VERA C. RUBIN OBSERVATORY

Revealing satellites and streams in the Local Volume with LSST

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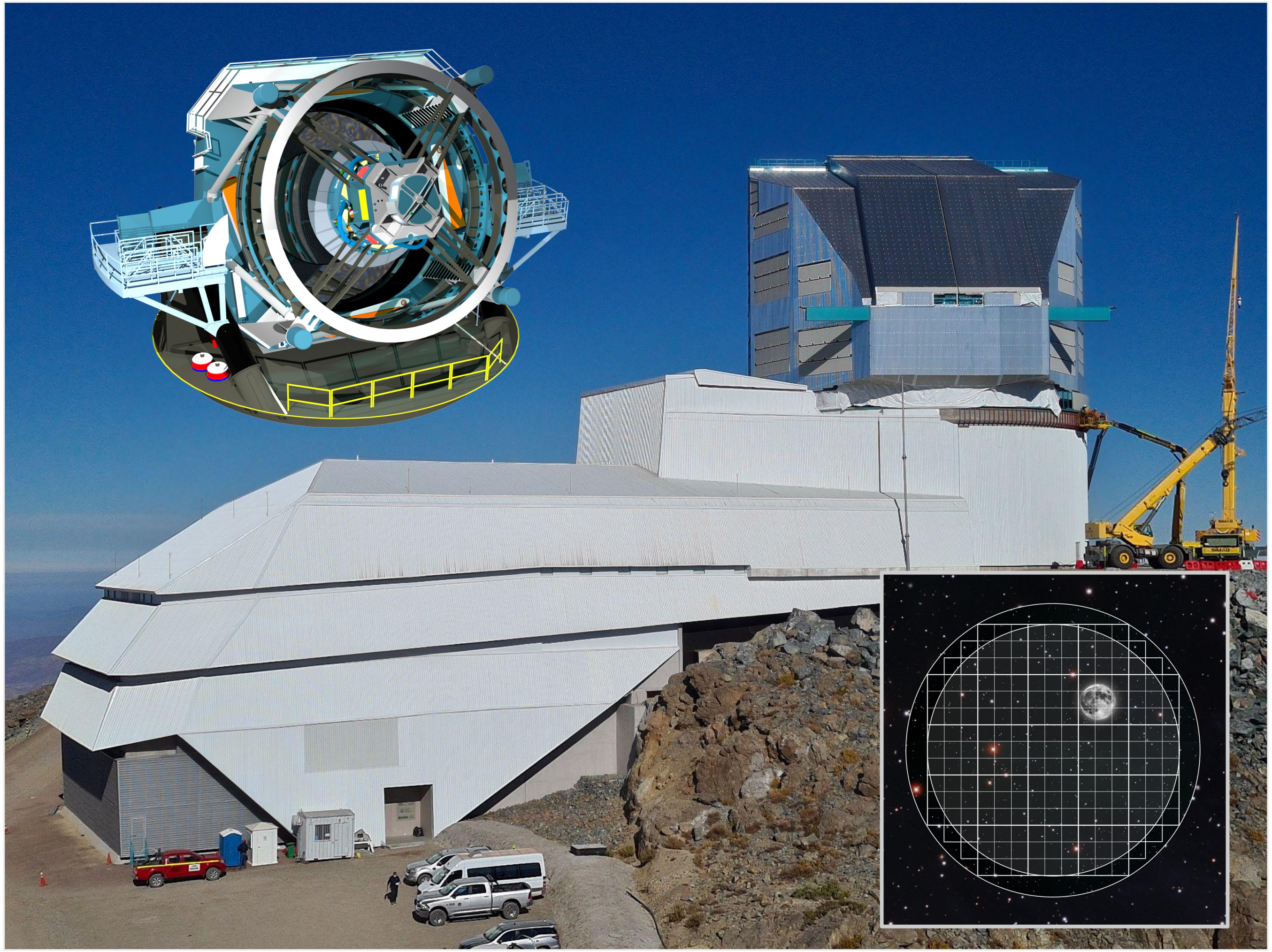
AURA/Vera C. Rubin Observatory

NSF AURA U.S. DEPARTMENT OF ENERGY SLAC CHARLES AND LISA SIMONYI FUND FOR ARTS AND SCIENCES LSST CORPORATION

VERA C. RUBIN OBSERVATORY

LSST
Legacy Survey of Space and Time

The Vera C. Rubin Observatory



The Vera C. Rubin Observatory is located on Cerro Pachón in Chile. The Simonyi Survey Telescope's primary mirror has a 6.7 meter *effective* diameter and its camera a 9.6 deg^2 field-of-view and six optical-NIR filters: *ugrizy*.

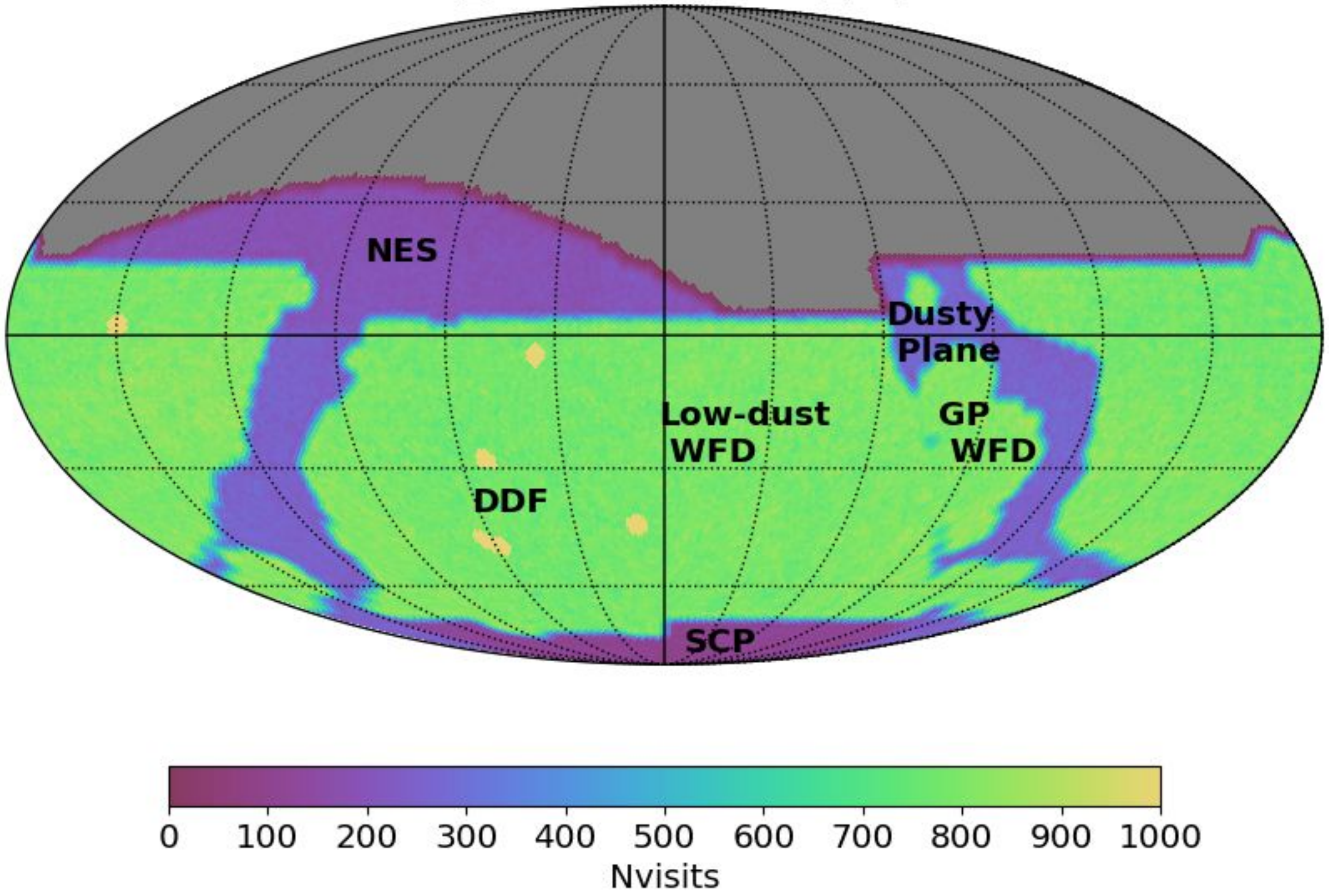
Once construction and commissioning are complete, Rubin Observatory will execute the 10-year Legacy Survey of Space and Time (LSST):

- single-image depths (point source; AB)
  - *ugrizy* = 23.9, 25.0, 24.7, 24.0, 23.3, 22.1 mag
- 10-year LSST depths (point source; AB)
  - *ugrizy* = 26.1, 27.4, 27.5, 26.8, 26.1, 24.9 mag

See Ivezić et al. (2019) for technical details about the design and the science goals.

Survey Strategy Basics

One of the most recent baseline survey simulations.



The **Baseline Survey Strategy** was designed to meet the basic requirements to achieve the core science goals of the **Legacy Survey of Space and Time** (LSST; requirements described in ls.st/srd).

Baseline design elements for the WFD area:

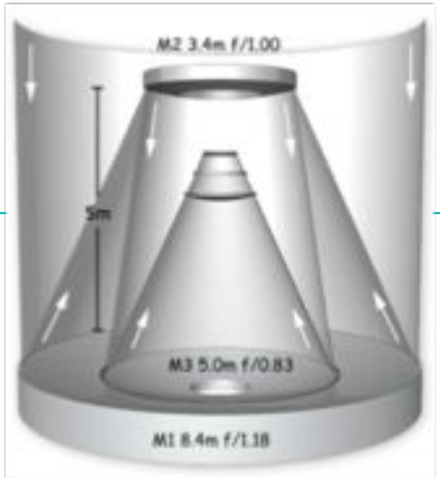
- should cover at least 18000 deg^2
- average of 825 visits per field over 10 years
- same-night same-field re-visit "pairs"

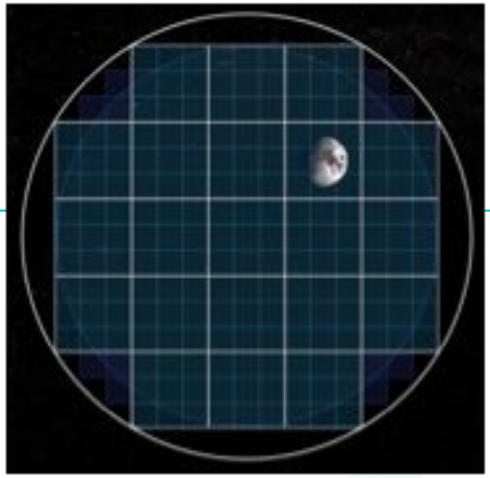
Additional areas covered should include:

- at least 5 deep drilling fields
- the North Ecliptic Spur, the Galactic Plane, and the South Celestial Pole

How to optimize the LSST to maximize scientific return is an open question.

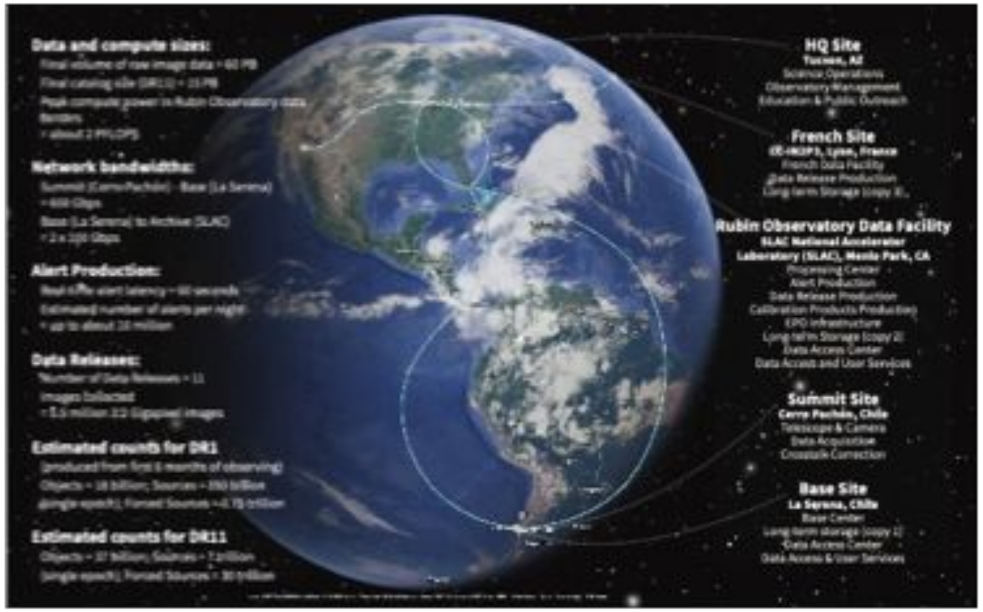
large aperture, fast telescope





huge facility

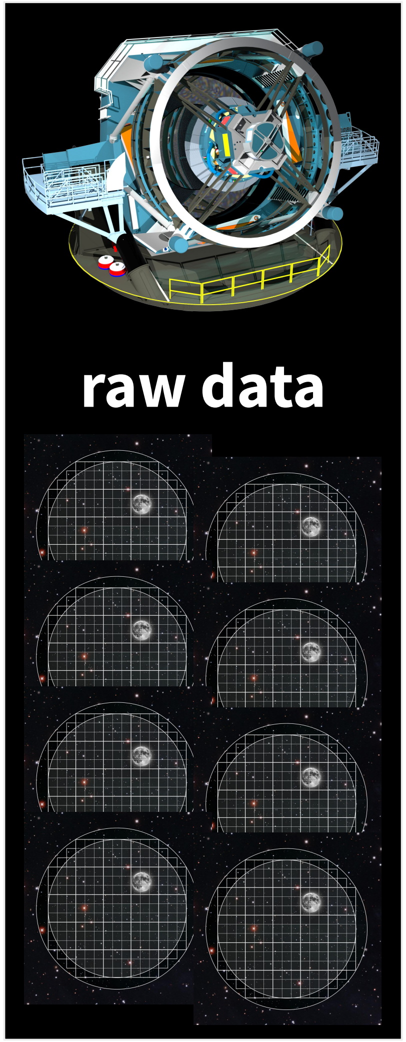
3.2 Gpixel camera with large field of view

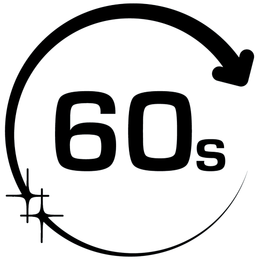


high bandwidth, rapid data transfer

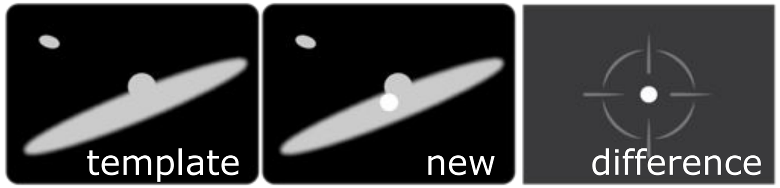
petascale computing facility,
~1 million lines of code

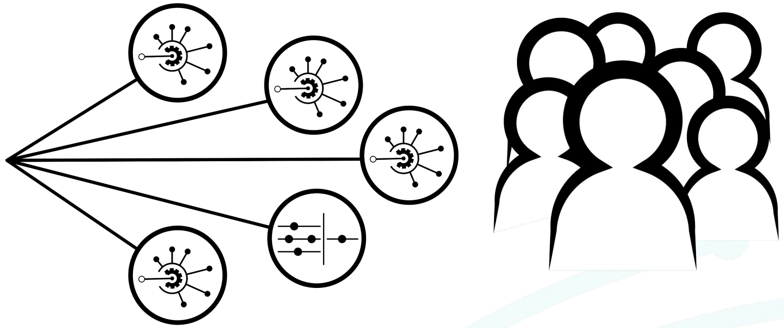
LSST Data Products





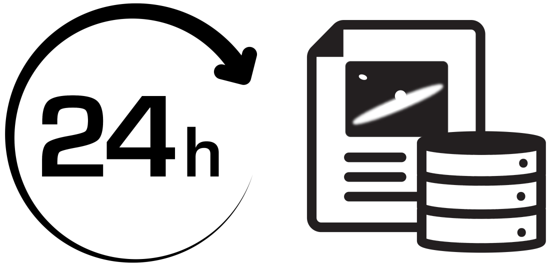
Difference Image Analysis (DIA)





Alert Production. Raw images are processed, a template is subtracted, and difference-image sources are detected, associated, characterized, and…

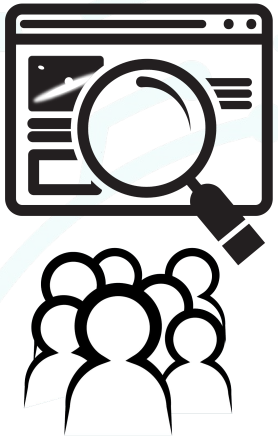
…distributed as alerts to brokers, where they can be rapidly analyzed by users.



Prompt Products. Images and catalogs from DIA.

Data Release. Deeply coadded images & associated catalogs, plus DIA products.

The Prompt and Data Release data products will be available to users via the Rubin Science Platform.



