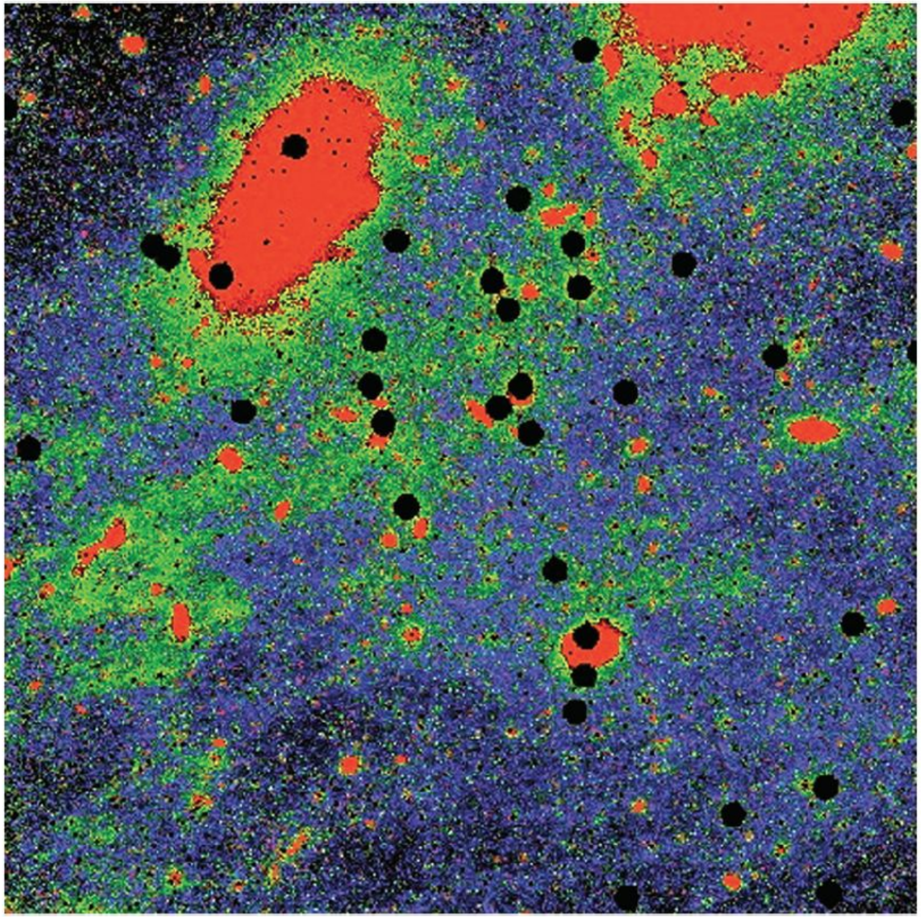
CWRU Burrell Schmidt: Arcturus 15 min

Reflection intensity can also be spatially dependent (think: CCD mosaic).

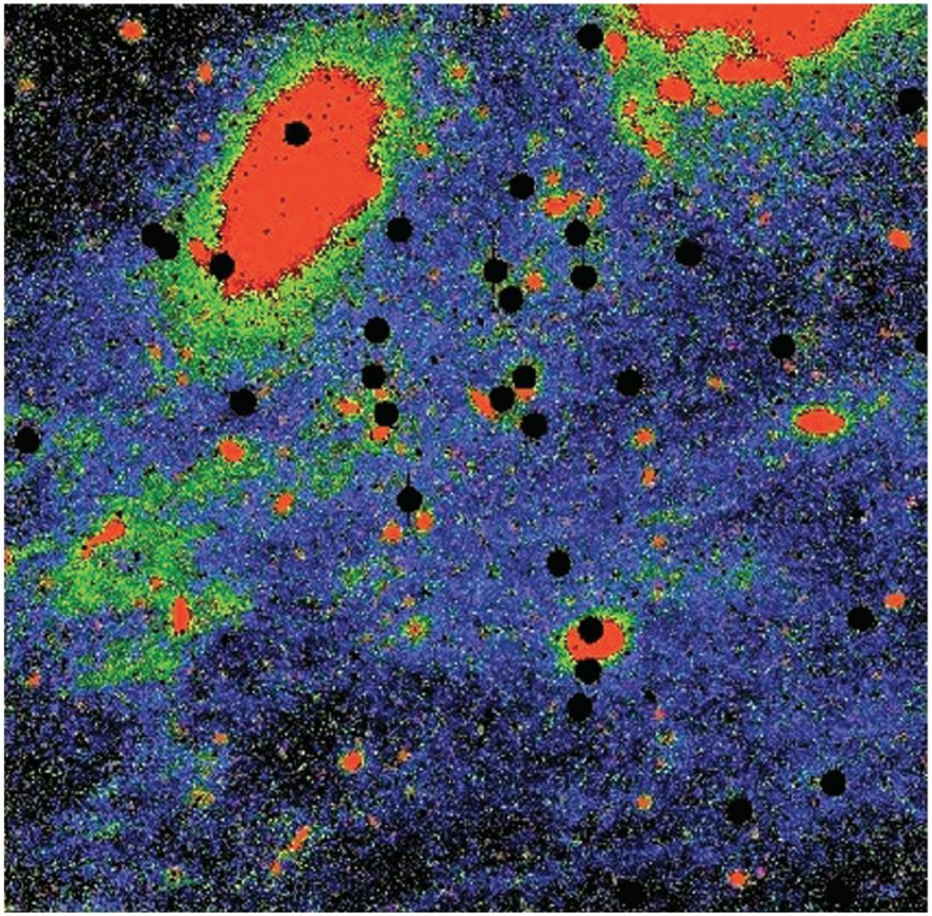
Reflections and scattered light need to be calibrated, modeled, and removed on **individual** exposures **before** co-adding.

