Searching for Extreme Stellar Systems in Survey Data

Aaron J. Romanowsky

San José State University;

Univ. California Santa Cruz

with:

Yimeng Tang, Duncan Forbes, Alexa Villaume, Asher Wasserman, Luísa Buzzo, Shany Danieli, Jonah Gannon, Pieter van Dokkum, Bob Abraham, Jean Brodie, Charlie Conroy, Warrick Couch, Anna Ferré-Mateu, Steve Janssens, Tom Jarrett, Michael Keim, Diederik Kruijssen, Seppo Laine, Chris Martin, Matt Matuszewski, Zili Shen, Sebastian Trujillo-Gomez, Joel Pfeffer

see posters from: Yash Bains, Leilani Kenoly, Logan O'Brien

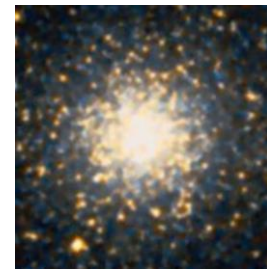Rare Gems in Big Data, 23 May 2024

The Universe in the year 2000: galaxies and star clusters
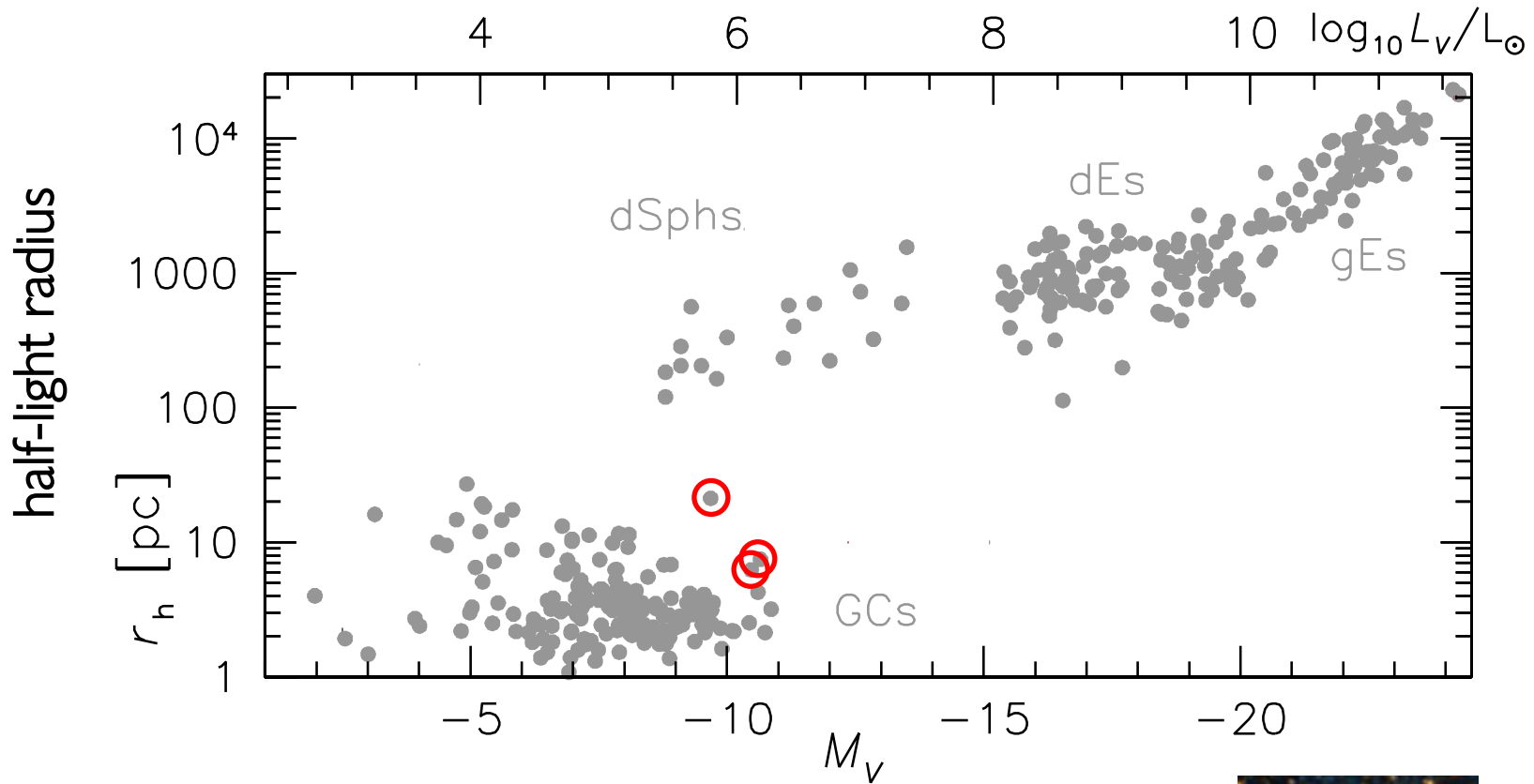
quiescent stellar systems, known as of year ~ 2000 :