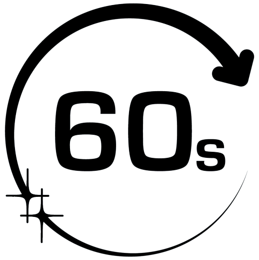
Data Products Definitions Document: ls.st/dpdd

LSST Data Products

Up to 10 million alerts/night

~6 million Solar System objects by year 10

~5.5 million images, 37 billion objects detected over 10 years



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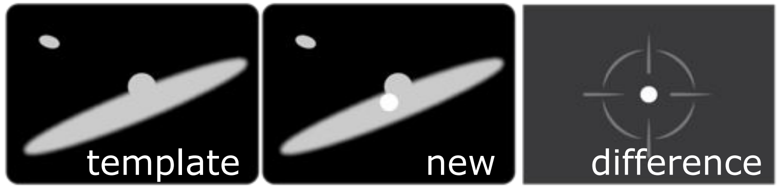

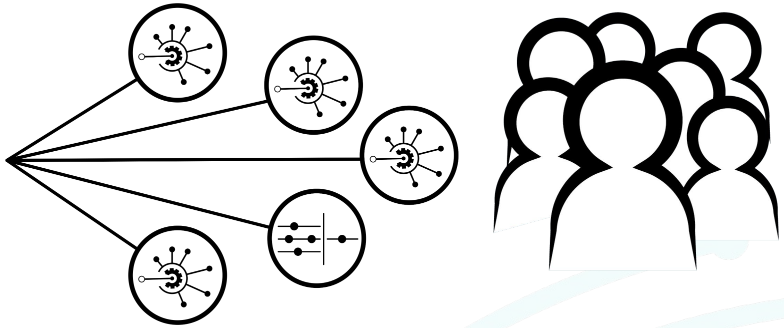

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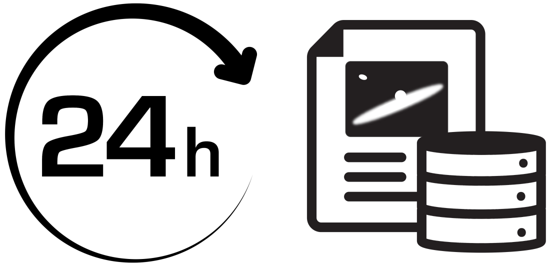

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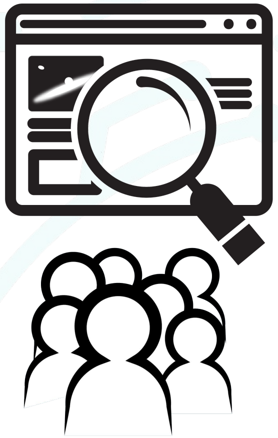


Rubin Obs/LSST will open ~1,000 times the volume for studying the Local Universe with resolved stars compared to SDSS

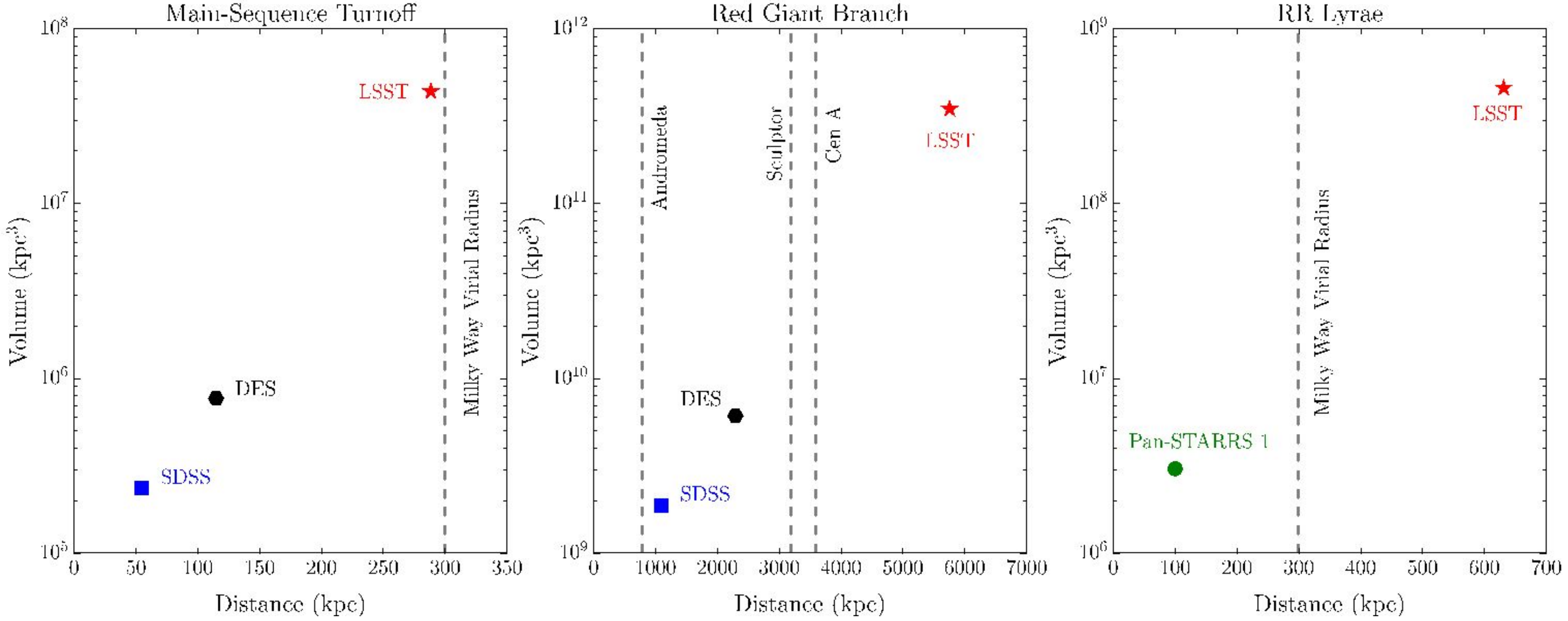


Figure: Keith Bechtol

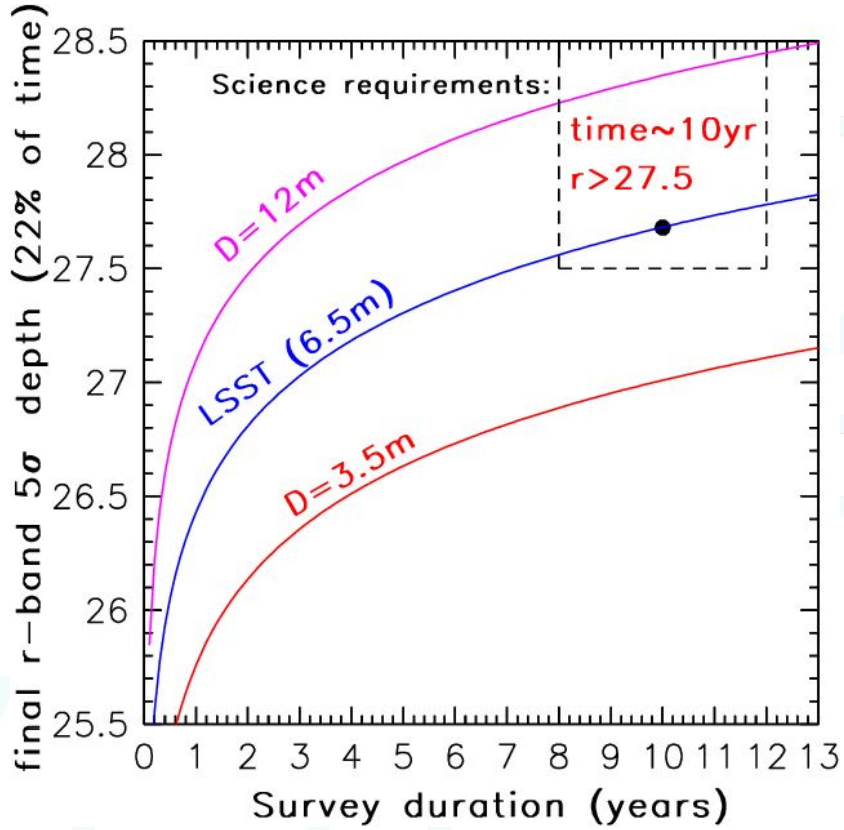


Figure: LSST Science Book

Opportunities and challenges*

- Star/galaxy separation at the faint end
- Detection of “partially resolved” systems (and “isolated” dwarfs)
- Detection of fuzzy blobs
- Finding blue, star-forming dwarfs
- Prioritizing follow-up (we can’t follow up everything!)
- Optimizing background subtraction for LSB science
- Characterizing the survey data (e.g., how survey properties affect matched-filter maps – see Ferguson poster)
- Synthetic Source Injection for characterization (and for precursor studies)
- Photometry in crowded fields/regions
- Proper motions

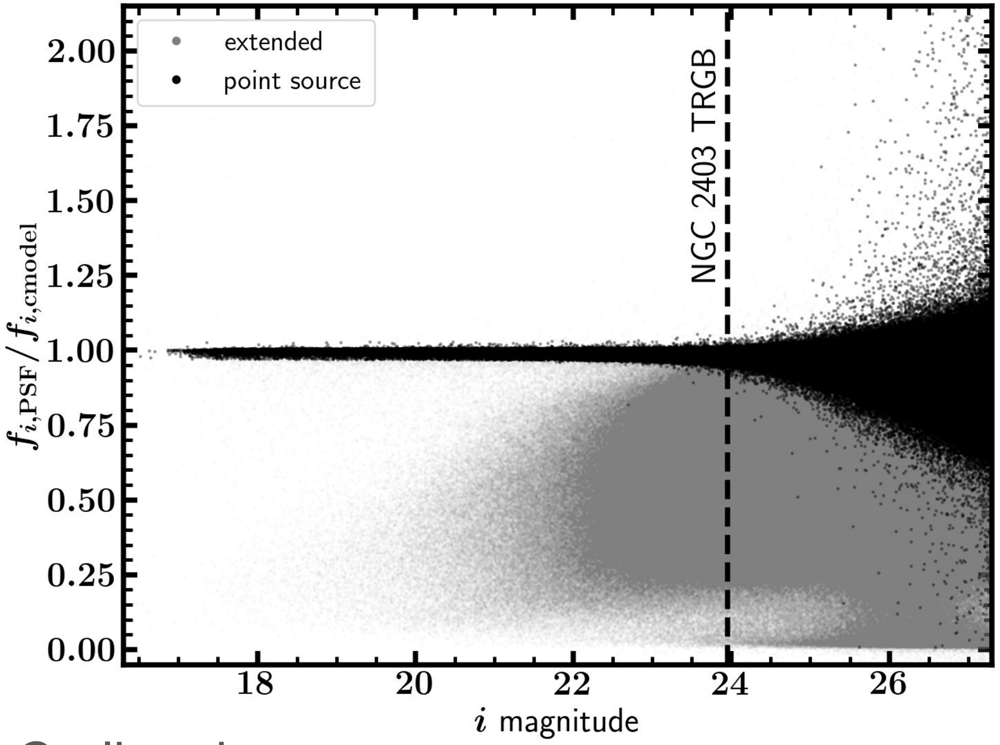
…and doing all of this over ~18000 deg^2 of sky

- Are models/simulations detailed/sophisticated enough to enable interpretation of LSST results?

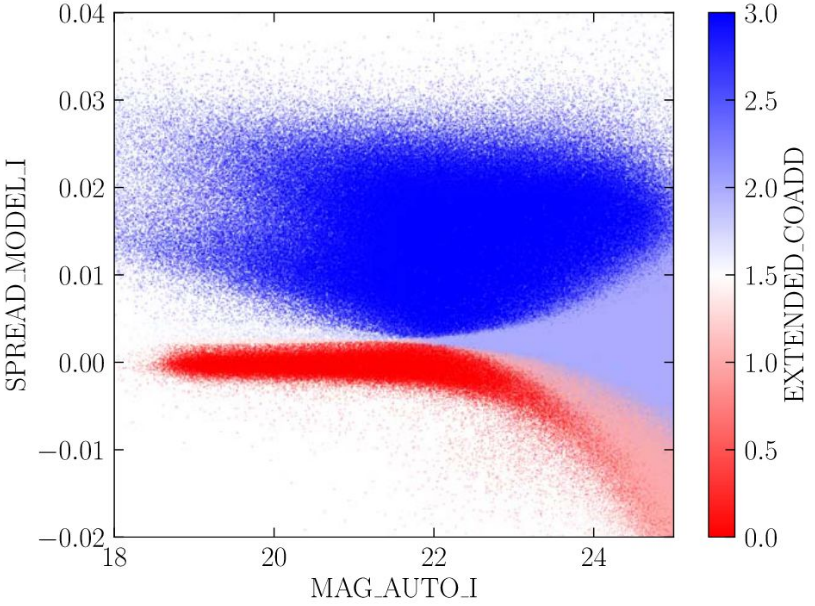
*Not a complete list!

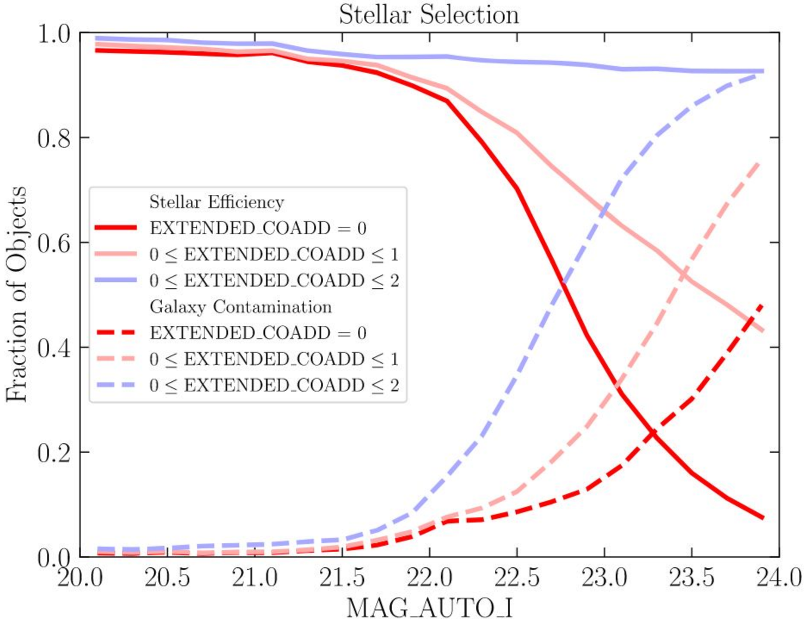
Star/galaxy separation

Current LSST pipelines use PSF/cmodel flux ratio to determine "extendedness"



Carlin+, in prep

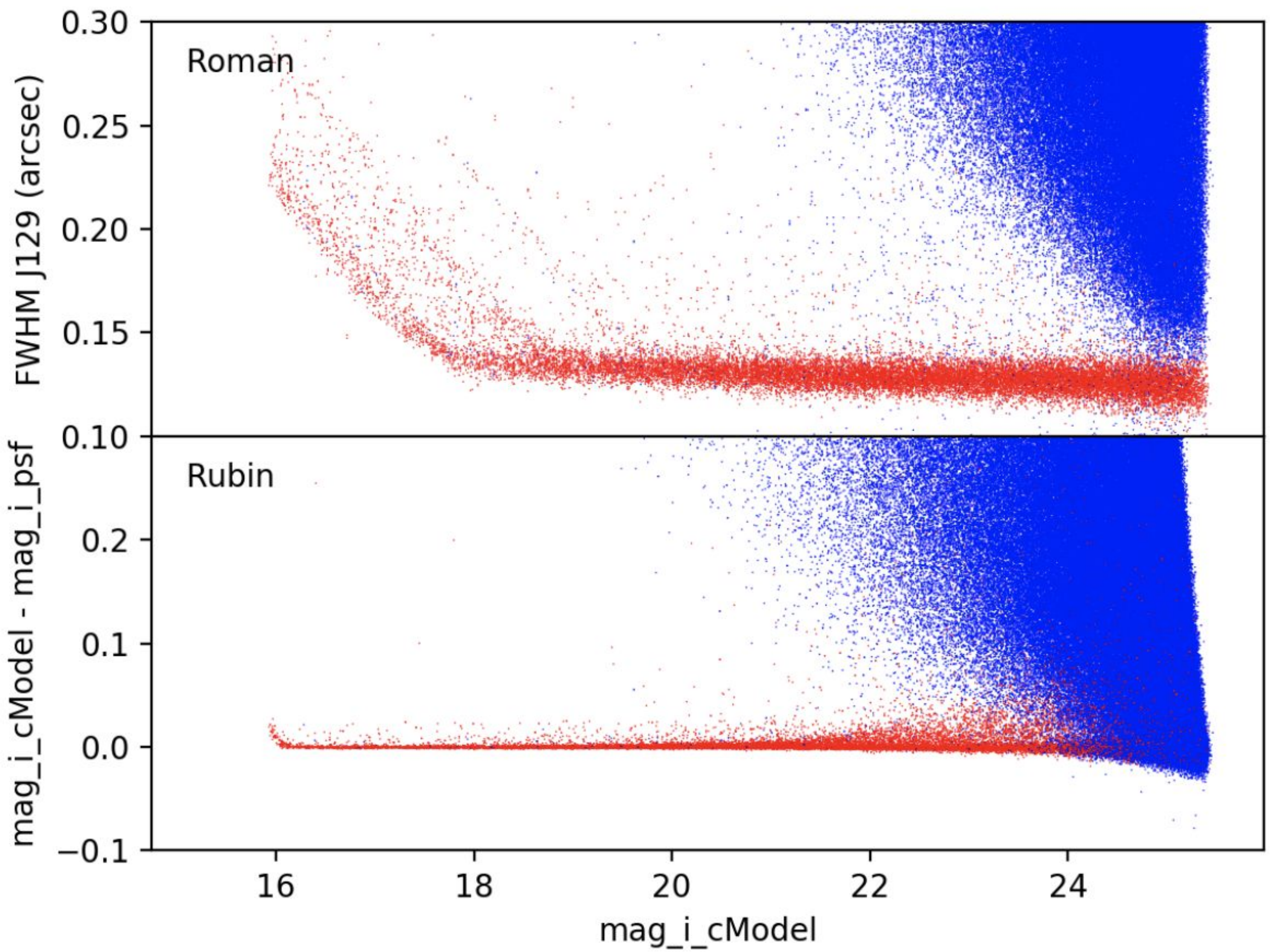


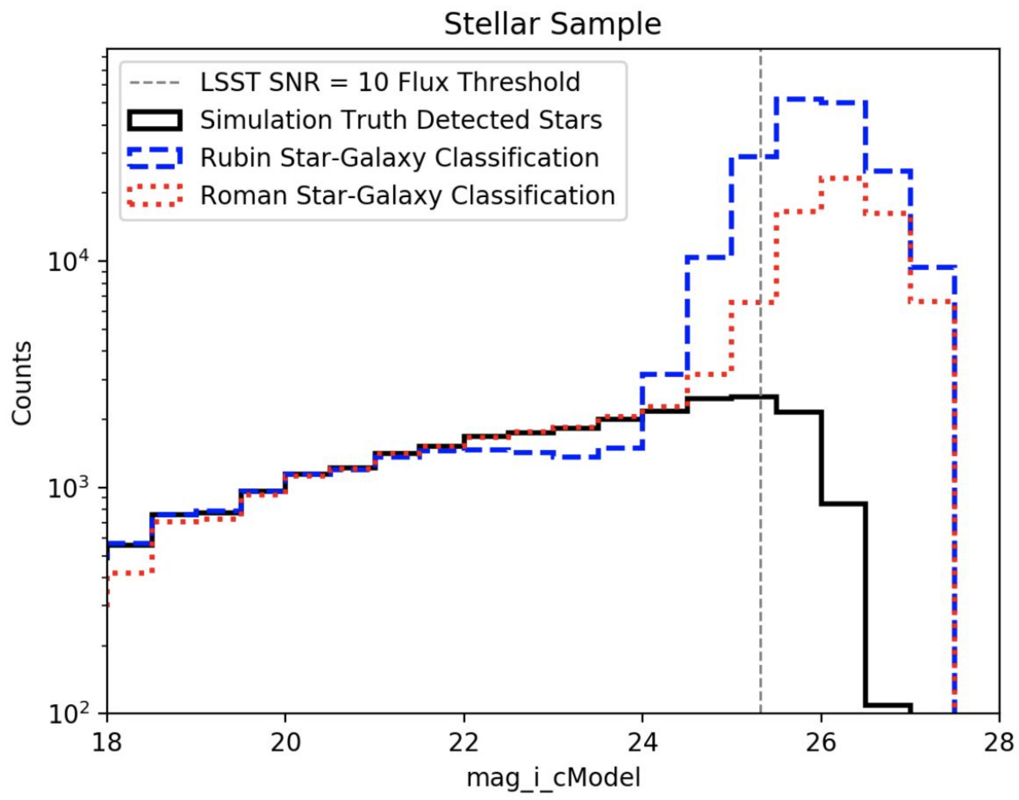


Abbott+2021 (ApJS, 255, 20; DES DR2)