Slater+ 09

No reflection subtraction



With reflection subtraction

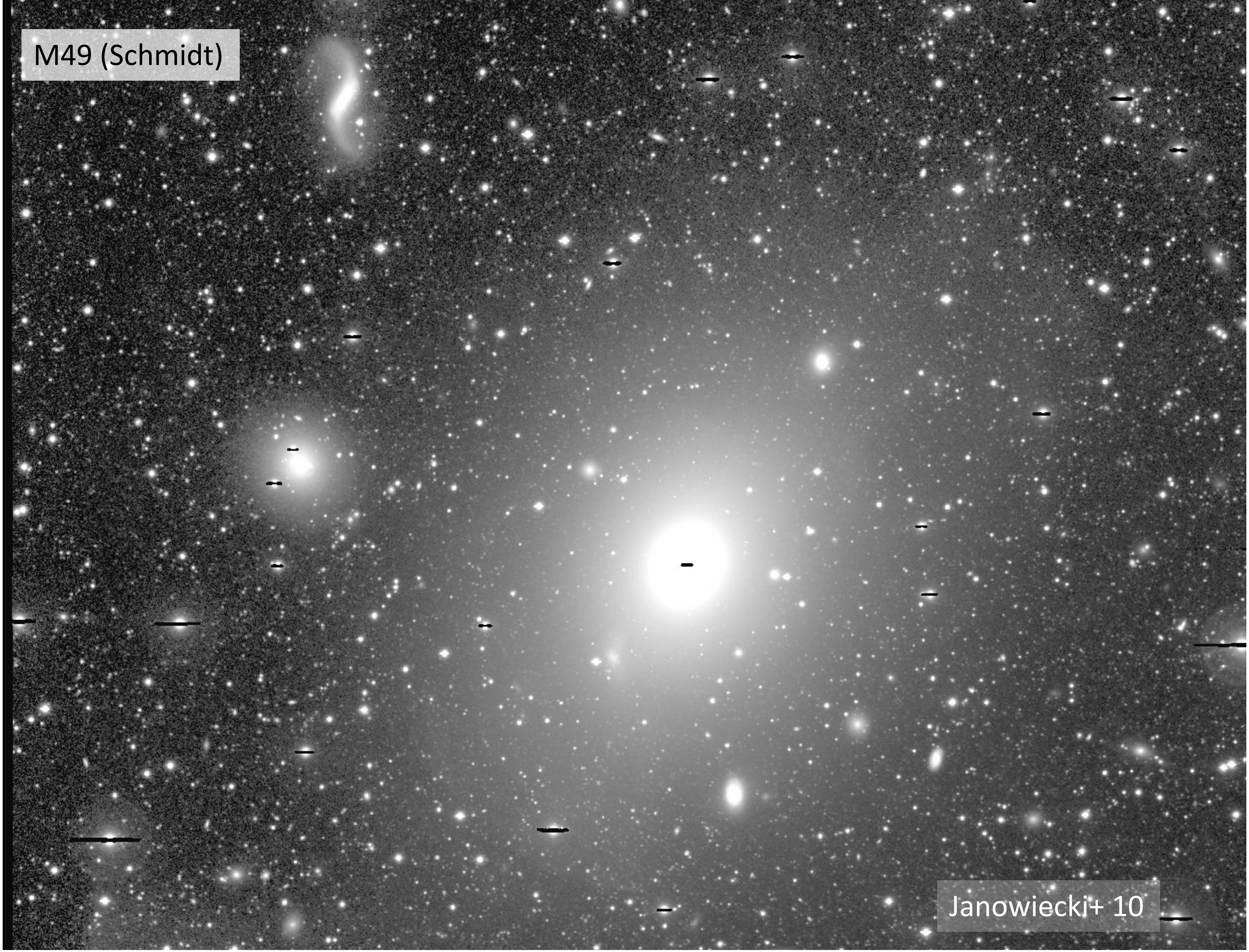


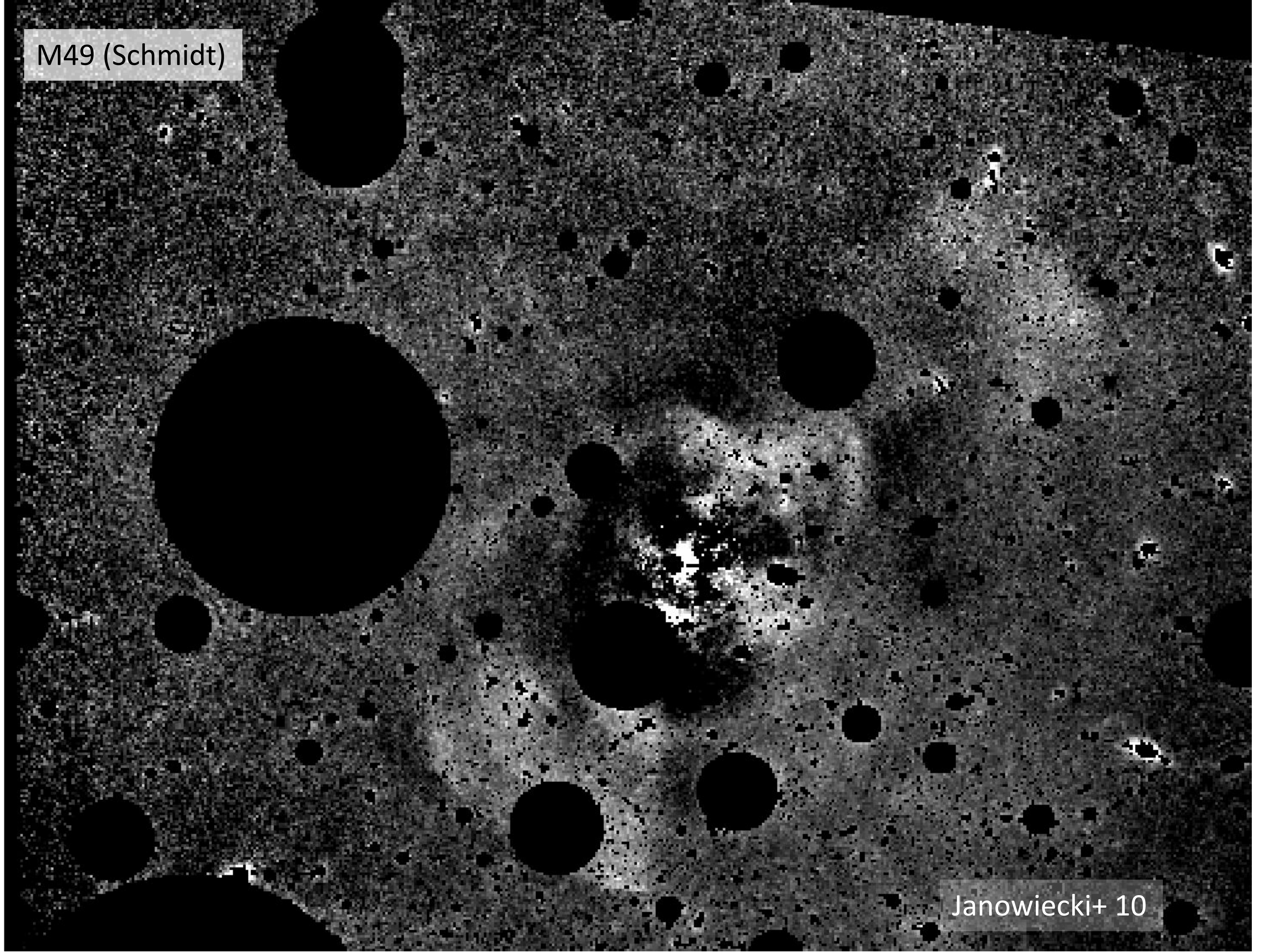
$\mu_V < 27$

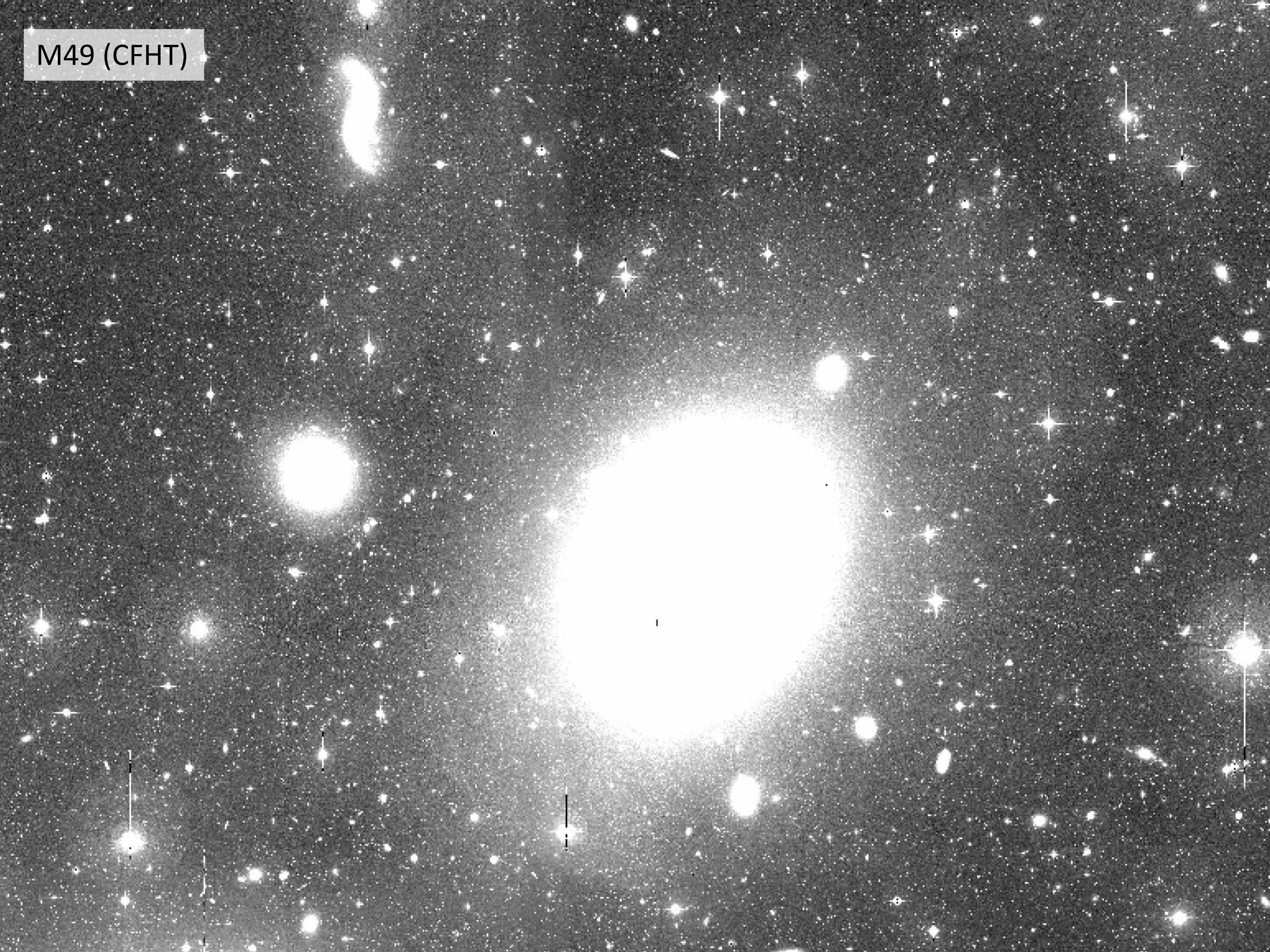
$27 < \mu_V < 28$

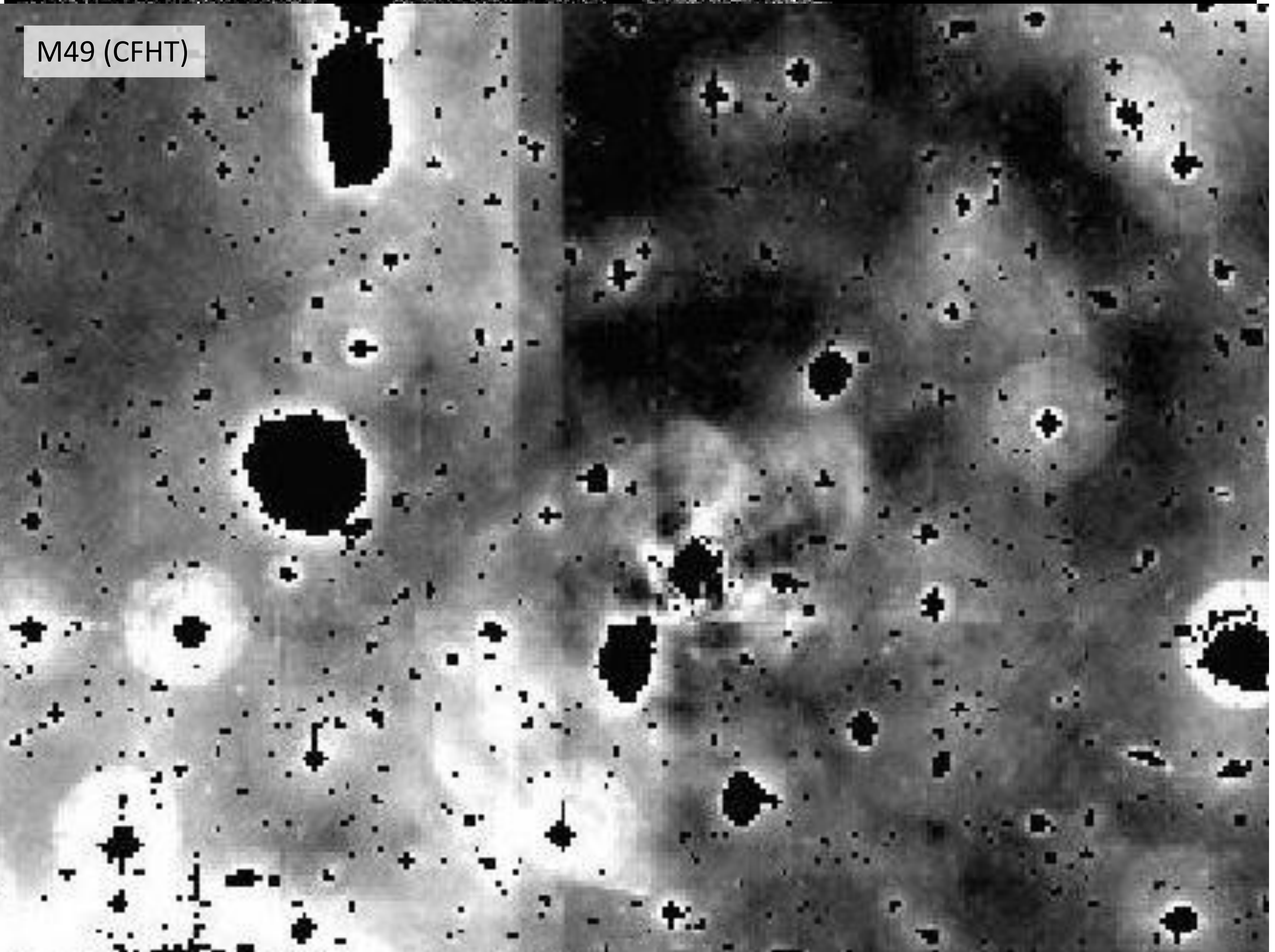