➤ dwarf spheroidals, dwarf E/S0s, giant E/S0s

➤ globular clusters

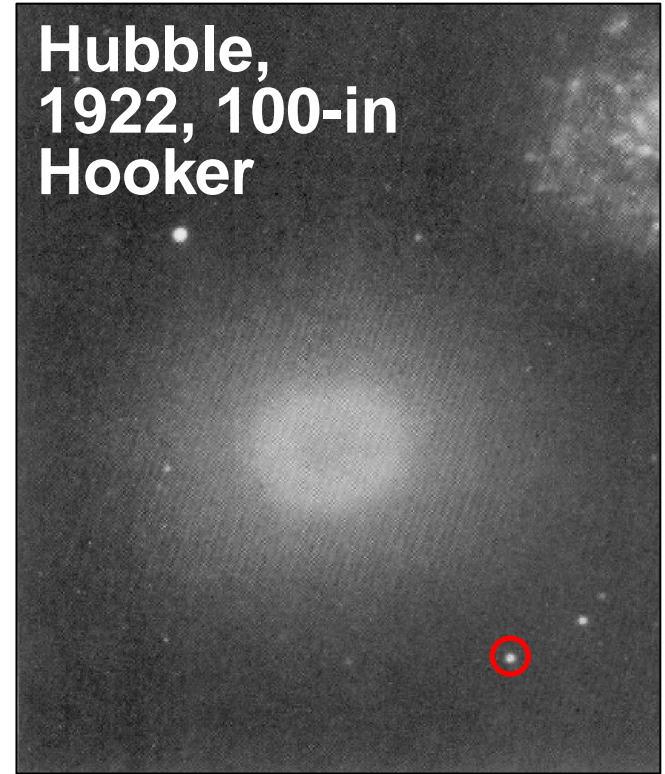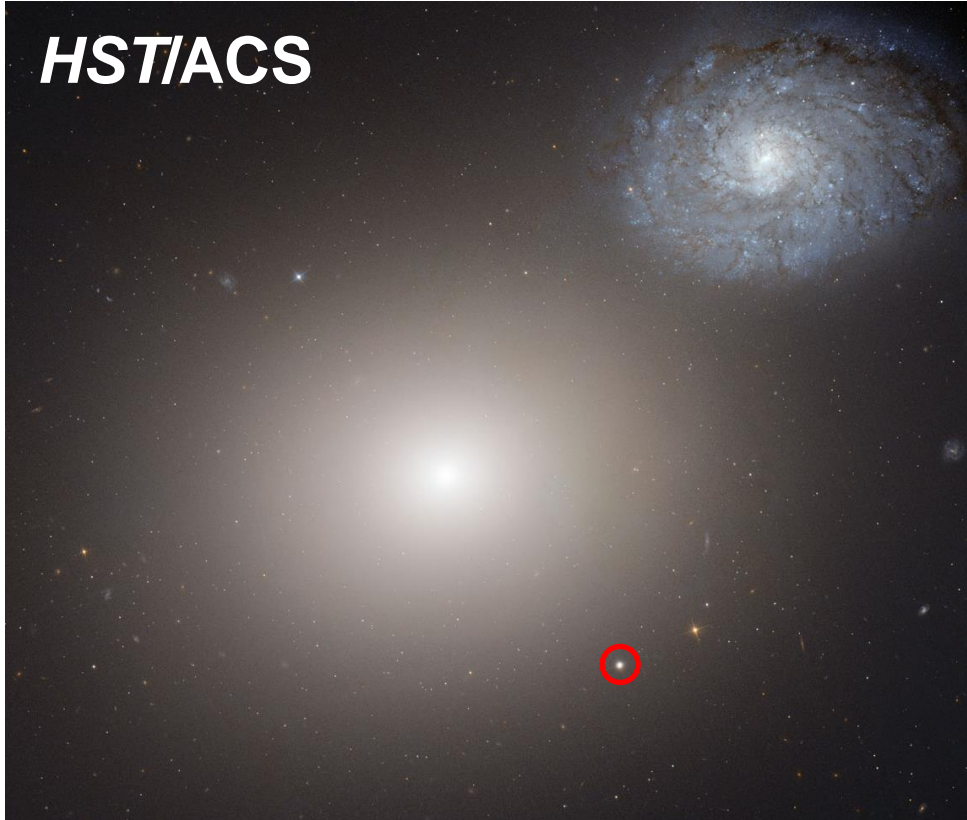… peculiar massive, extended clusters
    NGC 2419, M54, ω Cen