Star/galaxy separation

Bechtol+2023; “Roman Core Community Surveys White Paper: Coordinating Roman and Rubin for Cosmic Probes of Dark Matter with Resolved Stellar Populations” (https://asd.gsfc.nasa.gov/roman/wps_2023/files/016_Bechtol_HLWAS.pdf)



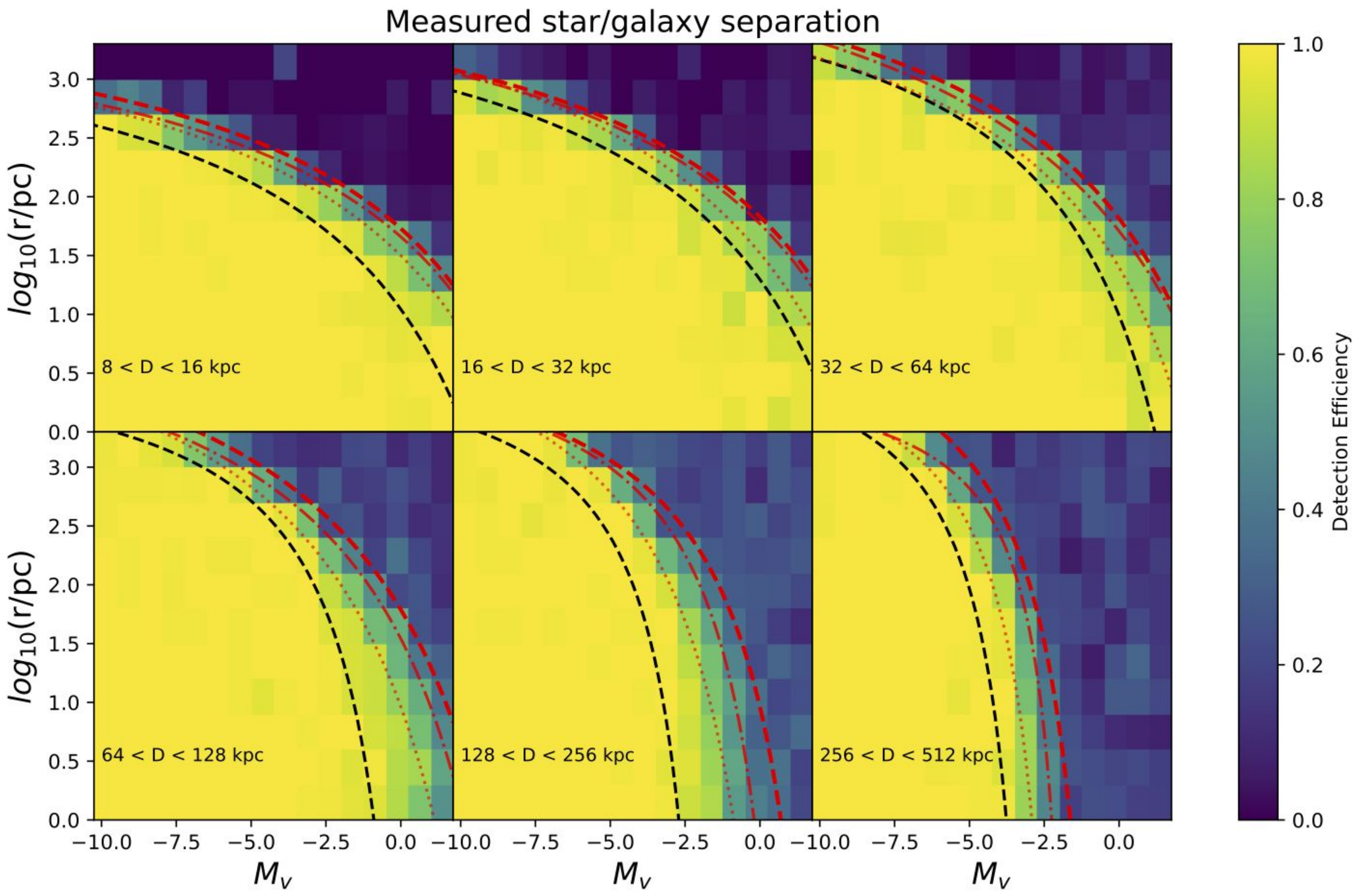


Star/galaxy separation

Tsiane, Drlica-Wagner+ in prep

Injected 10^5 artificial dwarfs into Rubin Data Preview 0 (simulated) dataset

Run dwarf galaxy detection algorithm, measure efficiency vs. distance, luminosity, half-light radius



Star/galaxy separation

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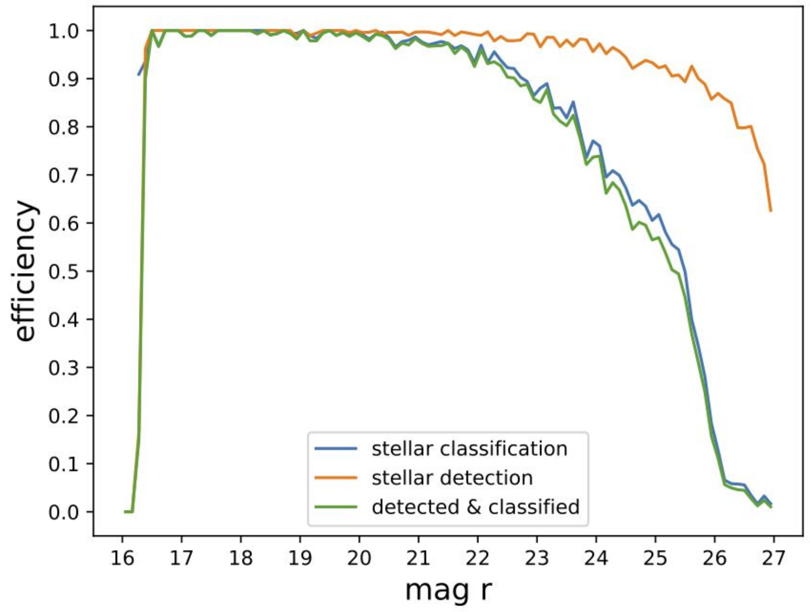
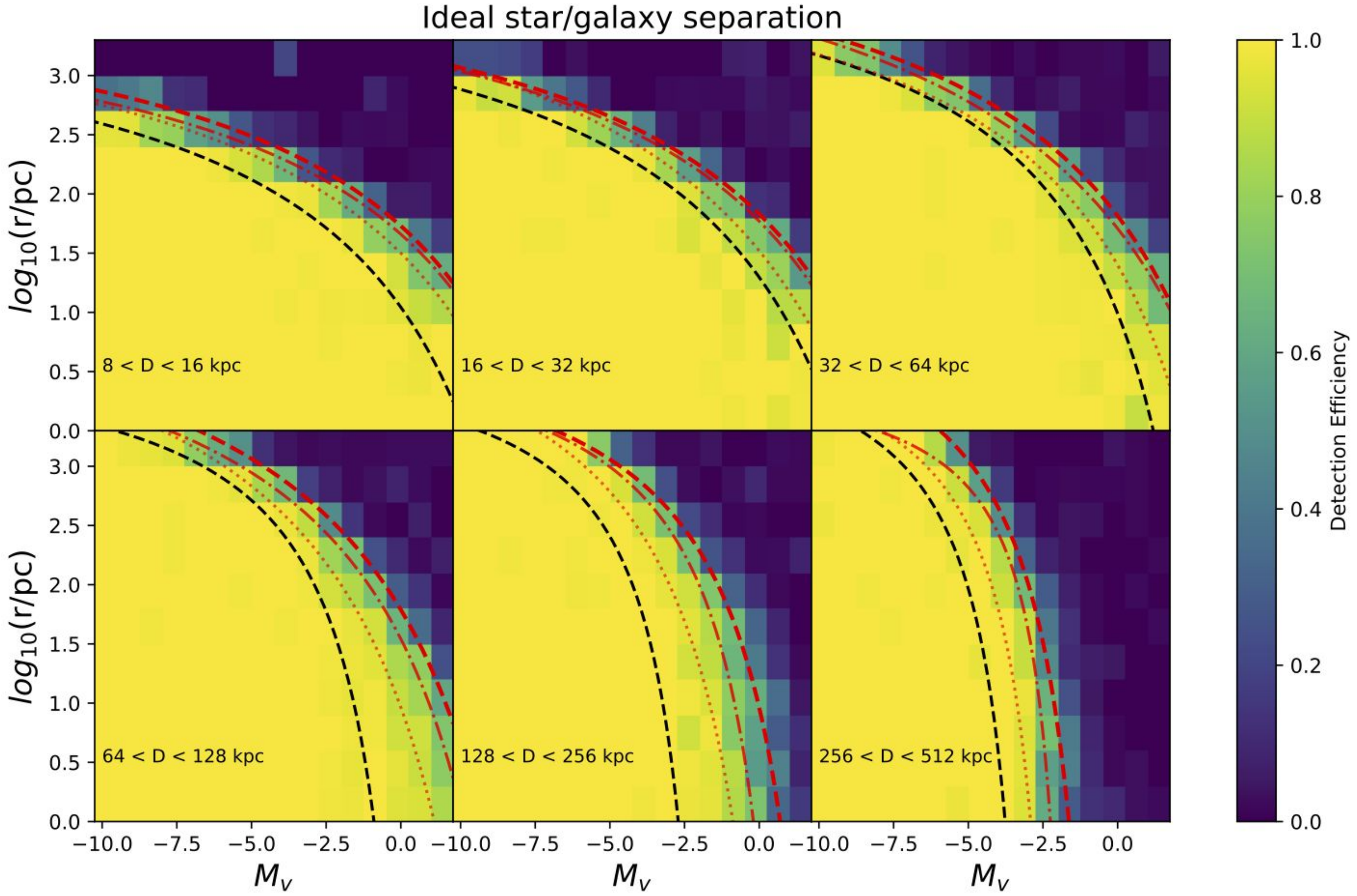




Acronyms & Glossary: ls.st/glossary

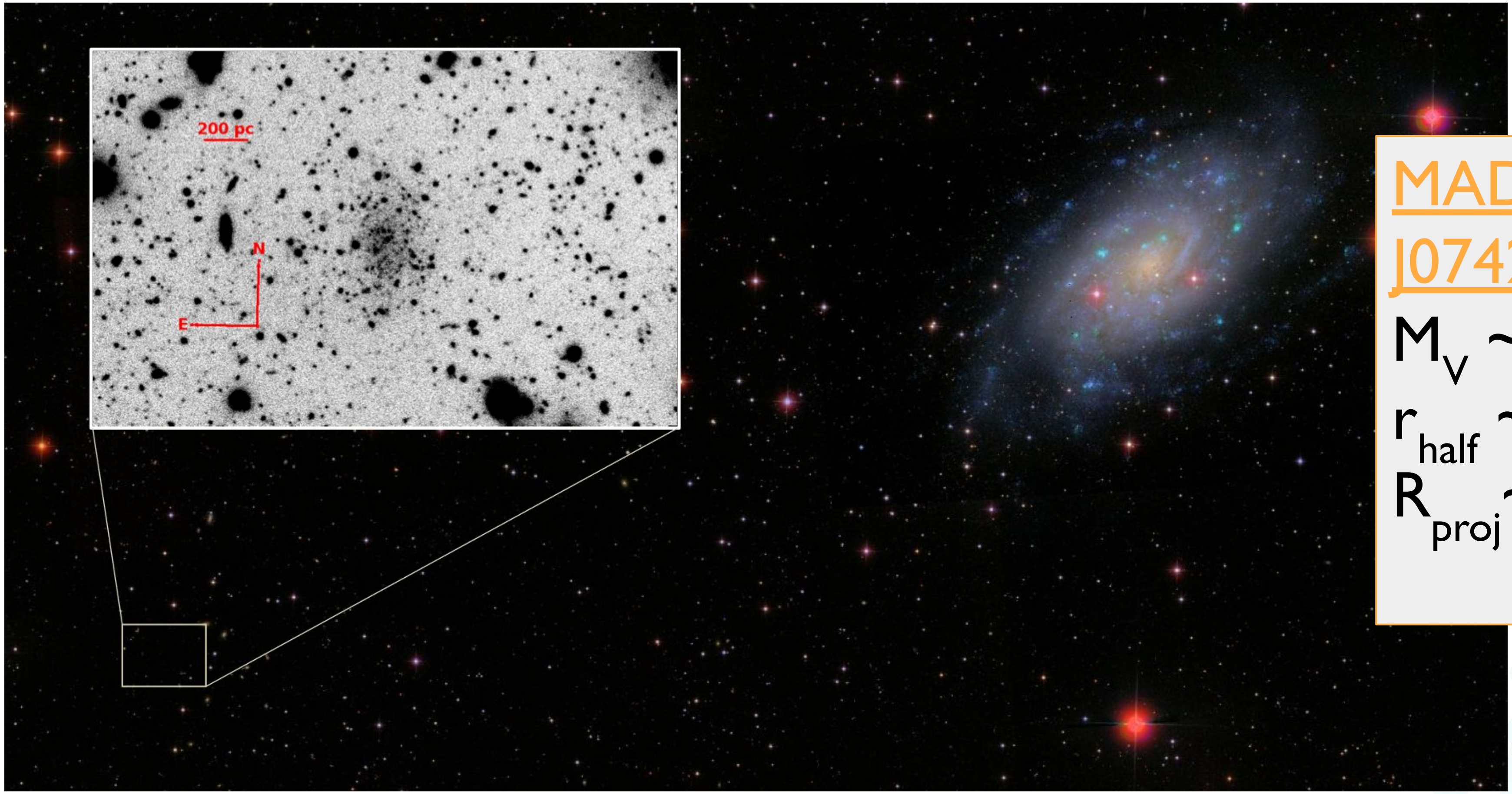
Detecting dwarfs, star clusters, and streams

Matched filter searches miss objects with a lot of unresolved emission

Many studies rely on visual inspection to find dwarfs and streams

Confirmation often requires space-based (HST, JWST) follow-up

Dwarf galaxy near NGC 2403
(D~3.2 Mpc, $M_* \sim 7\times10^9\ M_{Sun}$; ~2.5 $M_{*,LMC}$)



[MADCASH J074238+652501-dw](#)