$\mu_V > 27$

Slater+ 09


M49 (Schmidt)
Janowiecki+ 10

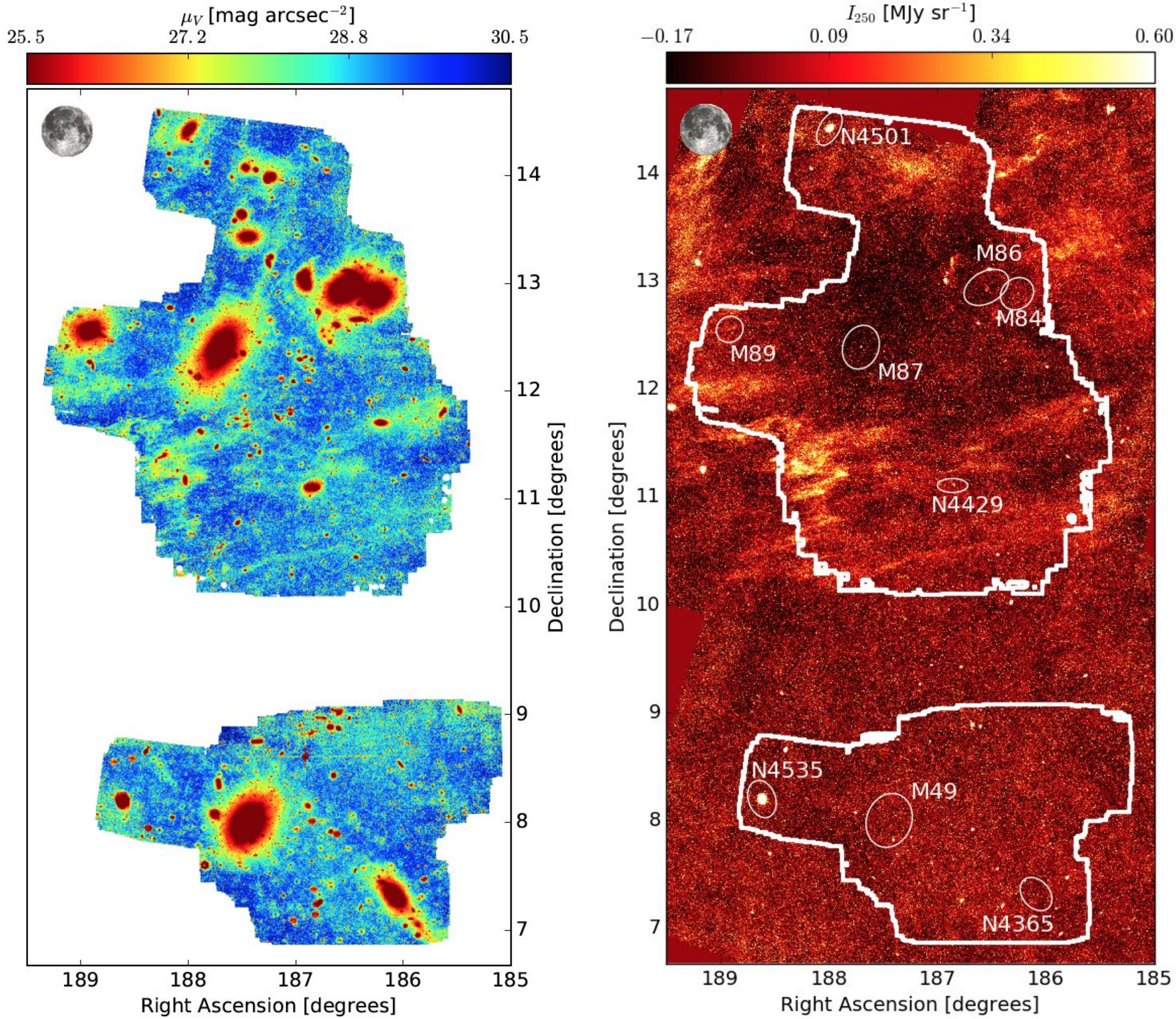

M49 (Schmidt)
Janowiecki+ 10


M49 (CFHT)


M49 (CFHT)

Diffuse Contamination: Galactic Cirrus

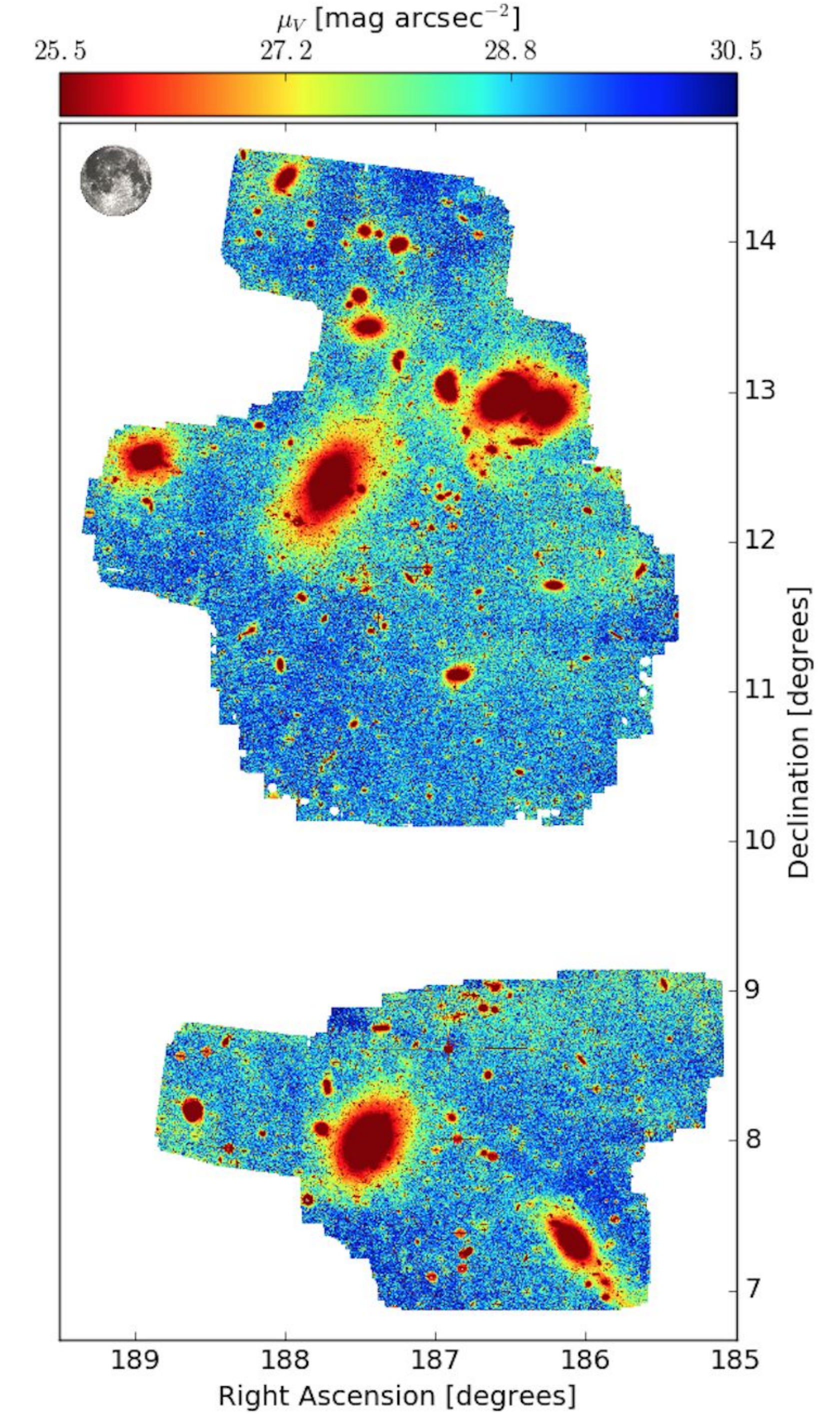
Chris Mihos, Case Western Reserve University