NGC 2419

ω Cen
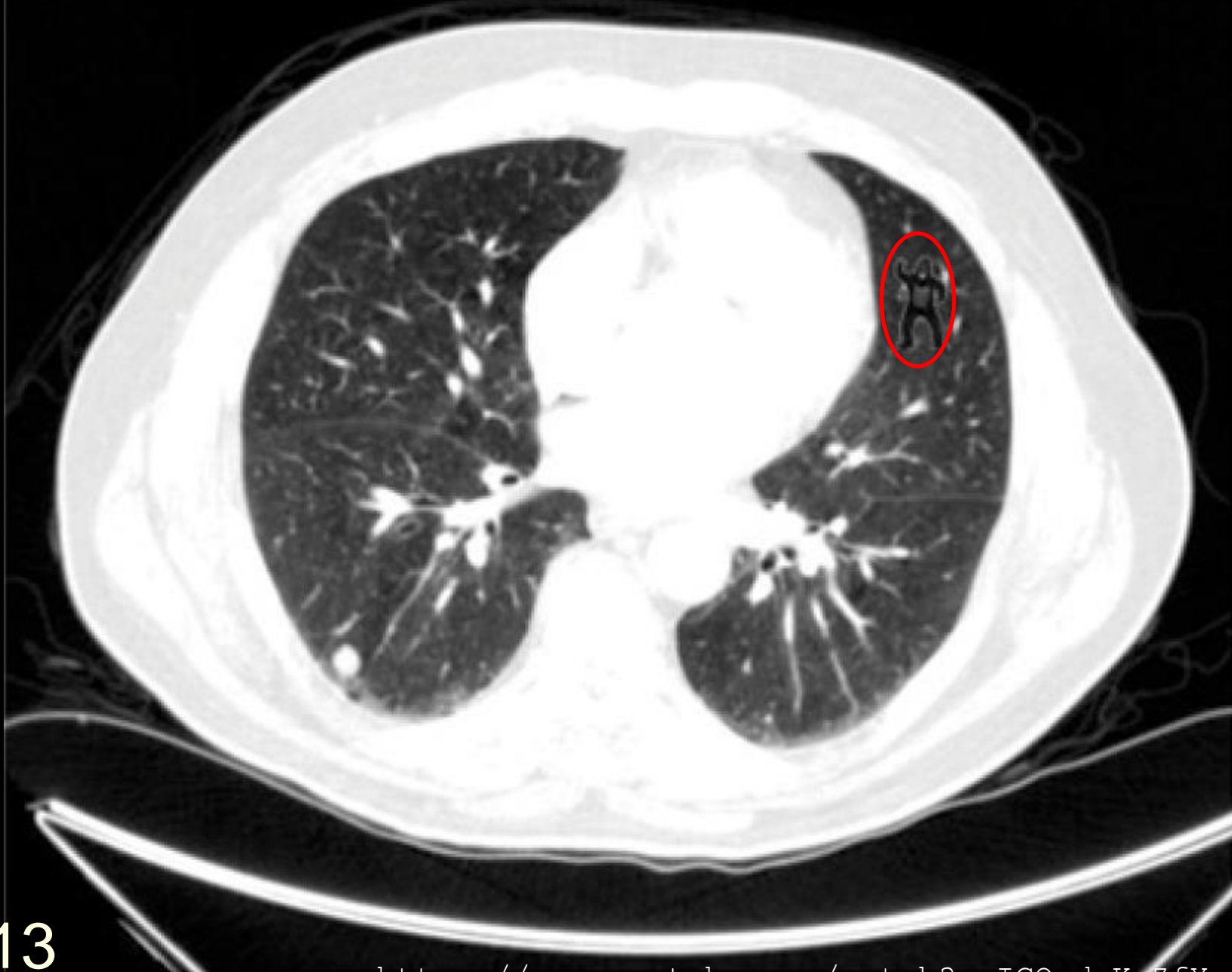
typical GC

Hiding in plain sight: extreme GCs/galaxies

M60-UCD1: "ultracompact dwarf" orbiting giant elliptical M60

(the "densest galaxy": Strader+13)

$$L_V = 4{\times}10^7 L_\odot ,$$
$$r_\mathrm{h} = 26 \text{ pc}$$

ω **Cen**

M60-UCD1

UCDs discovered by Hilker+99

why weren't they recognized

Concentration test / inattentional blindness

Drew+13

Online search for dense stellar systems

(Sandoval, Vo, Romanowsky+2015)

- SJSU undergrads searched through SDSS photometric + spectroscopic catalogs
- cross-match and follow-up with Subaru, *HST*, SOAR, Keck, LBT

Dense and denserer

new densest galaxy
$M_\star \cong 2 \times 10^8\ \mathrm{M_\odot}$, $r_\mathrm{h} \cong 20\ \mathrm{pc}$

overmassive SMBH w/AO:
implies stripped nucleus
(Ahn+18)