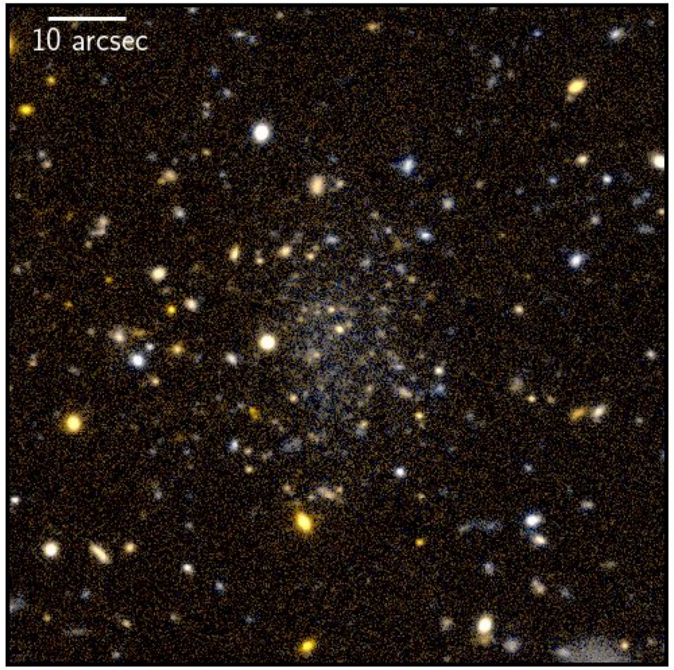
M_V ~ -7.8

r_{half} ~ 179 pc

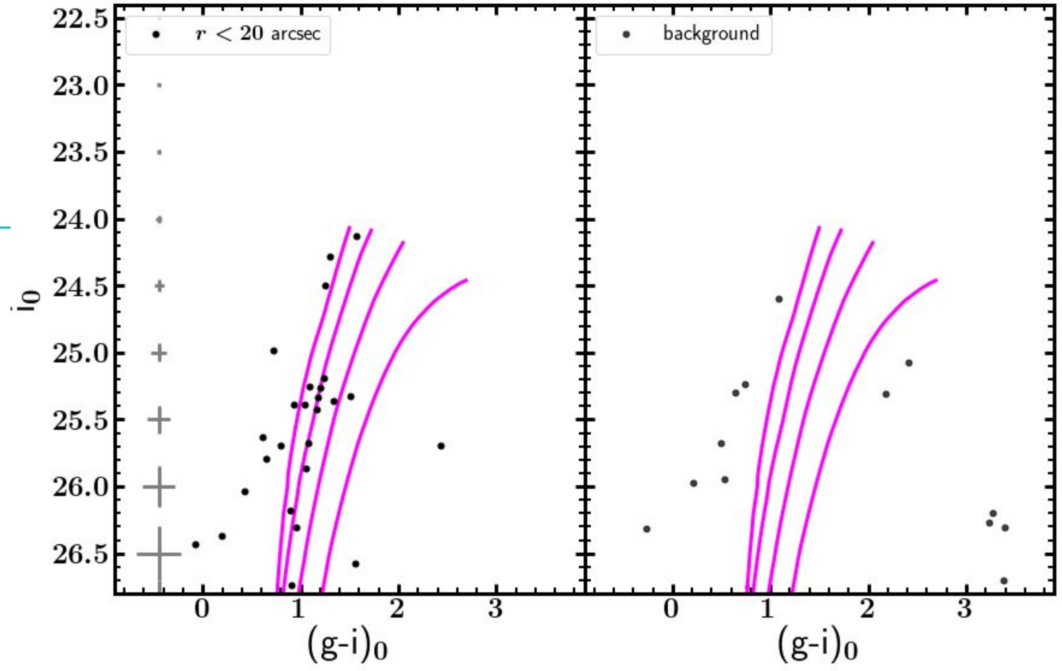
R_{proj}~35 kpc from NGC 2403

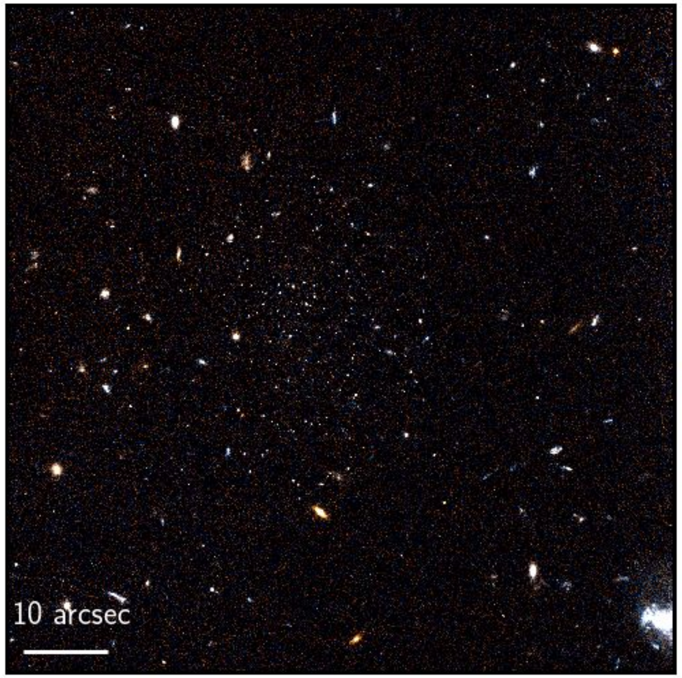
(aka "MADCASH-1")

Carlin+2016, ApJL, 828, 5

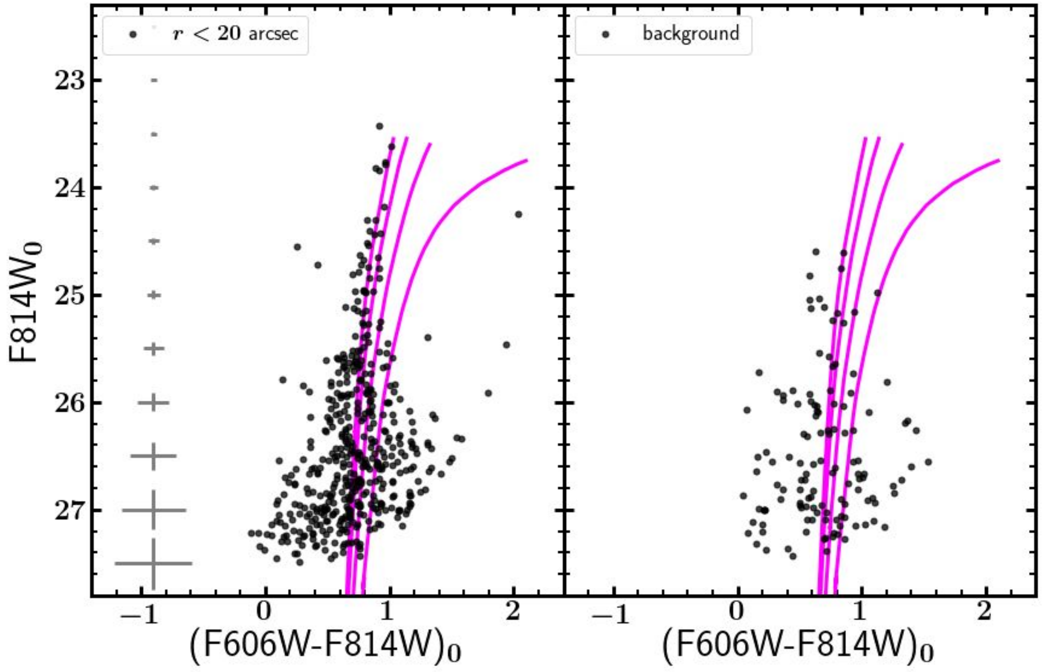


Subaru/HSC



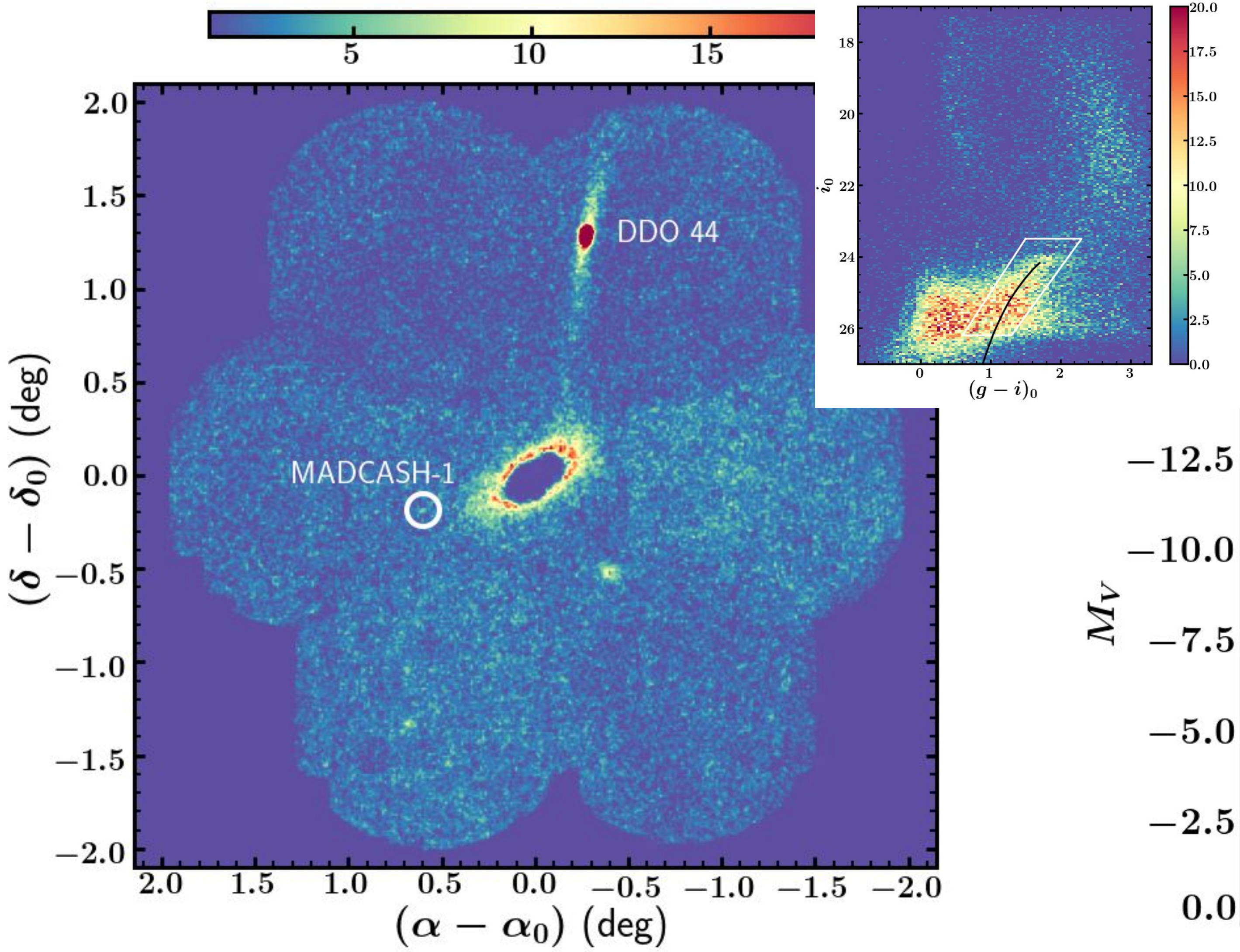


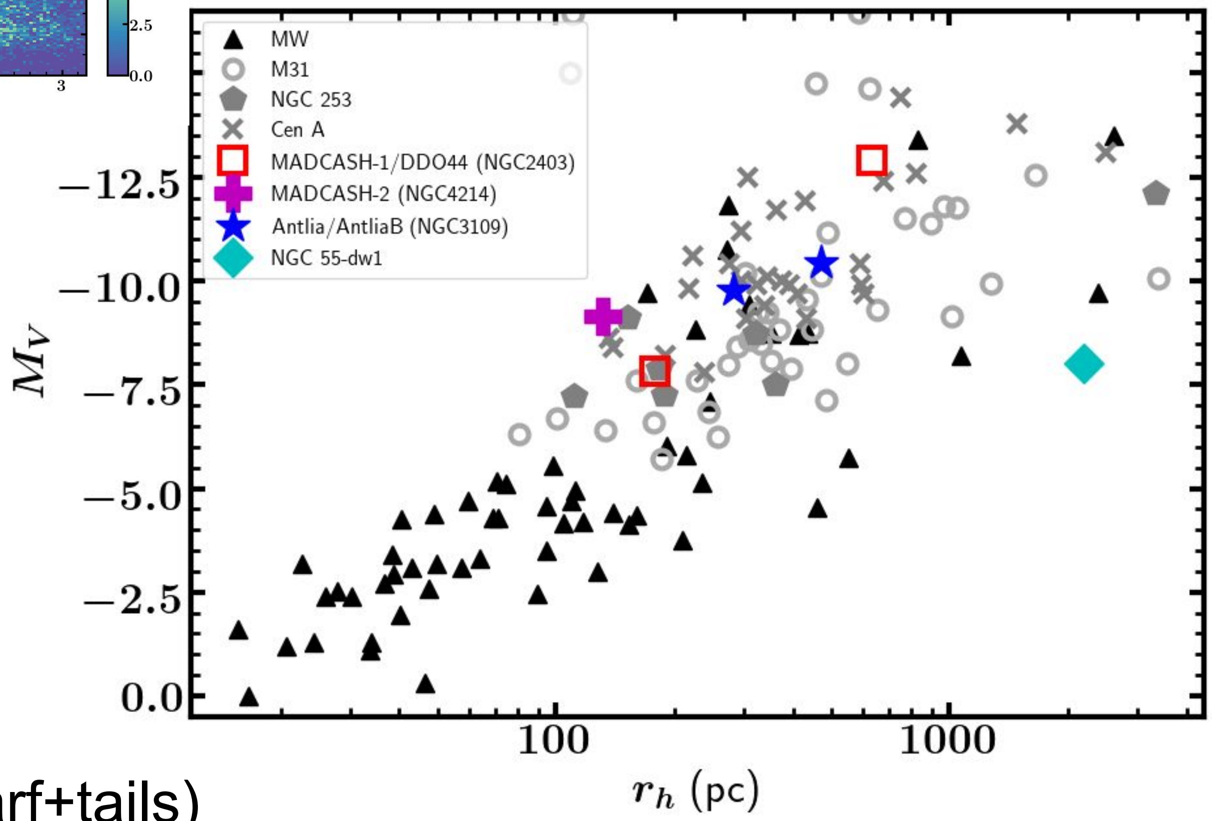
HST/ACS



Carlin+2021, ApJ, 909, 211

NGC 2403 (M_*~3 $M_{*,LMC}$) dwarf satellites





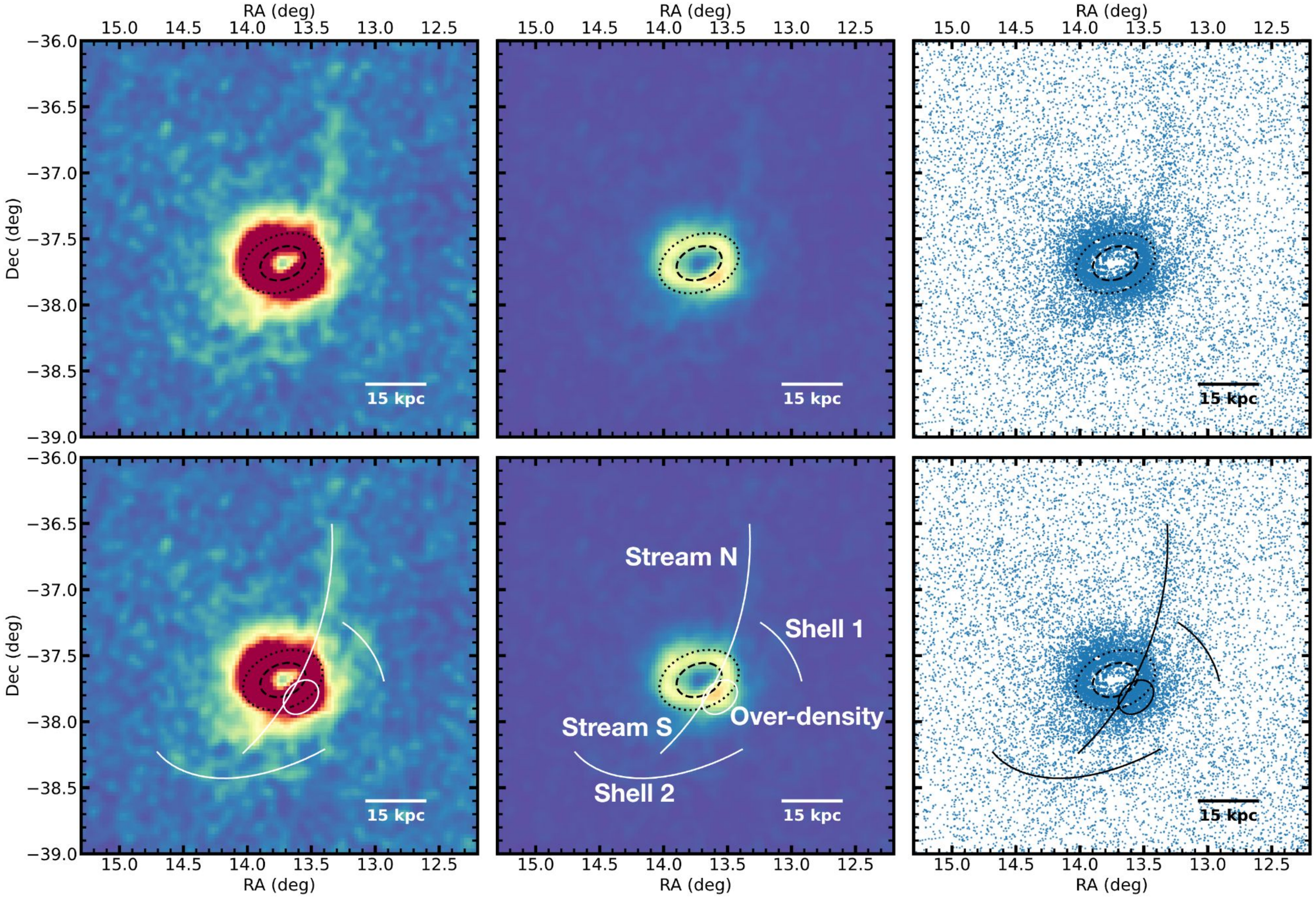
DDO 44 is tidally disrupting! Total luminosity (dwarf+tails) M_V ~ -12.9. Such pairings (NGC2403+DDO44) are extremely rare in Illustris models.