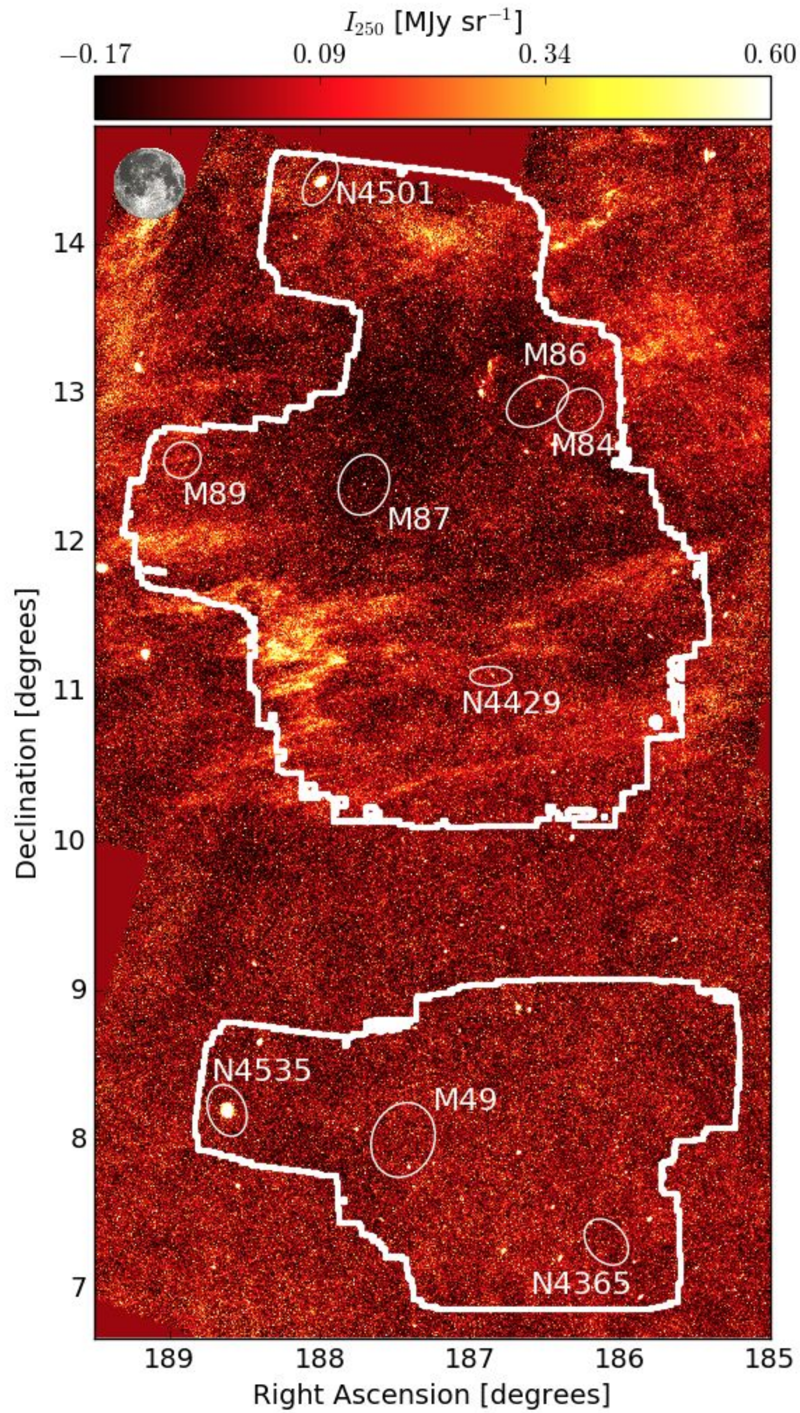


Virgo Cluster

V vs 250μ

Mihos+ 17

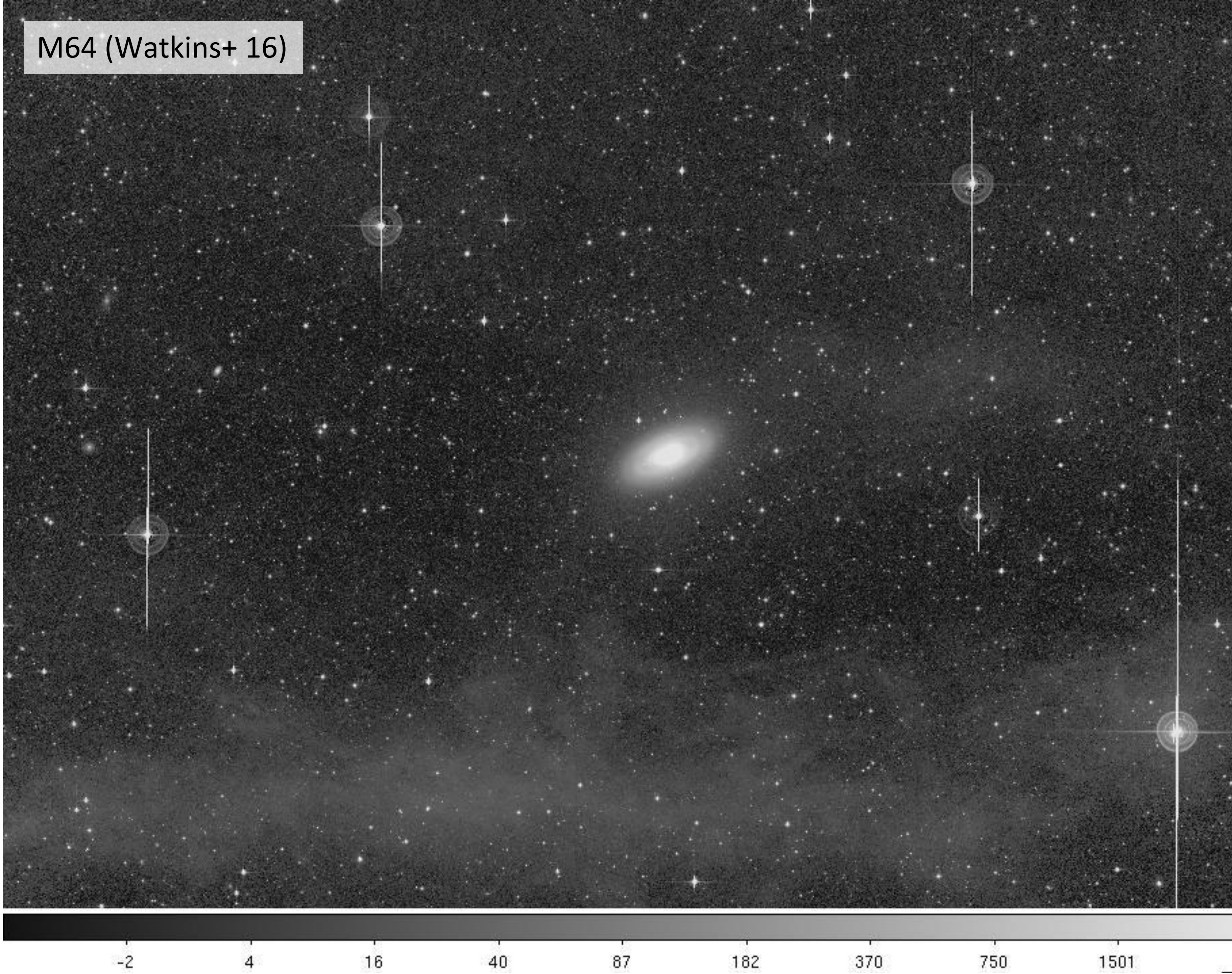




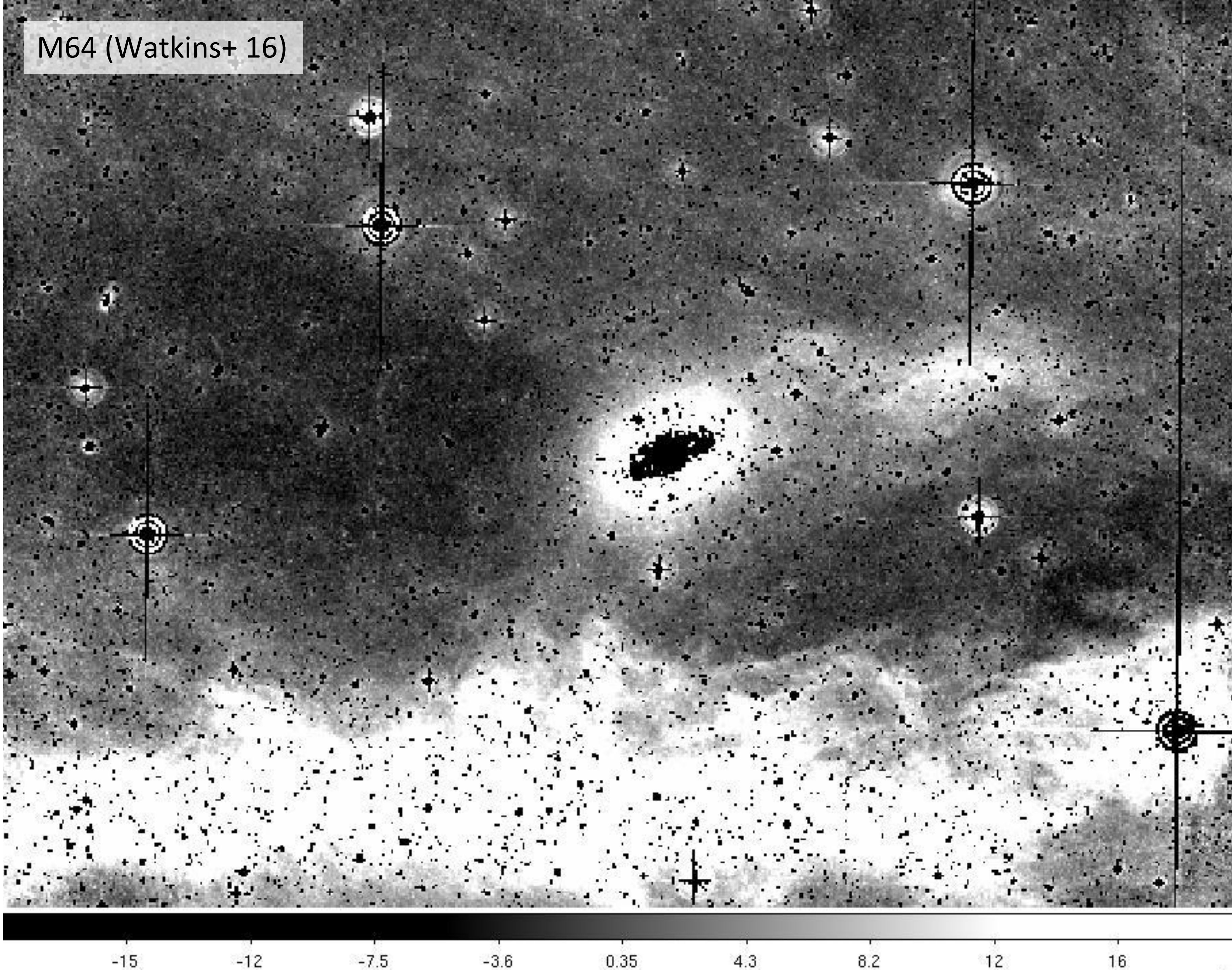
Virgo Cluster

V vs 250μ

Mihos+ 17