M59-UCD3
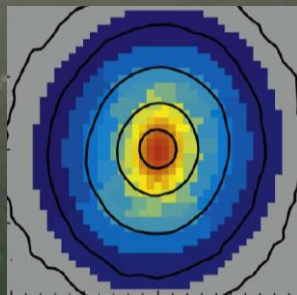
"hypercompact cluster":
densest free-floating
stellar system
$M_\star \cong 10^7\ \mathrm{M_\odot}$, $r_\mathrm{h} \cong 2\ \mathrm{pc}$
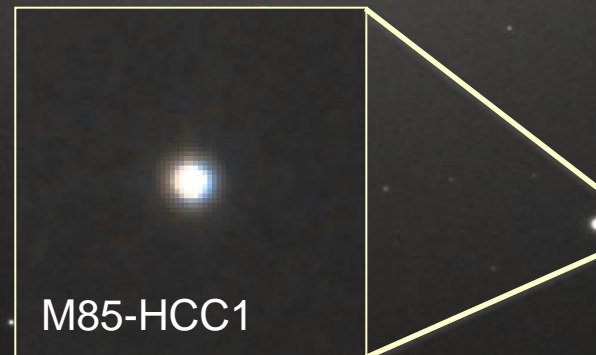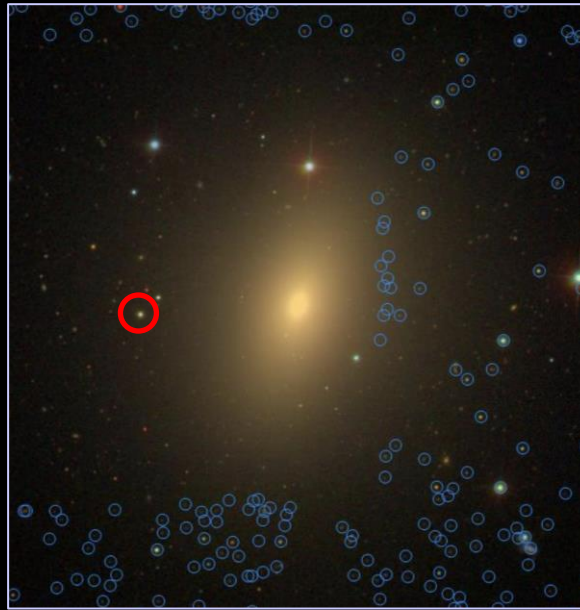