Carlin+2019 (ApJ, 886, 109)

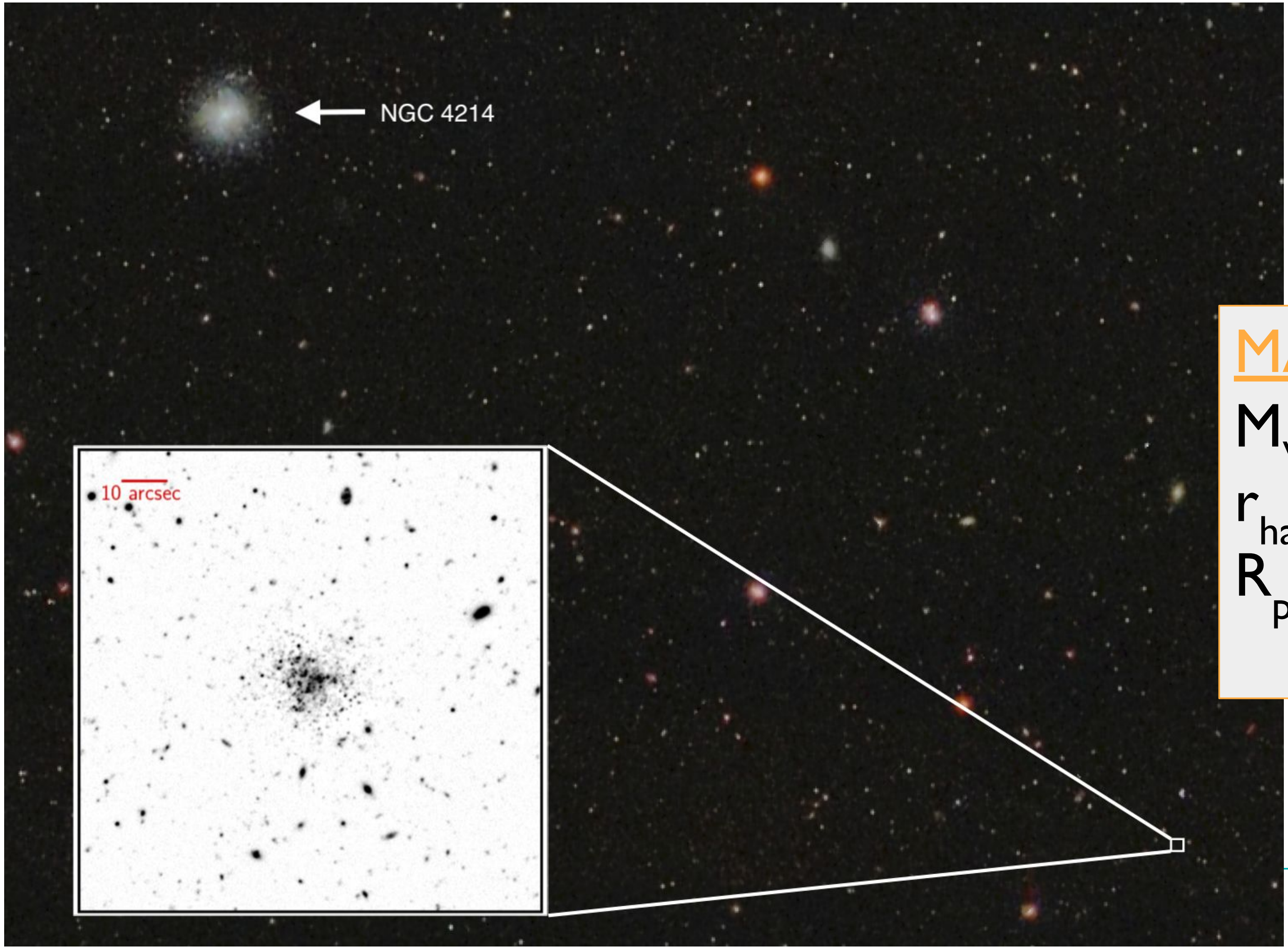
NGC 300 (~LMC mass) – tidal stream/debris found in DELVE-DEEP data

See Cat Fielder's poster for details!

(and Fielder+2024, in prep)



Dwarf galaxy near NGC 4214 (D~2.9 Mpc, $M_* \sim 1\times10^9\ M_{Sun}$; ~0.4 $M_{*,LMC}$)



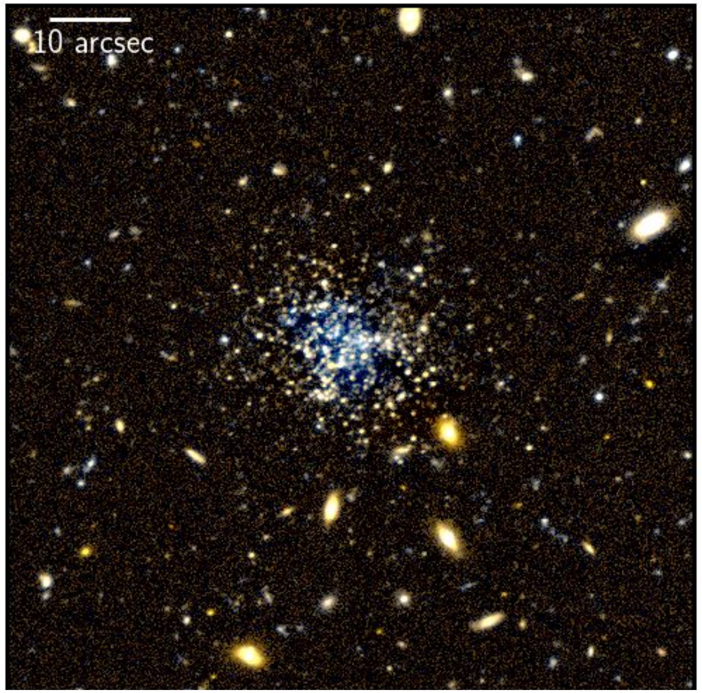
MADCASH J121007+352635-dw

M_V ~ -9.2

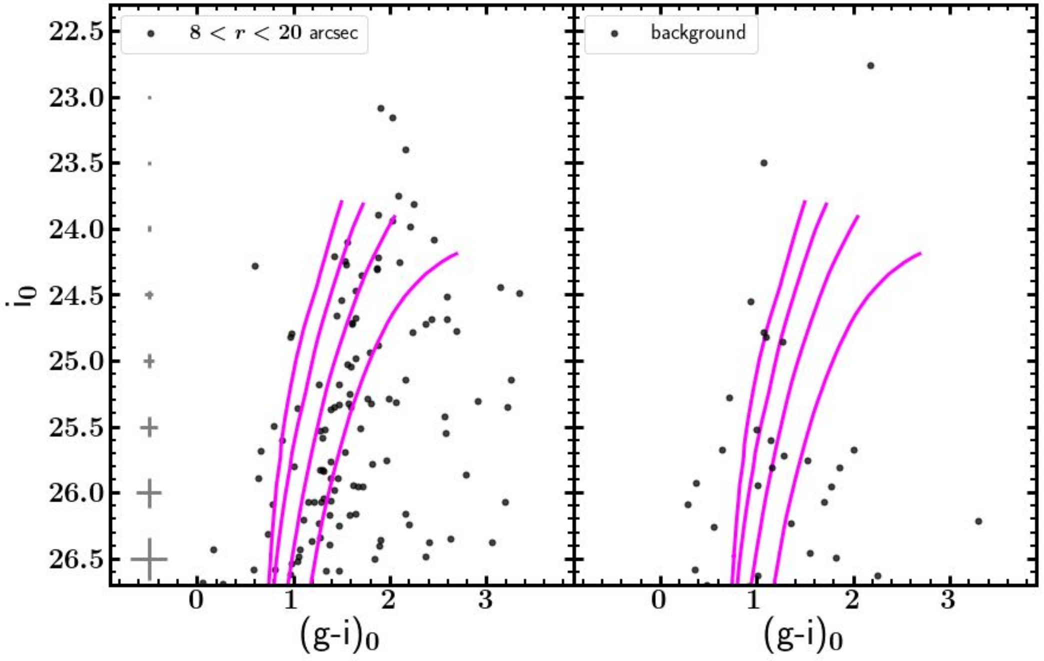
r_{half} ~ 131 pc

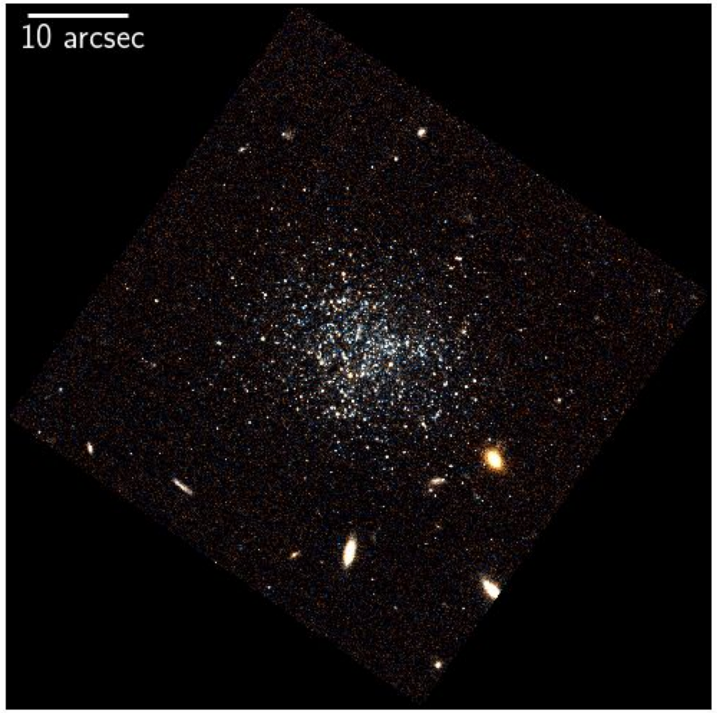
R_{proj}~70 kpc from NGC 4214

(aka “MADCASH-2”)

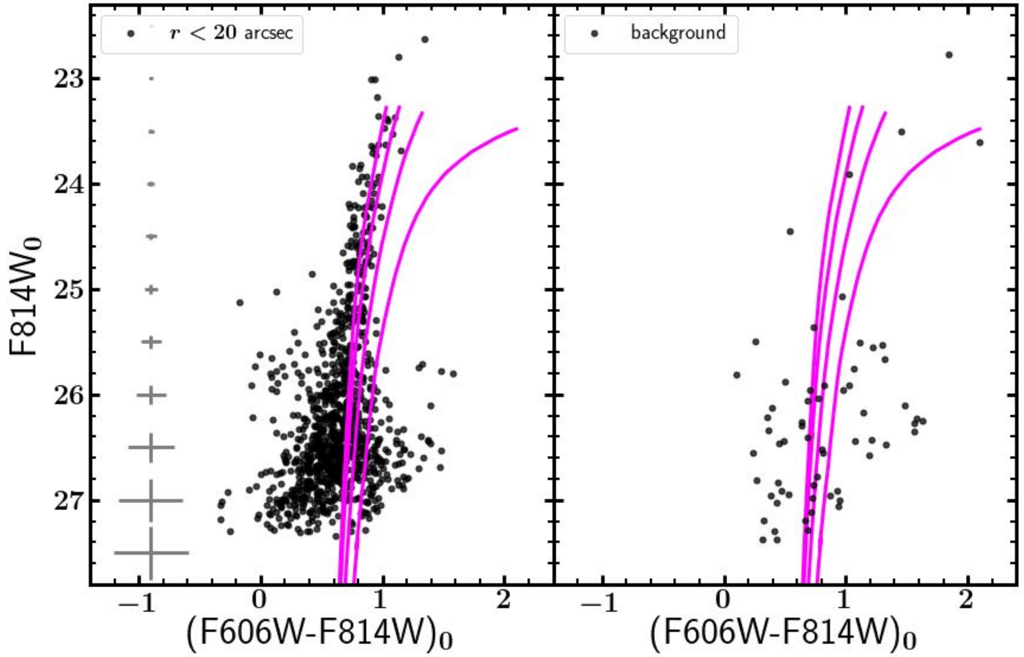


Subaru/HSC





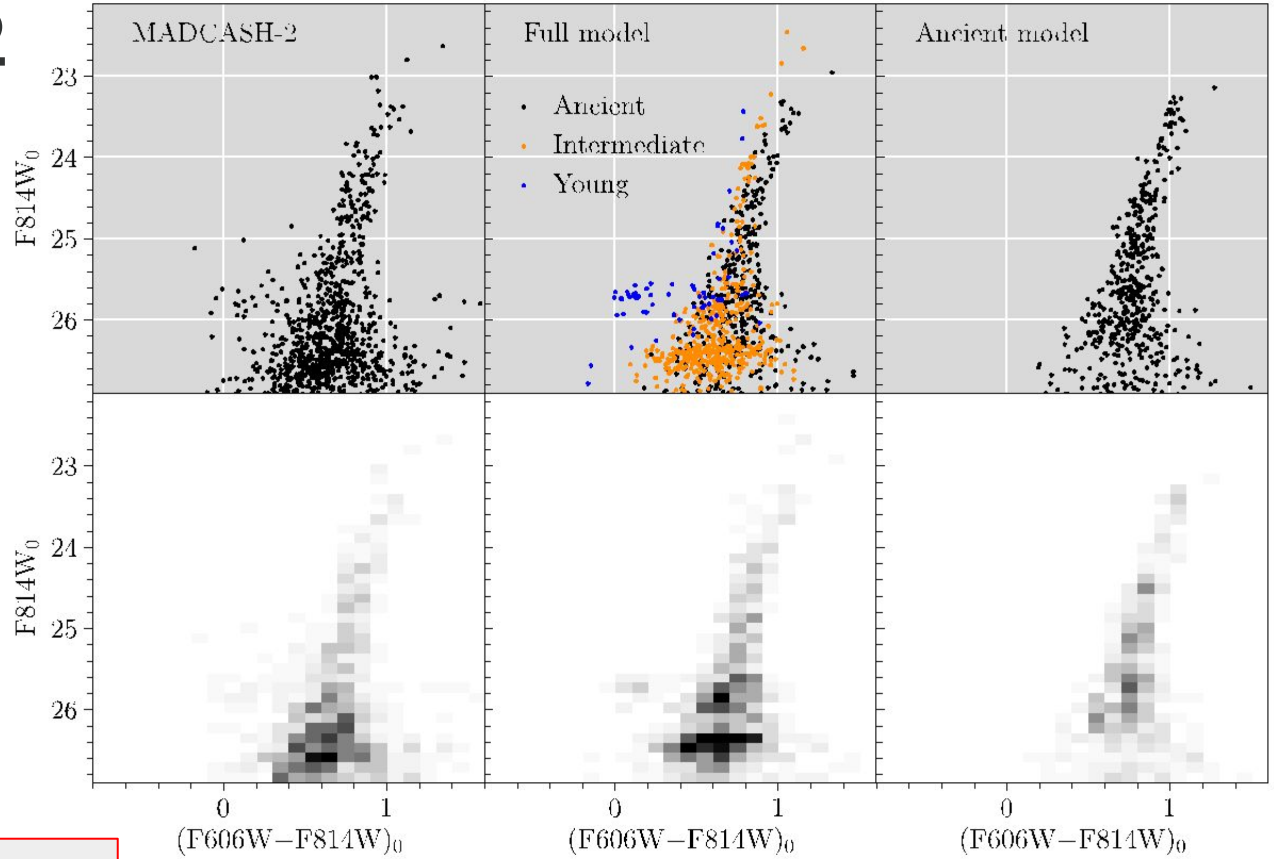
HST/ACS

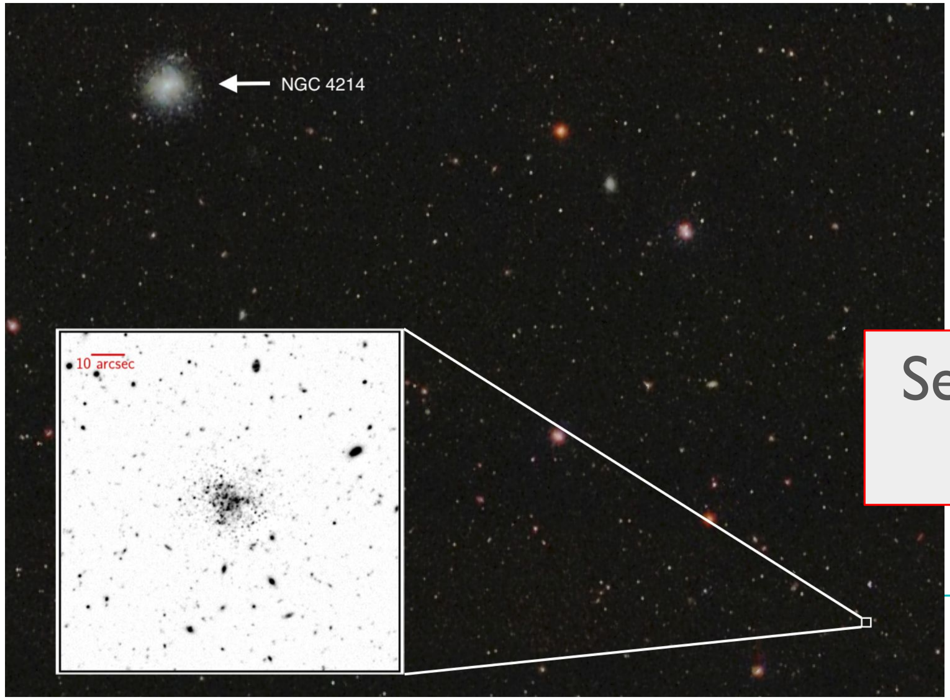


Carlin+2021, ApJ, 909, 211

Surprising results among satellites of nearby ~LMC hosts: young stellar populations in MADCASH-2

- ~10% of its stellar mass formed in the past ~1.5 Gyr
- No neutral hydrogen detected ($M_{HI} < 4.8 \times 10^4\ M_{sun}$)