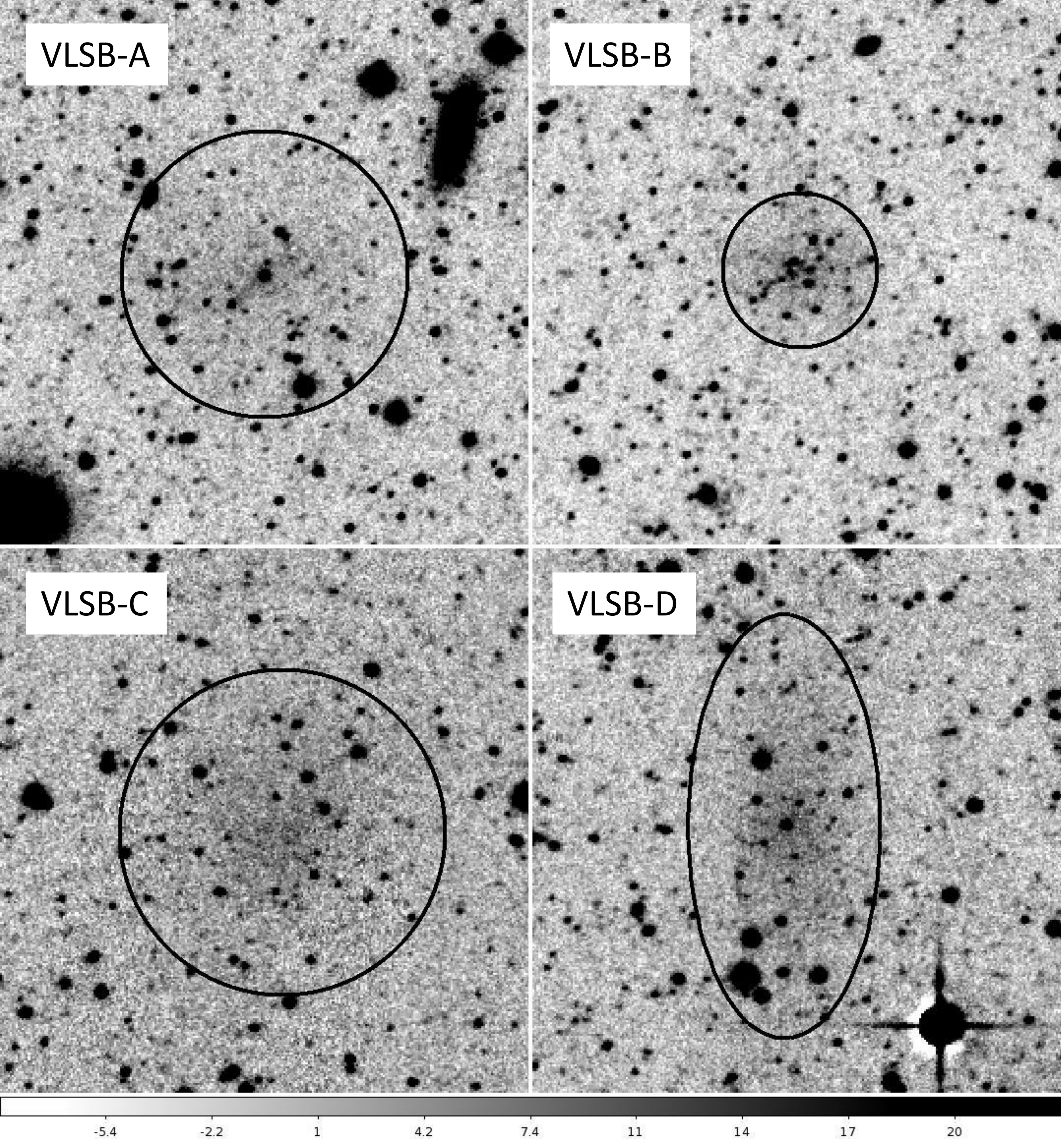


M64 (Watkins+ 16)
-2
4
16
40
87
182
370
750
1501


M64 (Watkins+ 16)
-15
-12
-7.5
-3.6
0.35
4.3
8.2
12
16

How do we detect *and define* extreme objects?