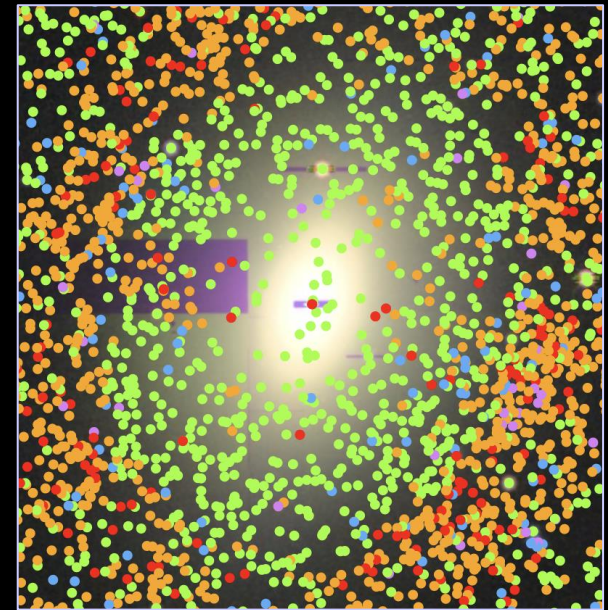
M85-HCC1

Archival photometry for M59-UCD3
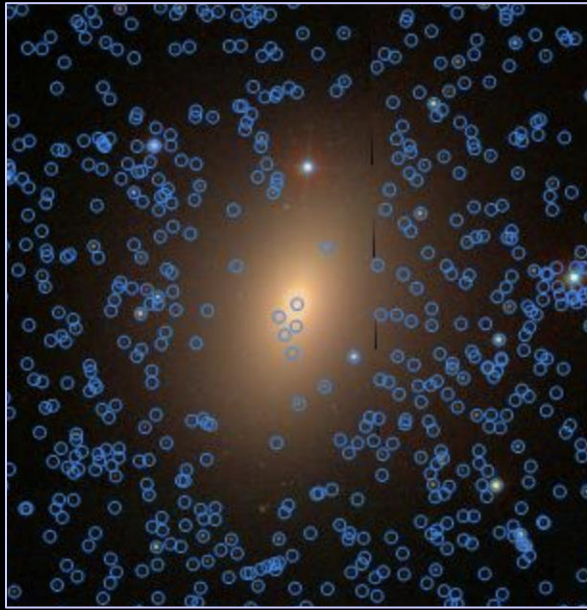
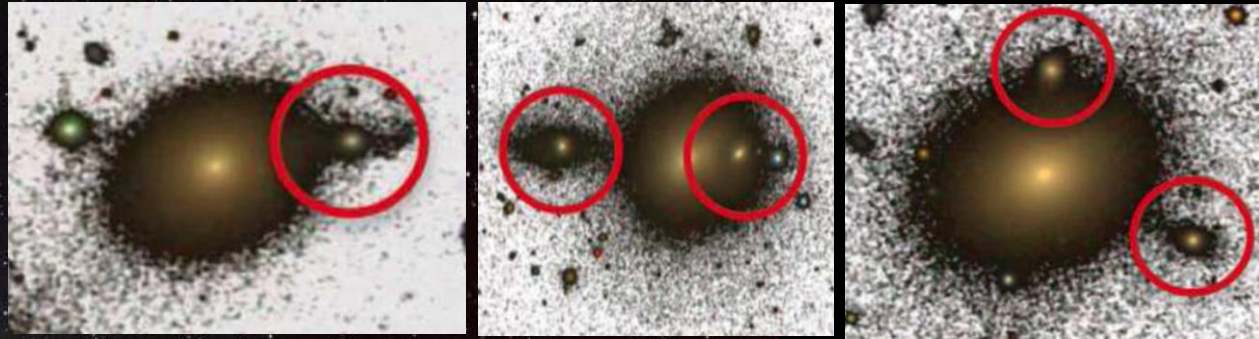SDSS DR7: "GALAXY"   SDSS DR18: N/A   Legacy DR10: "PSF/stellar"