See Carlin+2021, ApJ, 909, 211

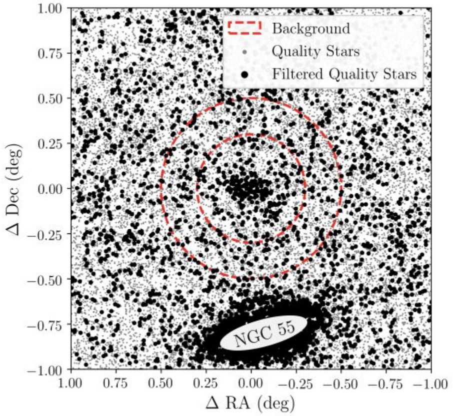
Properties measured from HST data:

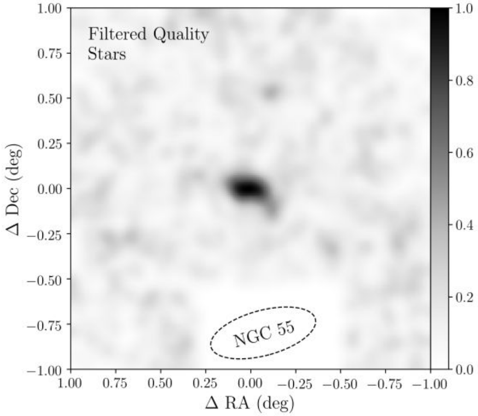
$M_V \sim -9.2$

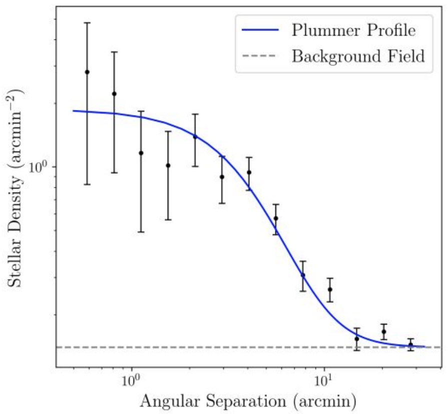
$r_{half} \sim 131$ pc

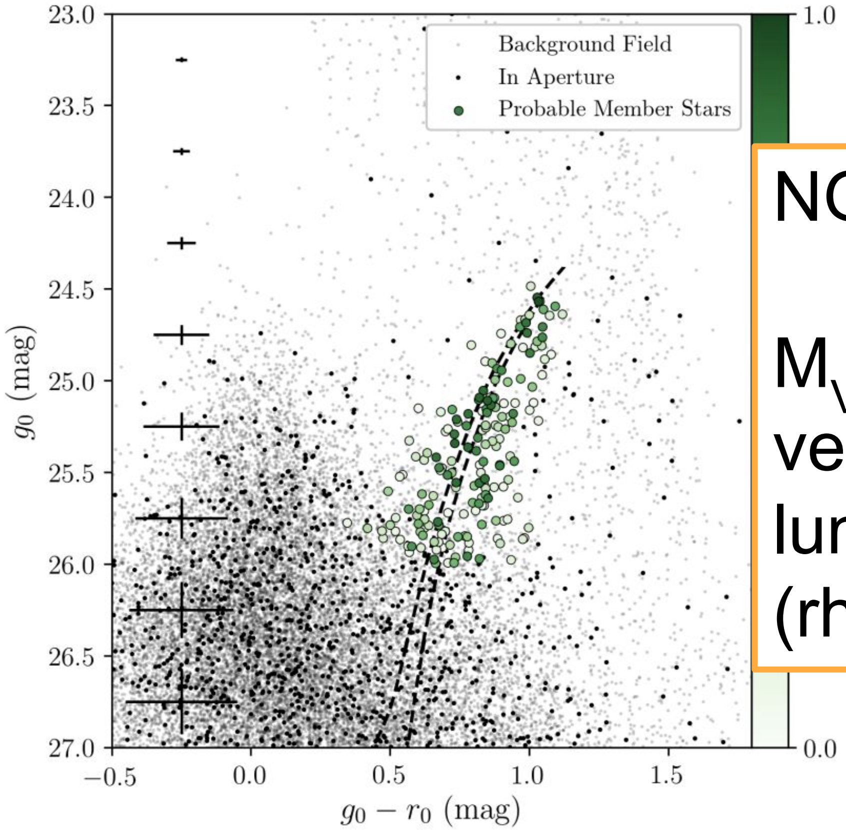
$R_{proj} \sim 70$ kpc from NGC 4214

NGC 55 ($M_* \sim M_{*,LMC}$) dwarf satellite



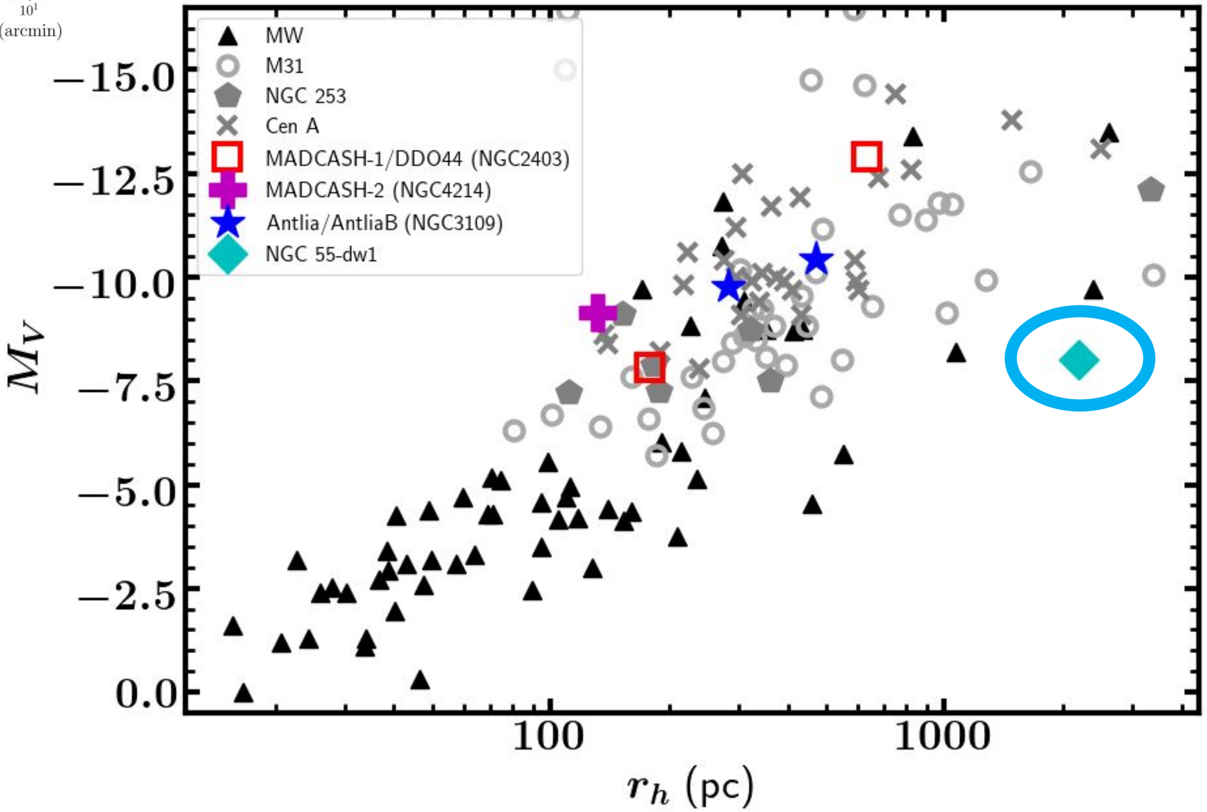






NGC 55-dw1:

M_V = -8.0,
very large for its luminosity
(rhalf ~ 2.2 kpc)



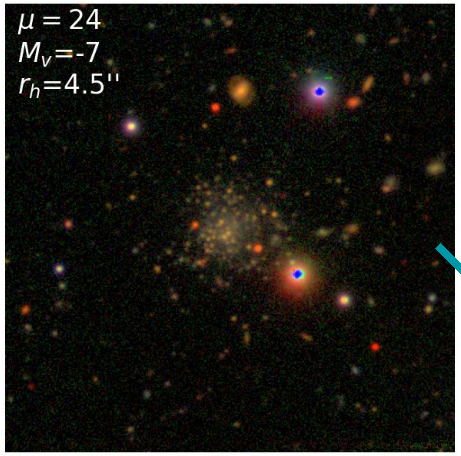
McNanna+2024 (ApJ 961, 126)

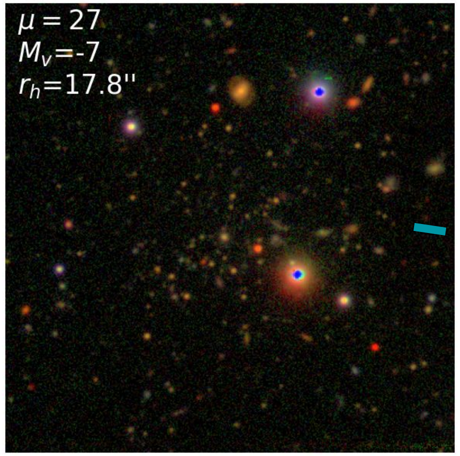
Most of these Local Volume dwarfs are discovered from the ground, but require space-based follow-up to confirm+characterize. How do we deal with this in the LSST era?

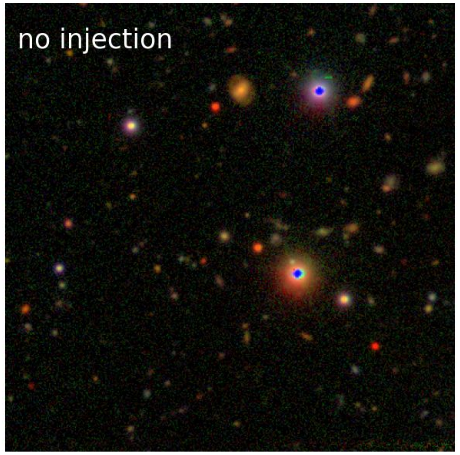
Detecting "partially resolved" dwarfs

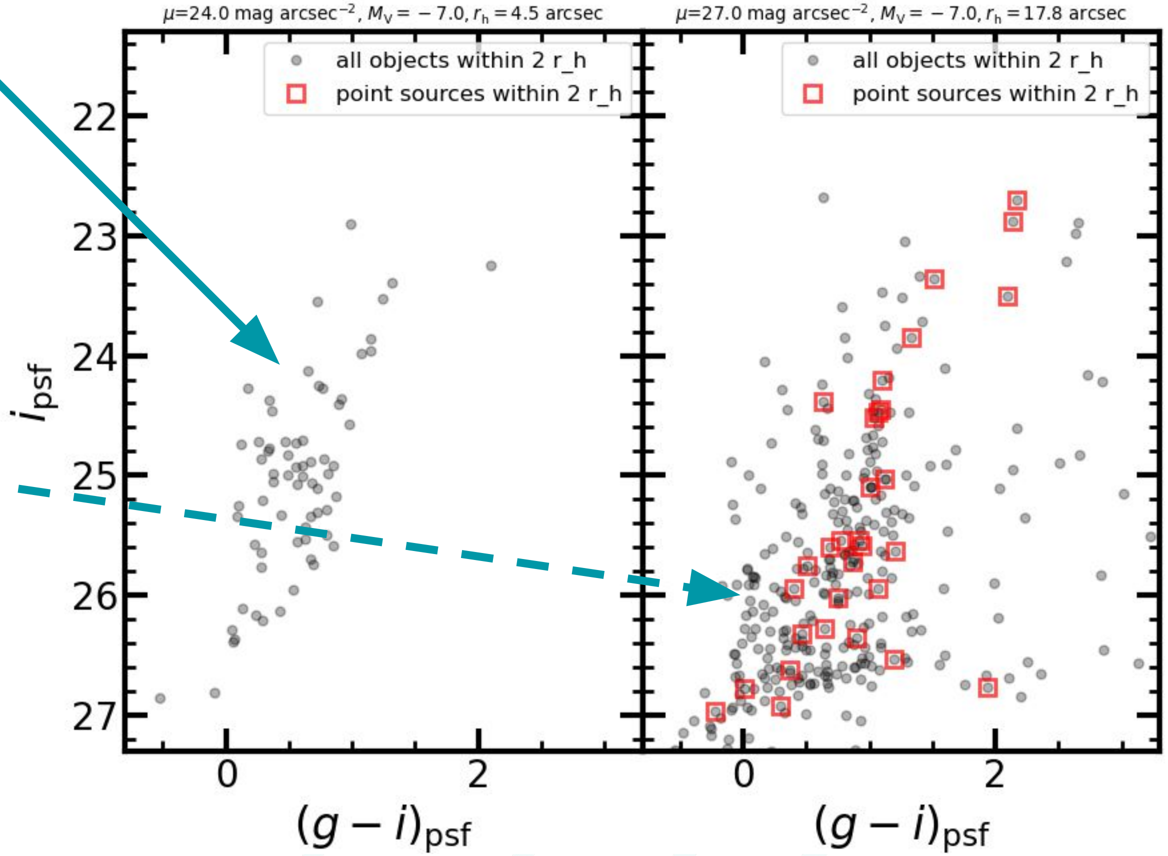
ongoing work (with Peter Ferguson – see his poster!):

1. inject dwarfs into Subaru+HSC images
2. train an RCNN to identify them
3. (search for dwarfs over the full LSST footprint)









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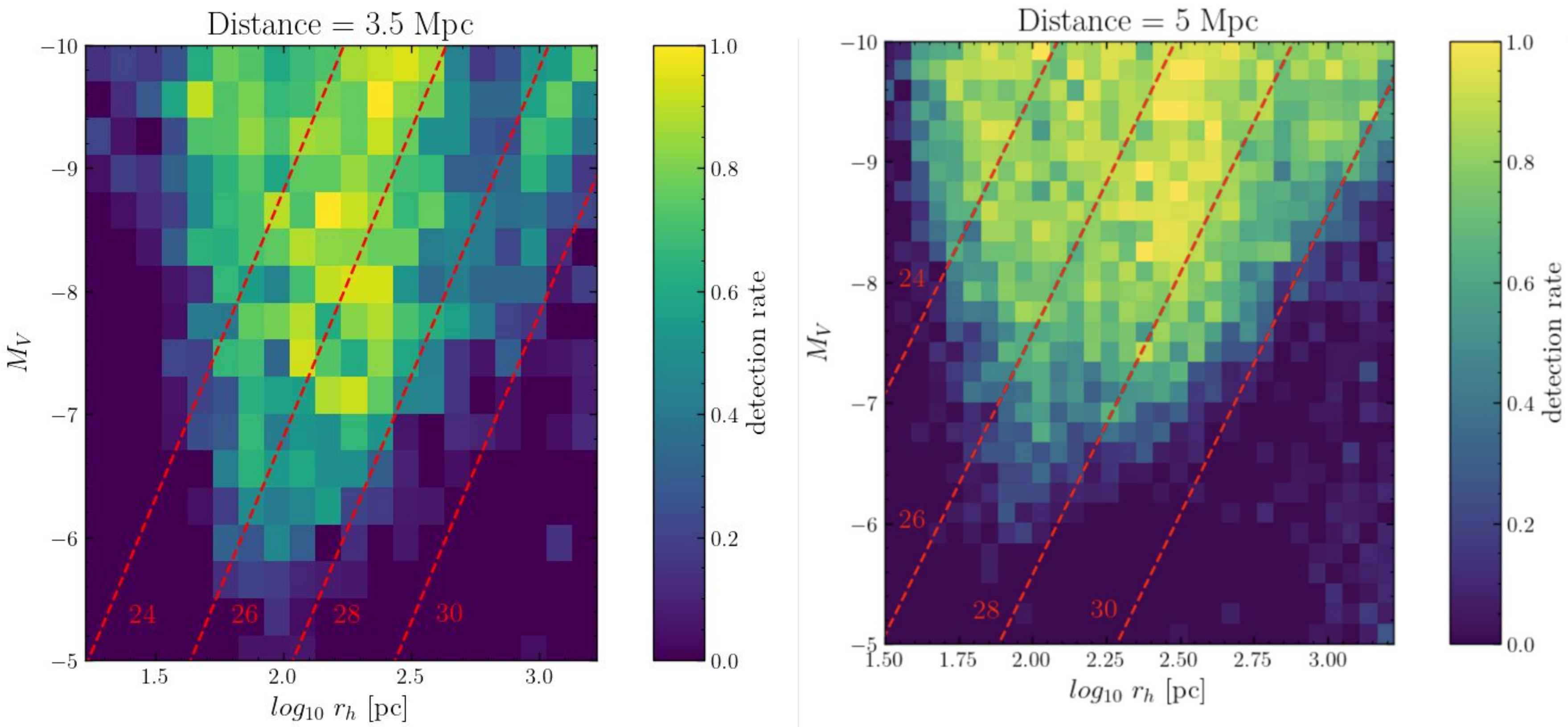
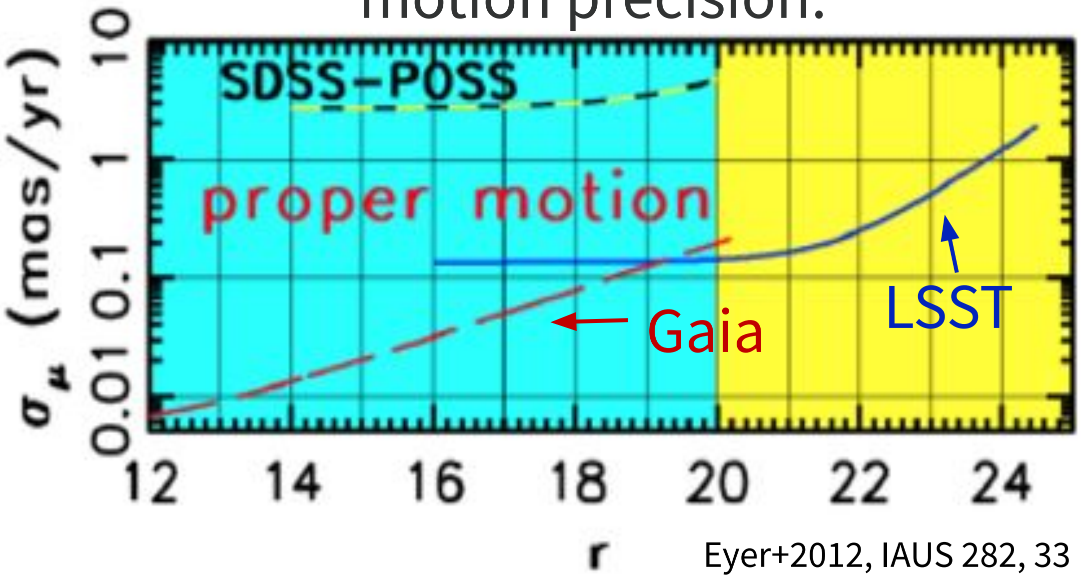
recovery rate at two distances:



Recovering fainter, and more compact, dwarfs than matched-filter detection!