Chris Mihos, Case Western Reserve University



Virgo UDGs
Mihos+ 15, 17

Schmidt

Summary

Pixel-based search techniques

- Pixel-based analysis can be applied to targets that are too distant for analysis of resolved stellar populations
- Method relies on high quality data from telescope-instrument designed for control of extended scattered light (eg., PSF halos and reflections).
- Survey requires observing patterns (large dithers) and calibration data that support detection, modeling, and suppression of PSF halo
- Analysis requires access to individual image frames
- Method employs source-subtraction, typically of all detected sources, background and foreground
  - Apply to individual images
  - May suppress compact sources associated with galaxies, biasing the measured magnitudes and colors.
  - Value of combined pixel and catalog approaches
  - Stack images after scattered light correction

Session 7: Beyond the Milky Way

Session 7: Beyond the Milky Way - summary

Techniques:

- HI all-sky surveys
- Faint fuzzies
- Resolved star RGB maps

Issues:

- Detection & struct. parameters for partially resolved dwarfs
- Distance estimates for un-/partially-resolved objects
- Follow-up?
- (test both the above, plus completeness, by injecting artificial dwarfs)
- Predictions are easier to make for a galaxy of a given size, rather than a certain volume

Questions addressed:

- Lumin./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 funct. of ~SMC-mass systems

Session 8: Dwarf galaxy problems

LSST will gives us

- Depth
  Detection of dwarfs about the MW, Local Volume & out to 100 Mpc
- Variable Stars
  Distances through RRLyr
- Proper Motions
  Internal motion and orbits around the MW
- Wide field
  Volumes probed, field vs. groups/clusters

Theoretical interests

- Number and distribution of dwarfs about MW/MW analogues within 100 Mpc
- Tidal effects
  Streams, morphological evolution
- Quenching of low-mass galaxies
  Role of environment
- Dark Matter Halos
  Mass/structure/kinematics
- Hierarchical Evolution
  Dwarf groups in the field & infall on massive hosts

Dwarf Galaxy Problems - Summary:

Main theoretical interests:

1. Number and distribution of dwarfs (Missing satellite problem)
2. Tidal Effects: streams, warps etc.
3. Quenching
4. DM halos: Mass, structure and kinematics
5. Hierarchical Evolution: Group infall, dwarf groups.

Low mass dwarfs : $M_\star < 10^5 M_\odot$
$M_h < 10^9 M_\odot$

1. LSST: Satellite population of the MW at Rvir > r > 100 kpc. Theory: New predictions from Hydrodynamic cosmological simulations of MW-like galaxies.
2. LSST: Observe the outskirts of these satellites - any signs of tidal stripping. Theory: How do these galaxies survive given the tidal field of the MW.
3. LSST : Resolved CMDs - any recent star formation? Theory: What fraction of these satellites are expected to be quenched?
4. LSST: ?? spectra .. Theory: push predictions of the velocity field of the stars.
5. LSST: Radial distribution of satellites - any clustering around the Clouds? Theory: Group infall of LMC + satellites

Classical Dwarfs: $10^5\,M_\odot < M_\star < 10^8\,M_\odot$
$10^9 M_\odot < M_h <\sim 10^{10} M_\odot$

1. LSST: # in outskirts of local group
2. LSST: Stellar streams in the outer halo (apocenters, may help find radial streams). Stream structure: width, density variations. Stellar outskirts of known dwarfs. Theory: Expected stream frequency at large radii given the merger history of the MW.
3. LSST: Detecting “splashback” galaxies (quenched at large distance from MW), Quenched fraction as a function of environment.
4. LSST: Density profiles using GCs. Theory: push predictions of the velocity field/density profile of the stars.
5. LSST: searching for companions around massive dwarfs.

Bright Dwarfs: $1\text{x}10^8\, M_\odot < M_\star < 5\text{x}\, 10^9\, M_\odot$
$\sim 10^{10}\, M_\odot < M_h < 3\text{x}10^{11} M_\odot$

1. LSST: Finding a complete sample of SMCs in the Local Volume/beyond
2. LSST: Cepheids / RRLyrae ages, extent of stellar disks & perturbations in the outskirts
3. LSST: Quenched fraction. Theory: Expected Quenched fraction at LMC mass scale in the field?
4. LSST: Extended old stellar populations. Theory: What causes the extended population in these dwarfs (Feedback, companions, angular momentum - core/cusp formation peaks at this mass), $M_\star$ or Mbar Mhalo relation.
5. LSST & Theory: Does the major merger sequence proceed in the same way at this mass scale. Luminosity function of satellites in LMC type hosts (5Mpc-8Mpc). Two point correlation statistics. Stellar halos.

Session 9: Unconference #1

No slides for the unconference - it was strictly discussion

Session 10: On-going and future surveys

Follow-up Strategies and Needs

Maximizing Science in the Era of LSST:
A Community-Based Study of Needed US OIR Capabilities

THE KAVLI FOUNDATION A report on the Kavli Futures Symposium organized by NOAO and LSST NOAO LSST

Chapter 3: Mapping Galaxies to Dark Matter Halos

Probing Galaxy Formation and the Nature of Dark Matter and Gravity in the Local Group

Joshua D. Simon (Carnegie Observatories), Douglas P. Finkbeiner (Harvard University), Eric F. Bell (University of Michigan), Alex Drlica-Wagner (Fermilab), Puragra Guhathakurta (University of California, Santa Cruz), Kathryn V. Johnston (Columbia University), Ting S. Li (Texas A&M University), Bryan W. Miller (Gemini Observatory), Constance M. Rockosi (University of California, Santa Cruz), Branimir Sesar (Max Planck Institute for Astronomy), and Erik J. Tollerud (Space Telescope Science Institute)

Milky Way/LV Science Cases

- Milky Way satellite luminosity function
  - medium resolution spectroscopy
- Dark matter content of dwarf galaxies
  - medium resolution spectroscopy
- Subhalo mass function from stream kinematics
  - medium resolution spectroscopy
- Mass of the Milky Way
  - proper motions, medium resolution spectroscopy
- Accretion history of the stellar halo
  - proper motions, medium+high resolution spectroscopy

The Scale of the Problem

Table 3.2. Resource Demand

	Infrastructure	< 3m	3–5m	8m	25m
Dark matter				**Multi-object spectroscopy: 4000 hrs** *Near-IR imaging: 300 hrs* *Single-object spectroscopy: 1200 hrs*	**Multi-object spectroscopy: 400 hrs**
Milky Way halo formation			Medium-band imaging: 5300 hrs	**Multi-object spectroscopy: 6700 hrs**	**Multi-object spectroscopy: 670 hrs**
Total On Sky Time			~ 1.5 years	~ 3.3 years	~ 0.3 year

Entries in boldface type indicate that the capability is **Priority 1 (critical).**
Roman type indicates Priority 2 (very important).
Italic type indicates *Priority 3 (important).*

Follow-Up Strategies and Needs

- Is there enough spectroscopic capacity to follow up all of the expected dwarfs?
- What other facilities/capabilities that we will want do not currently exist?
- What is the community strategy for pursuing the massively multiplexed spectroscopic facility that will be needed for LSST follow-up?

SnowPAC 2018

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Big Questions, Big Surveys, Big Data: Astronomy & Cosmology in the 2020s

March 11 - 16, 2018

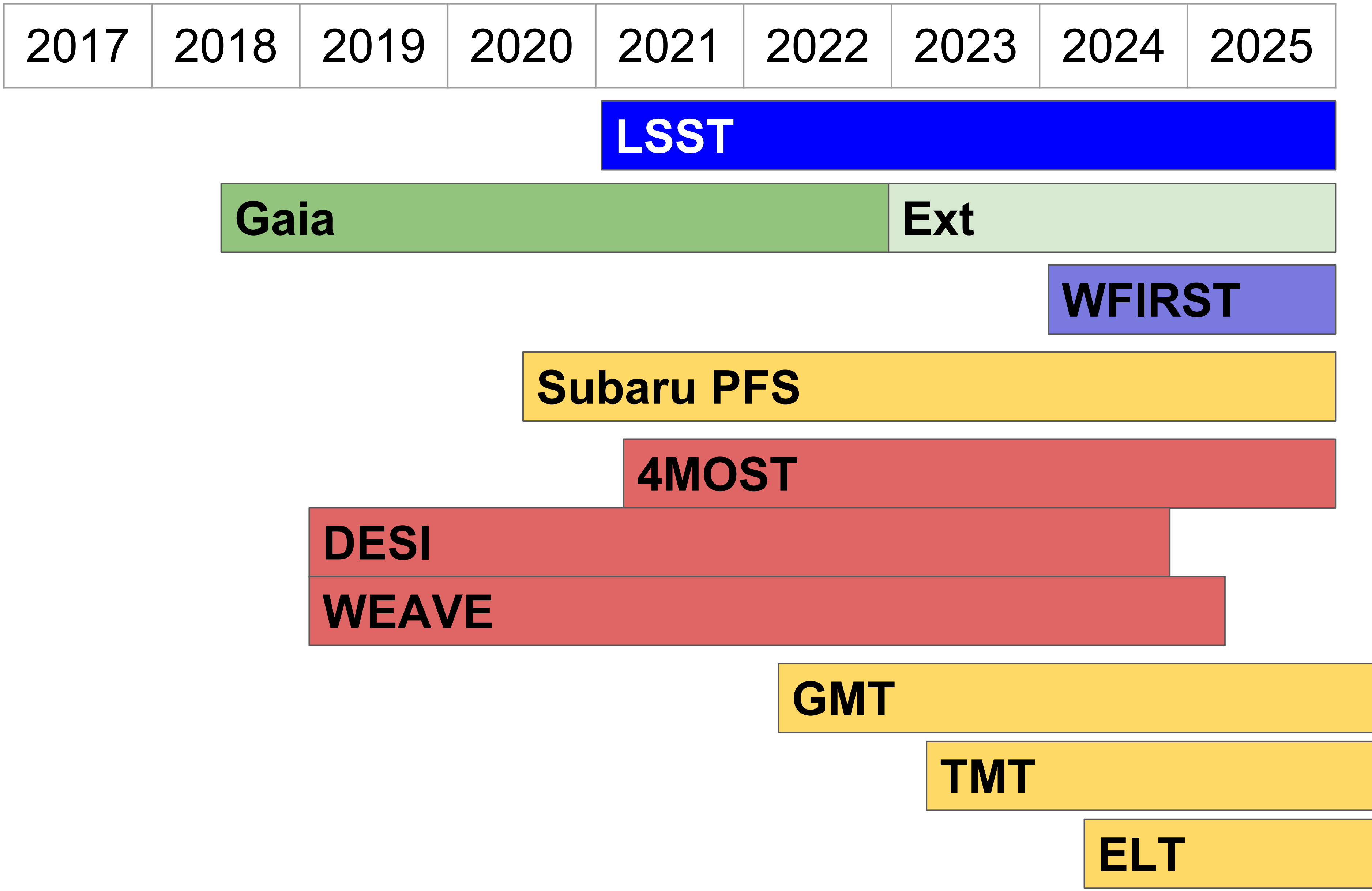
On the eve of the 2020s, observational astronomy and cosmology are confronted with questions about the origin of our Solar System, the demographics of extrasolar planets and their host stars, the structure of our Milky Way Galaxy, the evolution of galaxies and their dark-matter halos over cosmic time, the nature of the mysterious “dark energy” that is driving the accelerated expansion of the Universe, and the completeness of our current theory of gravity. Across all these areas, the progress of science and technology has led to a landscape characterized increasingly by ambitious multi-year optical and infrared (OIR) surveys that cover large fractions of the sky and deliver petabyte-scale data streams and archives. These large-scale projects—such as SDSS, Pan-STARRS, DES, ZTF, DESI, Gaia, LSST, Euclid, and WFIRST — are redefining the scientific opportunities and methodologies available to new generations of astronomers and physicists.