We were lucky to do the search with SDSS DR7.

We could still be missing many bright UCDs and hypercompact clusters around nearby galaxies…

M32 as a rare gem?

M31

M32

SDSS search for nearby compact ellipticals: mostly stripped galaxy origins (Ferré-Mateu+18,21)

Finding (ultra)compact galaxies with CNN

cEs and UCDs

VCC1627 cE

NGC5846cE/J150634.27+013331.6 cE

VUCD7 UCD

M59cO UCD

contaminants

Contaminant 3

Contaminant 4

Contaminant 7

Contaminant 8

- Image training set of nearby cEs/UCDs is only 14 → data augmentation (rotations)

- ResNet CNN, transfer learning after training first on Galaxy Zoo (20,000 i

- 8
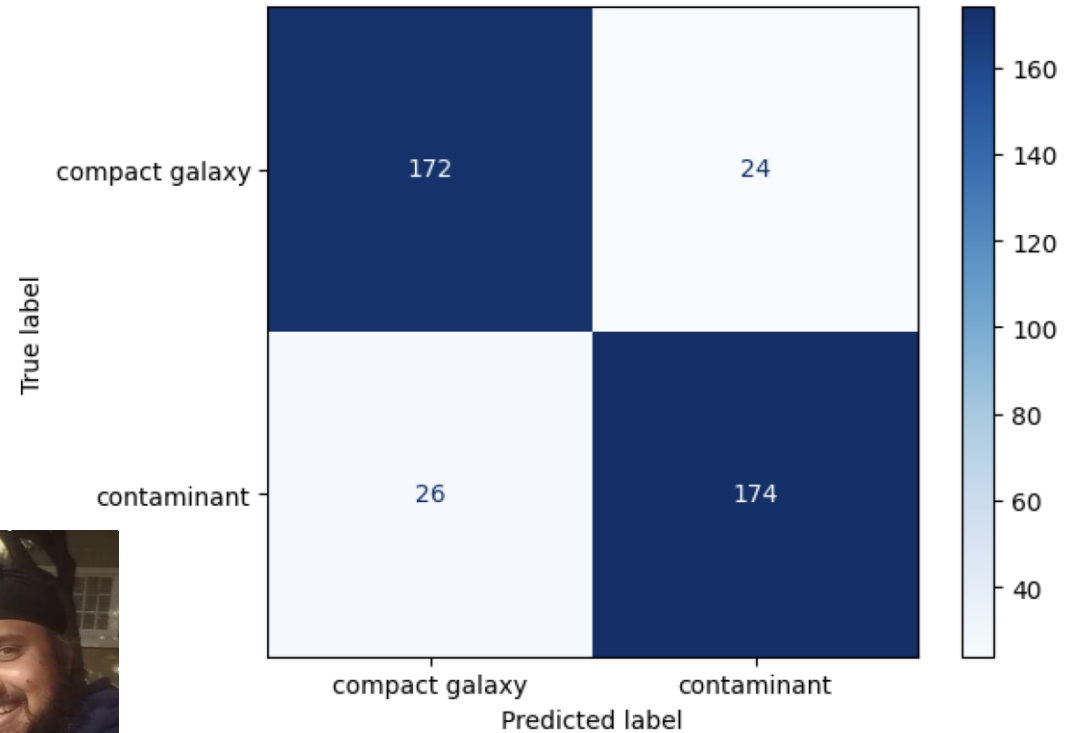
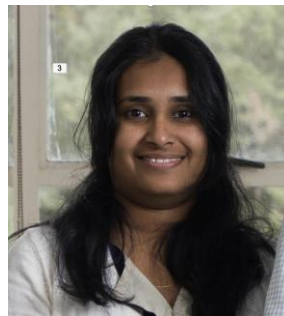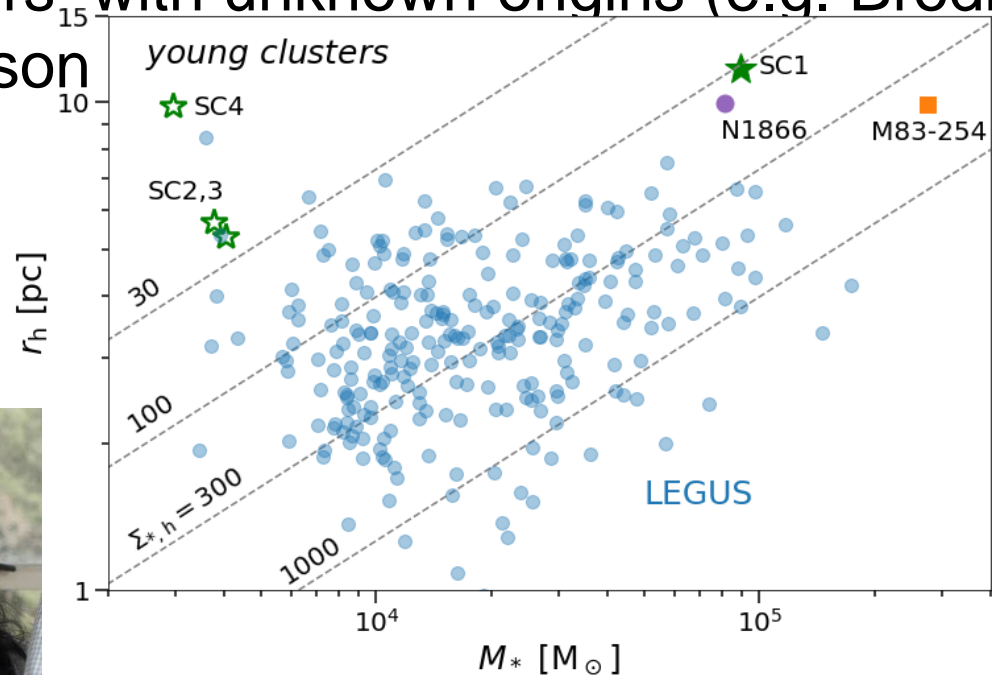|	compact galaxy	contaminant
compact galaxy	172	24
contaminant	26	174