LSST proper motions

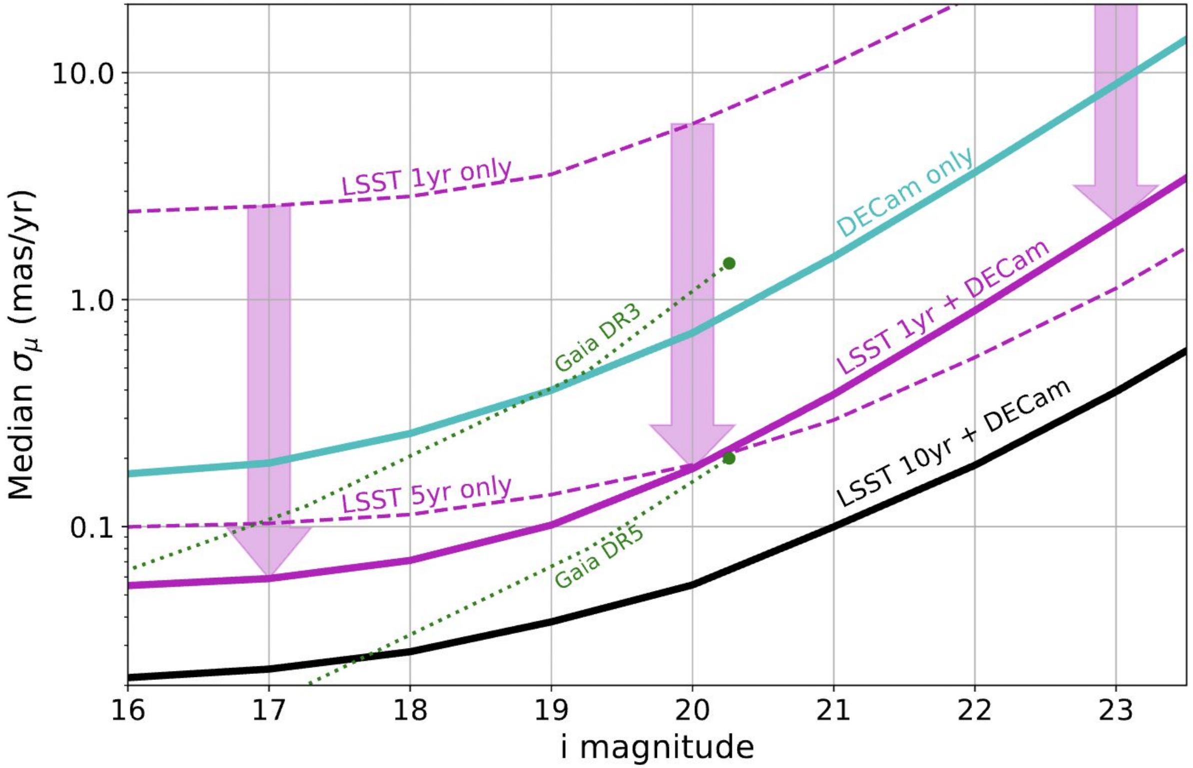
Expected proper motion precision:



Eyer+2012, IAUS 282, 33

Proposal: improve LSST proper motions by using DECam data as baseline (A. Drlica-Wagner, G. Bernstein, et al.)

- Provides high-precision proper motions early in the survey (possibly DR1 or DR2)
- Longer baseline significantly increases the precision



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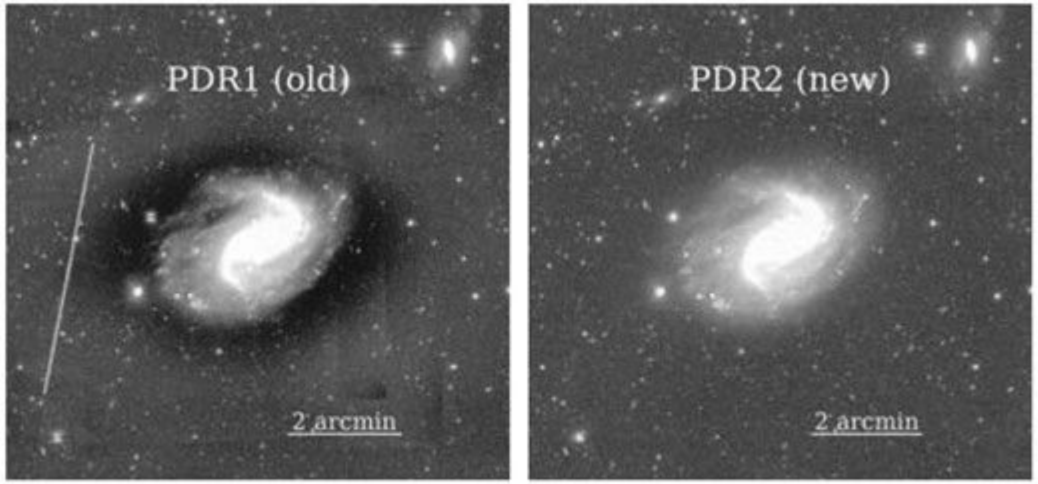
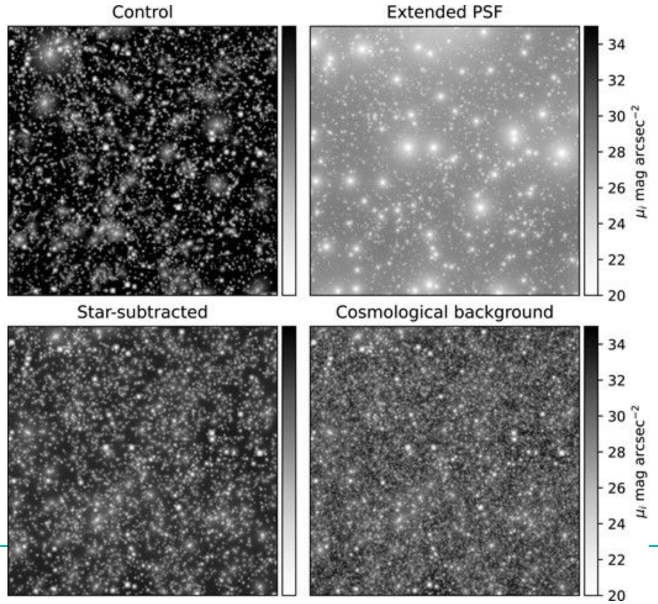
Optimizing background subtraction for LSB science

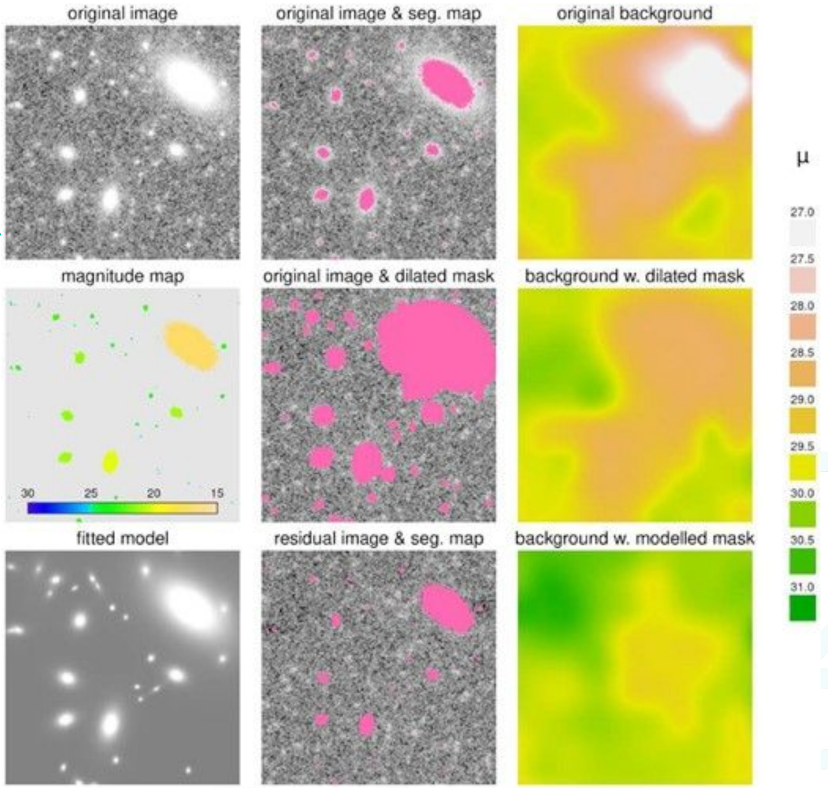


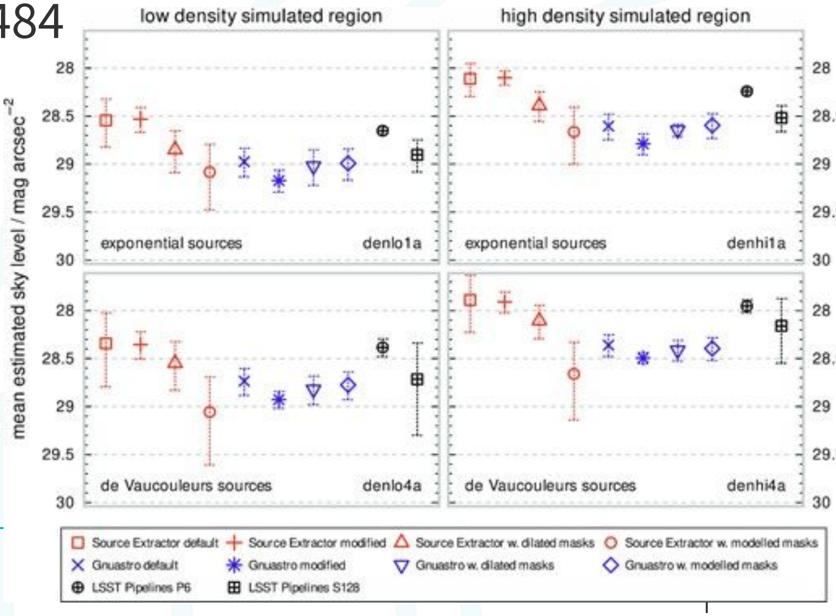
Aihara+2019, PASJ, 71, 114



Watkins+2024, MNRAS, 528, 4289

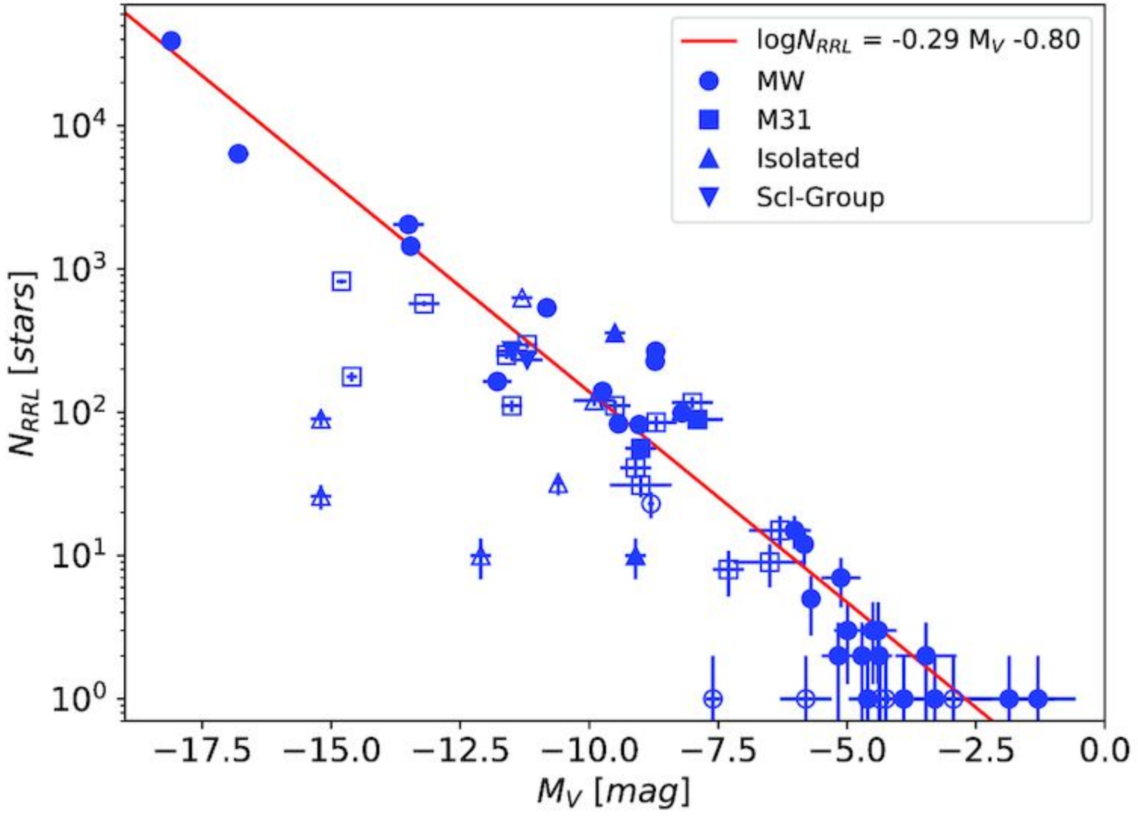
Kelvin+2023, MNRAS, 520, 2484



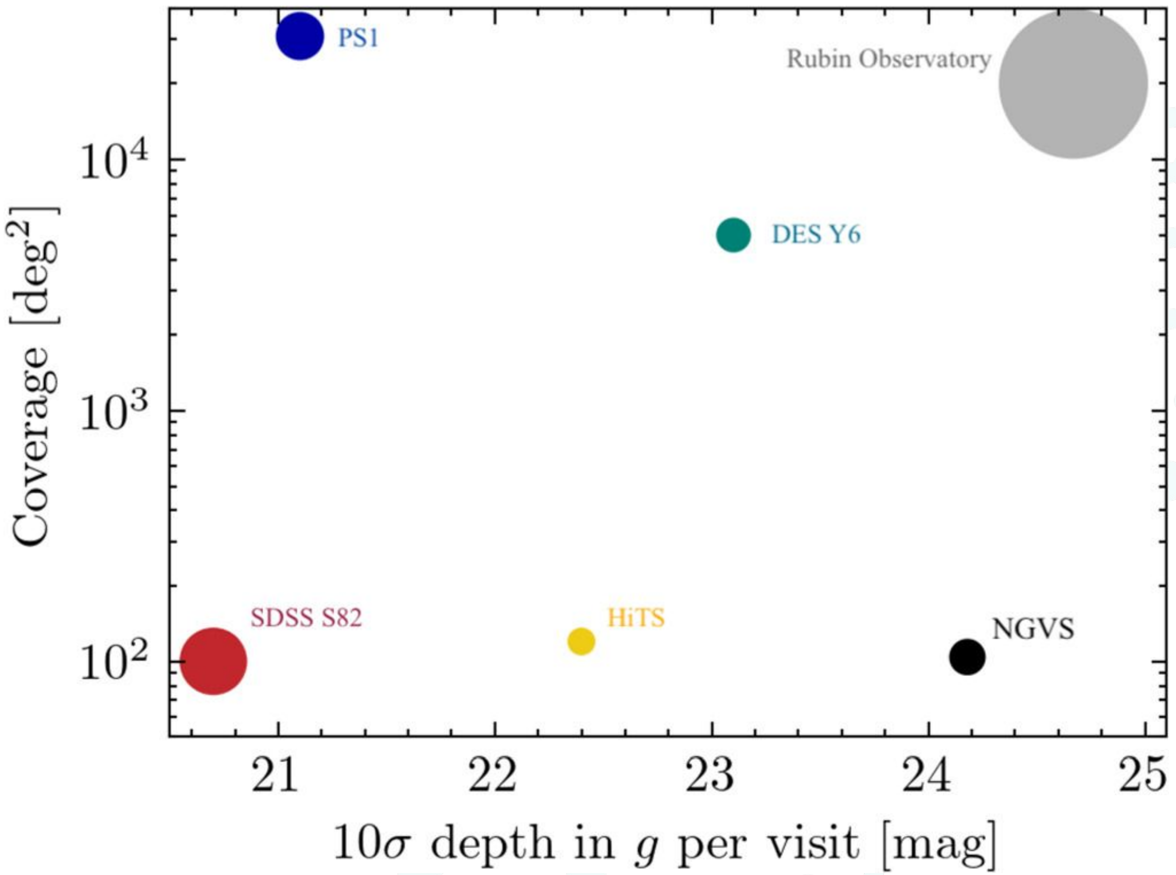


RR Lyrae as satellite beacons

Most MW dwarfs have RR Lyrae (e.g., Martinez-Vazquez+2019, MNRAS, 490, 2183):