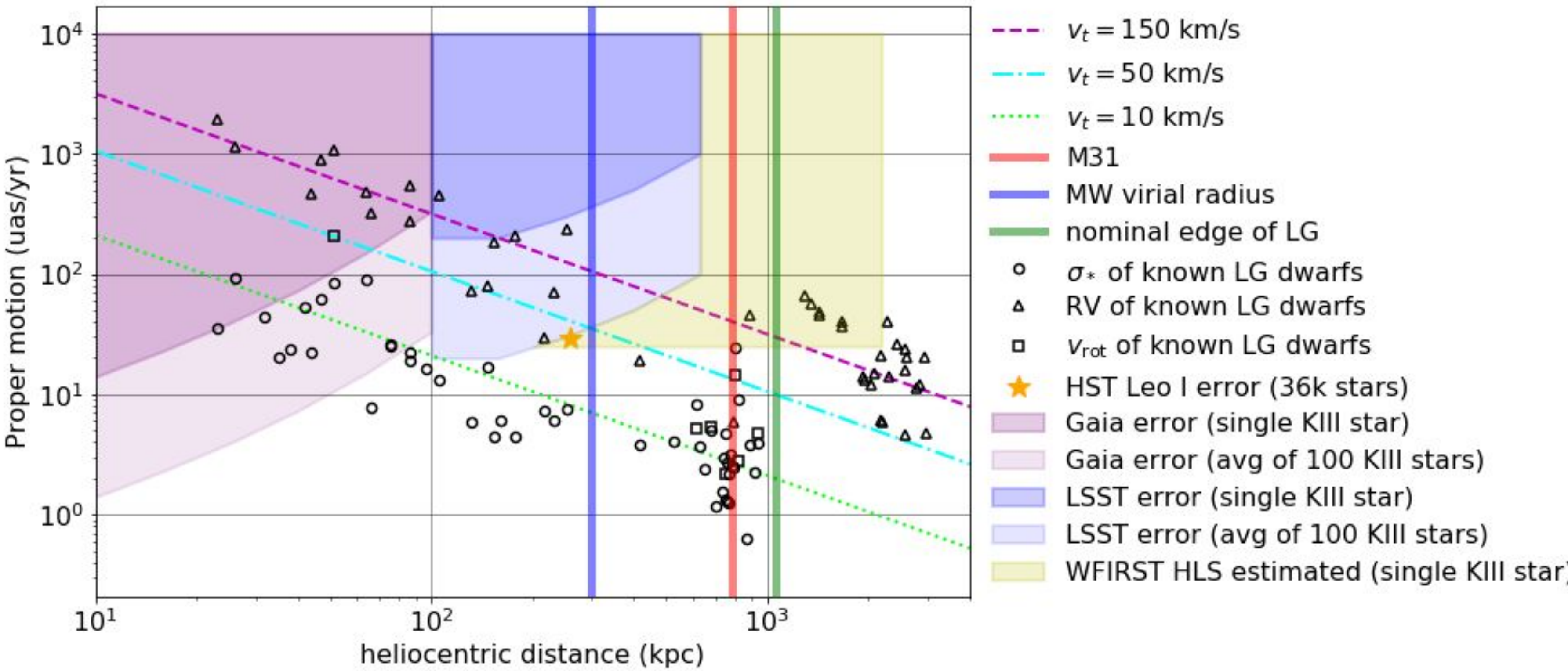
This workshop is being organized on the occasion of the upcoming 2020 Decadal Survey in Astronomy and Astrophysics to gather community input and facilitate broad collaboration and coordination in addressing the following questions in OIR survey astronomy and cosmology:

- *What are the most significant scientific questions of the 2020s that can be directly addressed by survey-scale projects and datasets using OIR facilities?*
- *What are the highest priority observing facilities for survey-scale astrophysics and cosmology, considering potentially new facilities as well as extended missions for existing facilities?*
- *What computing and software facilities, tools, and technologies will be required to maximize the data-intensive scientific opportunities that the large OIR survey datasets of the next decade will provide?*
- *How will theory and simulation connect to large-scale survey datasets in the 2020s?*
- *What are the most significant opportunities for survey-scale and data-intensive collaboration across multiple scientific areas and agencies?*
- *What new technologies in hardware and software—either existing or anticipated—merit further study for their potential to deliver transformative scientific capabilities?*
- *What are the major challenges and potential solutions in education and workforce development that are most important to the long-term success and sustainability of major survey projects with long timescales?*

Pre-registration open now:
http://www.physics.utah.edu/snowpac/

Timeline for other surveys & instruments

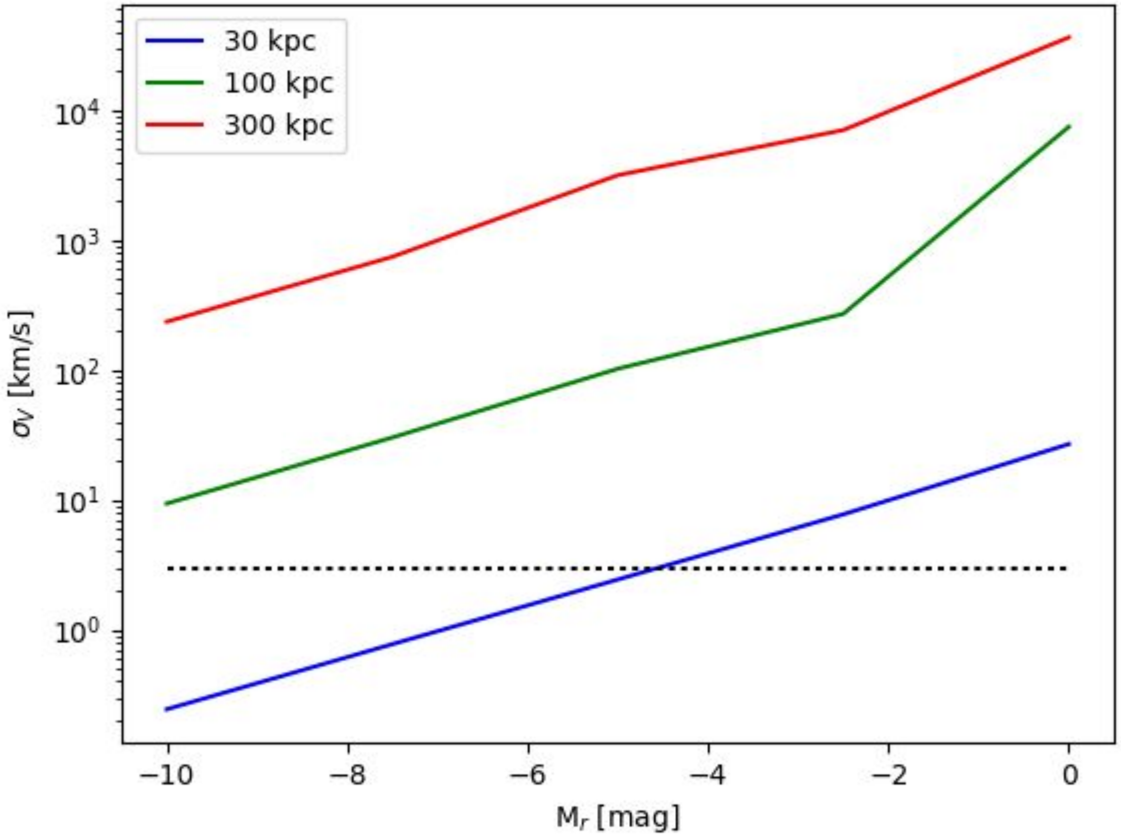




Proper motion (uas/yr)
heliocentric distance (kpc)
10^4
10^3
10^2
10^1
10^0
10^1
10^2
10^3
$v_t = 150$ km/s
$v_t = 50$ km/s
$v_t = 10$ km/s
M31
MW virial radius
nominal edge of LG
σ_* of known LG dwarfs
RV of known LG dwarfs
$v_{\rm rot}$ of known LG dwarfs
HST Leo I error (36k stars)
Gaia error (single KIII star)
Gaia error (avg of 100 KIII stars)
LSST error (single KIII star)
LSST error (avg of 100 KIII stars)
WFIRST HLS estimated (single KIII star)