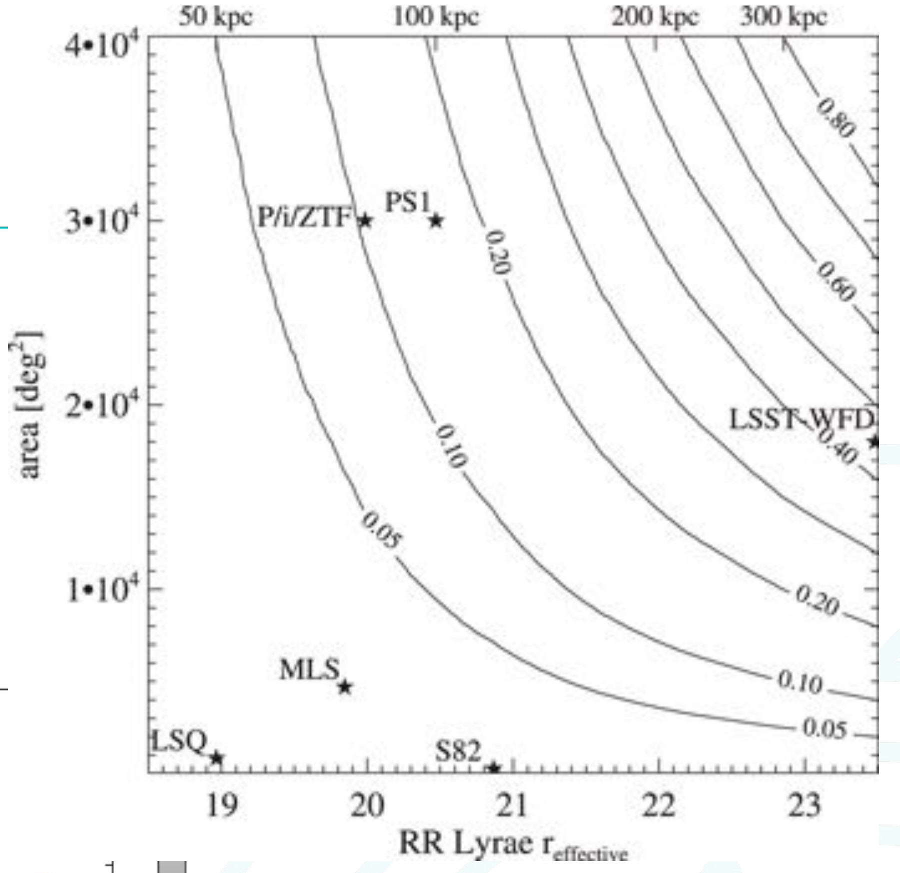


LSST will identify RR Lyrae beyond the MW virial radius, over ~20000 deg^2 of sky

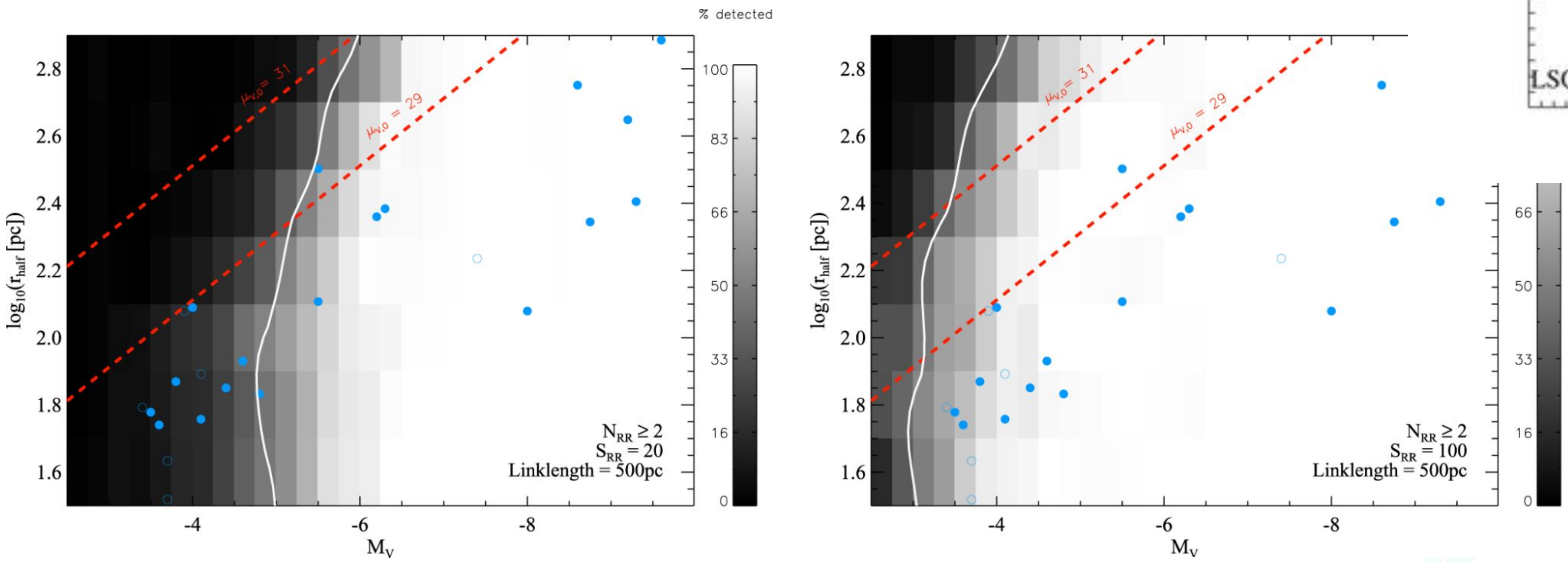


Feng+2024, ApJ, 966, 159

RR Lyrae as satellite beacons



MW dwarfs at D>100 kpc can be reliably identified as groupings of 2-3 RR Lyrae (within some "linking length" of, e.g., 500 pc; Baker+Willman 2015, AJ, 150, 160). (See also Sanderson+2017, MNRAS, 470, 5014.)



For an example of a dwarf (Leo V; d~170 kpc) identified via RR Lyrae, see Medina+2017, ApJL, 845, 10.

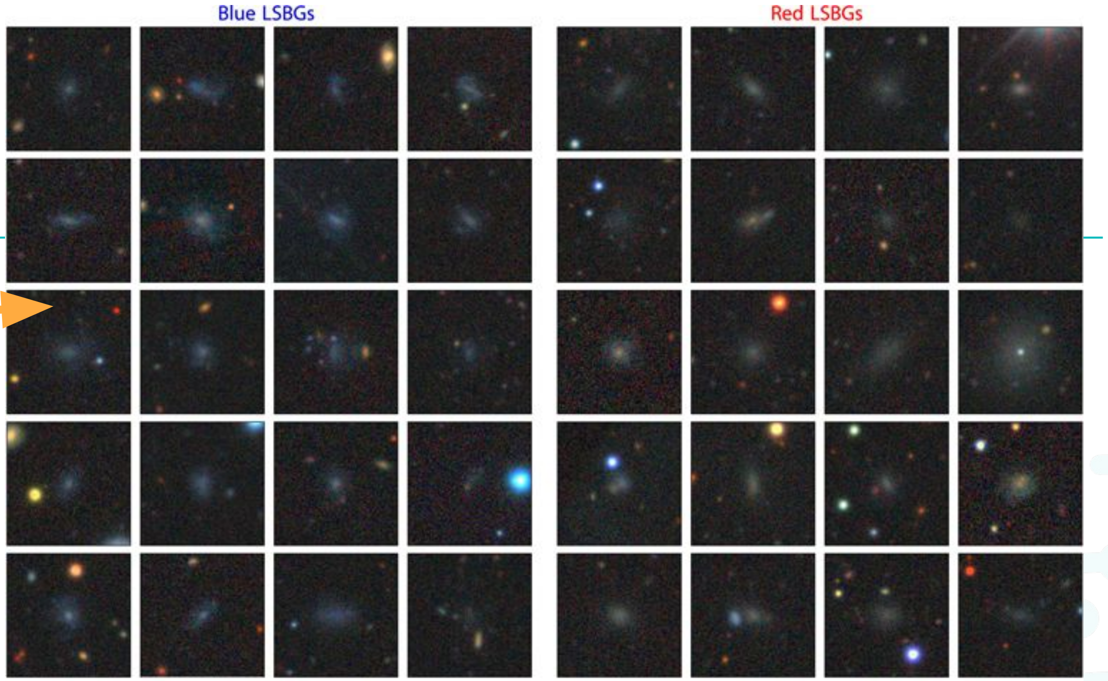
Figures: Baker & Willman 2015

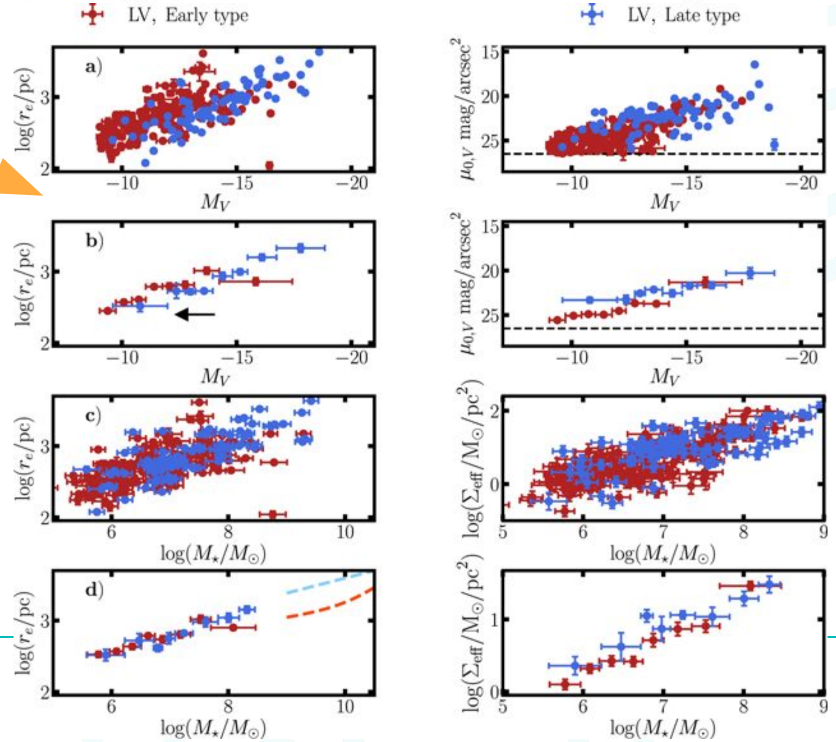
Unresolved or partially resolved LSB galaxies

VERA C. RUBIN OBSERVATORY

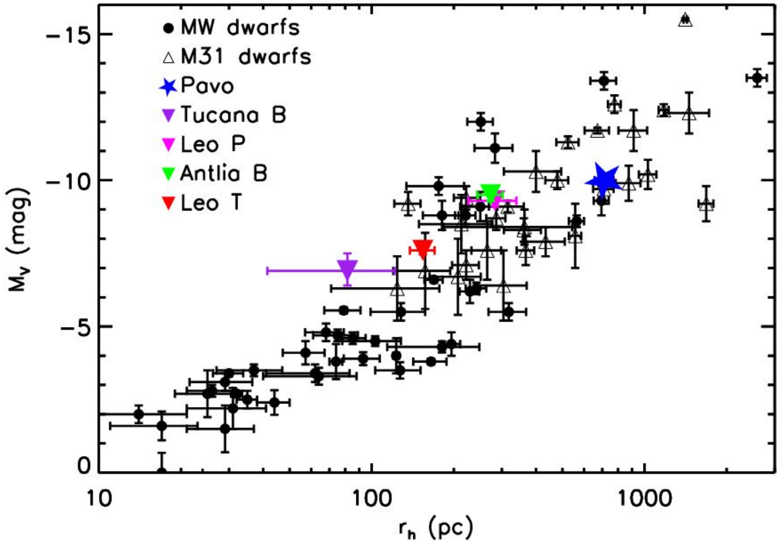
- LSB galaxies in DES – Tanoglidis+2021 (ApJS, 252, 18)
- Local Volume dwarf (M_V < -9) satellites using data from DECam, CFHT/Megacam, Subaru/HSC --

  Greco+2018 (ApJ, 857, 104); Carlsten+2021 (ApJ, 922, 267); Carlsten+2020 (ApJ, 891, 144); Carlsten+2020 (ApJ, 902, 124); Carlsten+2021 (ApJ, 908, 109); Carlsten+2022 (ApJ, 933, 47; ELVES)
- SAGA – spectroscopically confirmed dwarf (M_V < -12.3) satellites of 100 MW analogs – Mao+2021 (ApJ, 907,85); Geha+2017, (ApJ, 847, 4)

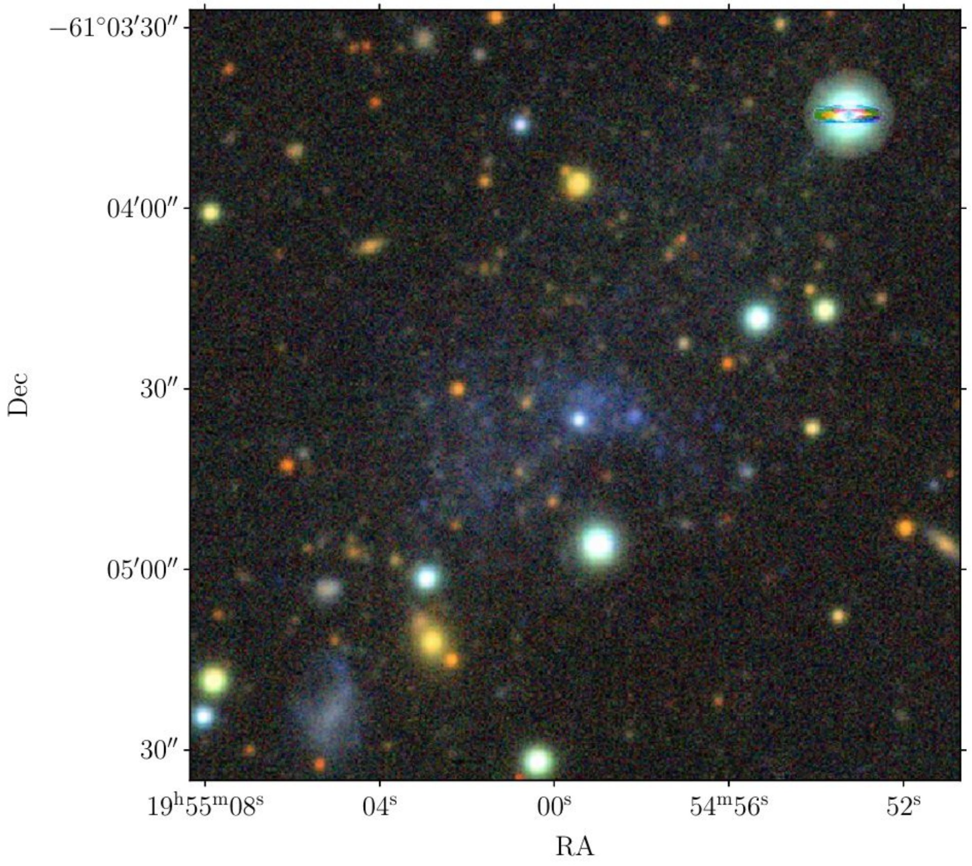


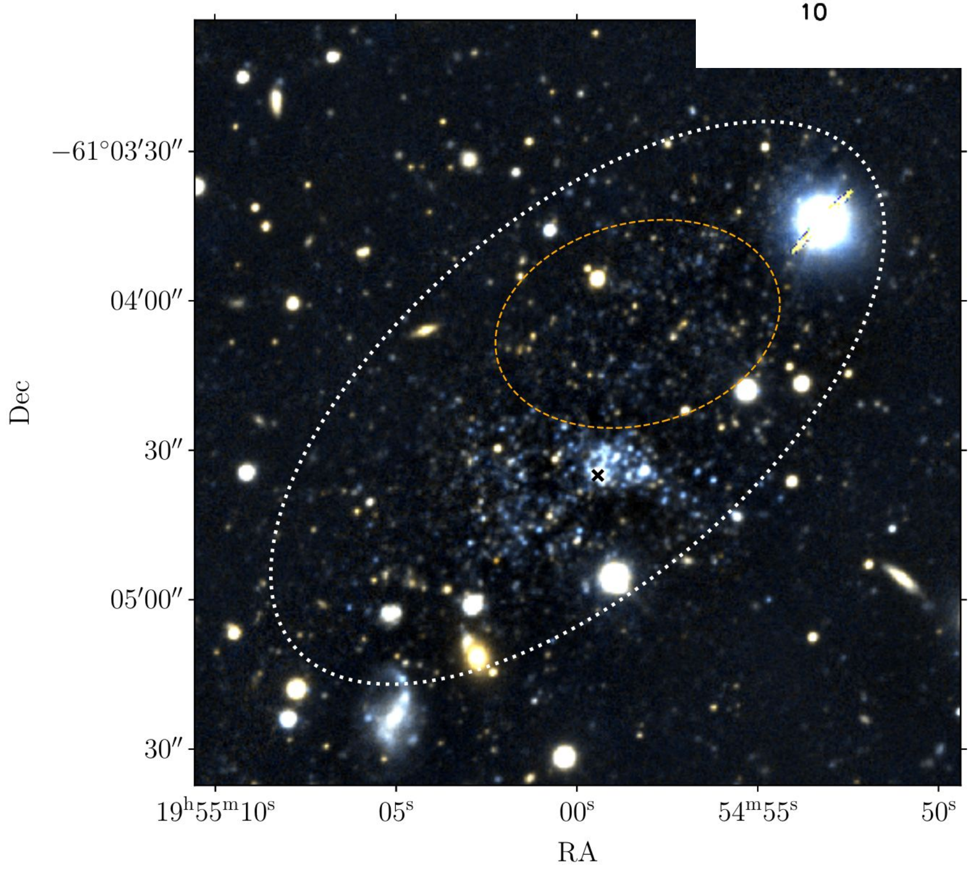


Pavo: a blue, star-forming, gas-rich, isolated dwarf at D~2 Mpc



Jones+2023 (ApJL, 957, 5)





Found using ML classification trained on LV dwarfs, ultra-faint dwarfs, SHIELD galaxies, etc.

lossary: ls.st/glossary

Thank you!