RV precision from LSST

Uncertainty in RV



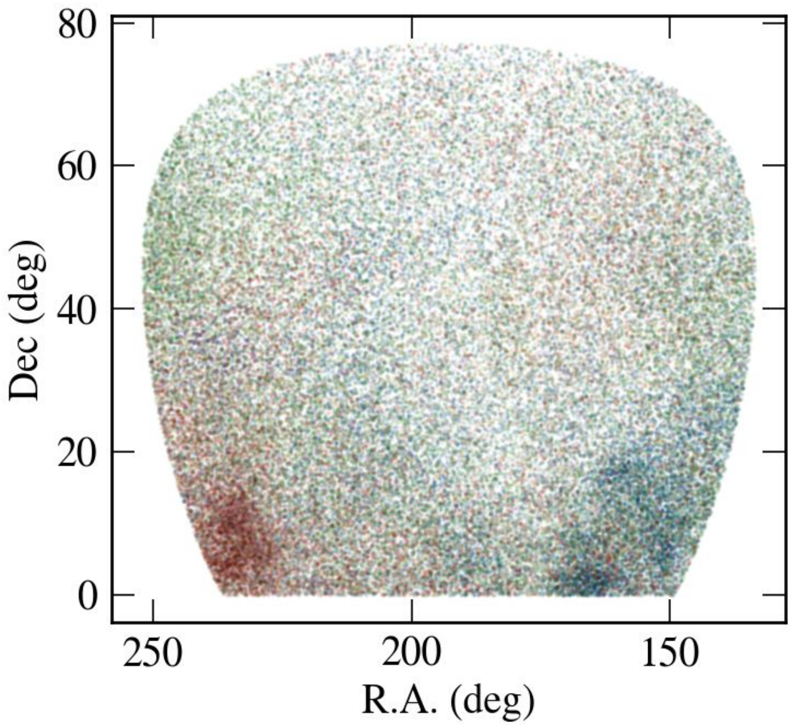
Future Tools, Databases, Computing Resources

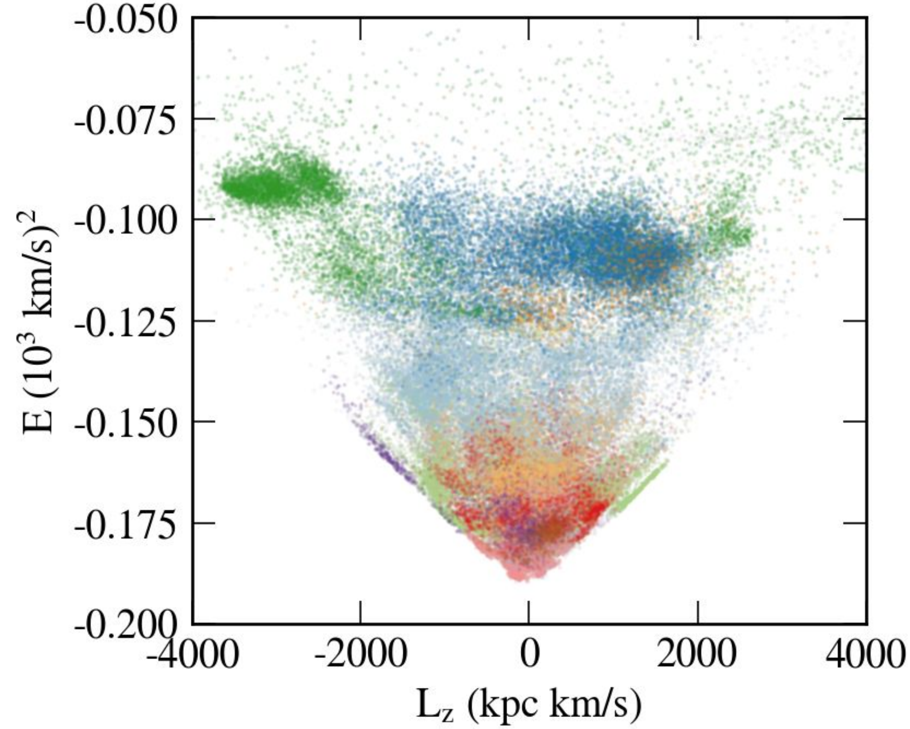
- What do observers need from theorists?
- What do theorists need from observers?
- Is there a role for citizen science?
  - Following up low-significance candidates?
- What cross-matching between LSST and other catalogs is envisioned/needed?

LSST Synergies with Current/Future Facilities

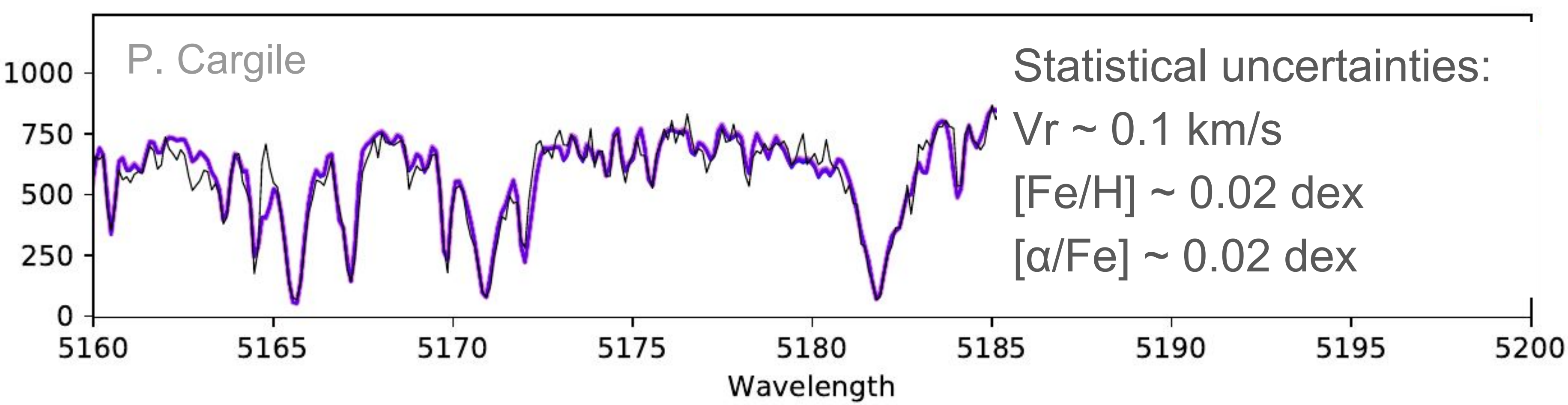
- Gaia
- Spectroscopic facilities (Keck, Subaru, VLT, Magellan)
- WFIRST, EUCLID
- GSMTs
- Anything else?
- Will these synergies solve star-galaxy separation?
- What's missing? UV?

H3: Hectochelle in the Halo at High resolution





Based on Lowing et al. (2014)



Beyond LSST

- Will it be important to have deeper coverage in the north so as to avoid an asymmetric view of the MW satellite population?

Ongoing and Future Surveys

- DES, HSC
- MagLiteS, BLISS, DECaLS, DECaPS

Future Obs / Strategies

- Need for spectroscopic followup a major unresolved problem!

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

- Confusion / modeling / computation limits for lower latitudes? Proper motions for foreground rejection?

Workshop Report to LSST

Report to LSST from Dwarf Companion Workshop

- Increased U depth
  - For contrast of dwarf to background sources
- Macroscopic dithering (including rotational)
  - To help suppression of secondary reflection and scattering
- Extensions of coverage – maybe/ with WFD cadence, maybe proposed as mini-surveys – reduced survey reaches valuable depth, e.g. 26.5
  - Need time series and PM, for RR Lyr as extinction control and for target detection
  - Coverage extended to pole (full LMC sky)
  - Improved coverage closer to galactic plane
    - Due to inhomogeneous distribution of companions, cannot do completeness correction for MW plane, without better coverage near plane – dynamical reasons to expect near-plane objects
      - To what latitude (longitude dependent?)
    - What filters
  - Coverage extended further north
  - Simple summary – WFD from SGP to +20
- Source-subtraction an essential processing stage
  - Stacked background subtracted images
  - Stacked subtracted image – a desired LSST product
  - Individual visits - for best analysis
    - If not offered by LSST, then support access for secondary processing

Request special survey simulations

- Baseline survey with deeper U-band (more visits or longer integration)
- Baseline survey plus WFD to south galactic pole
- Baseline survey plus WFD to galactic plane
- Baseline survey plus WFD to +20
- Baseline survey plus all of the above