True label

Predicted label

Singh & Romanowsky, in prep

A young "faint fuzzy" star cluster

- found during GC search in low-mass spiral NGC 247 at 3.5 Mpc (Subaru/HSC)
- *HST* follow-up: r_h = 12 pc, $M_\star \sim 10^5\ M_\odot$
  300 Myr age (CMD fitting)
- cf. old faint fuzzies / extended star clusters with unknown origins (e.g. Brodie & Larson
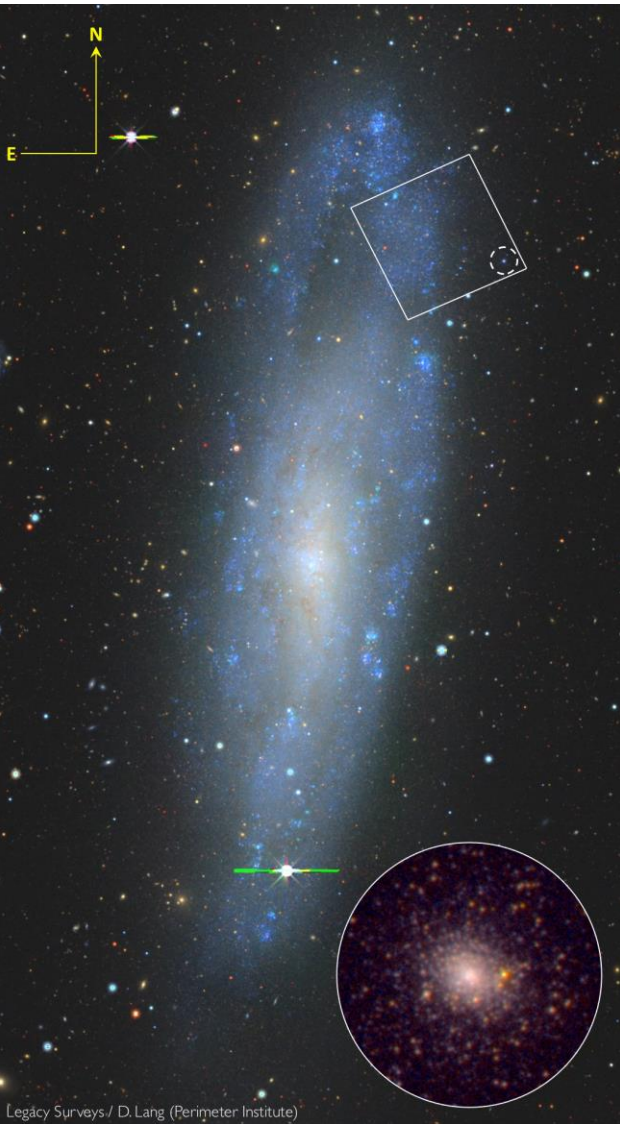
Romanowsky et al.
incl. Santhanakrishnan
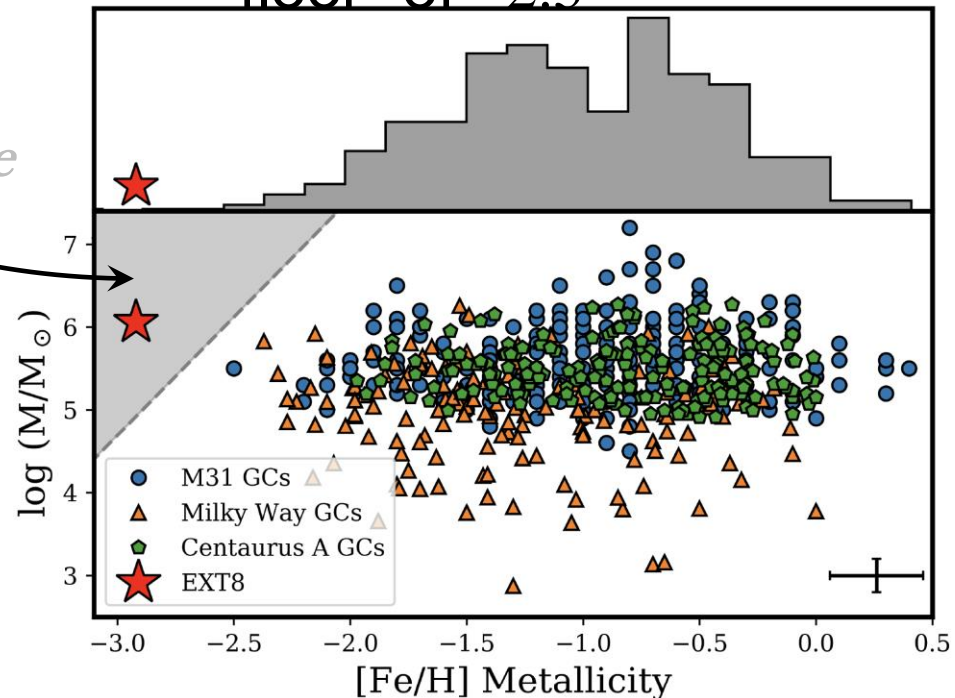
Impossible globular cluster in M31

WFC3
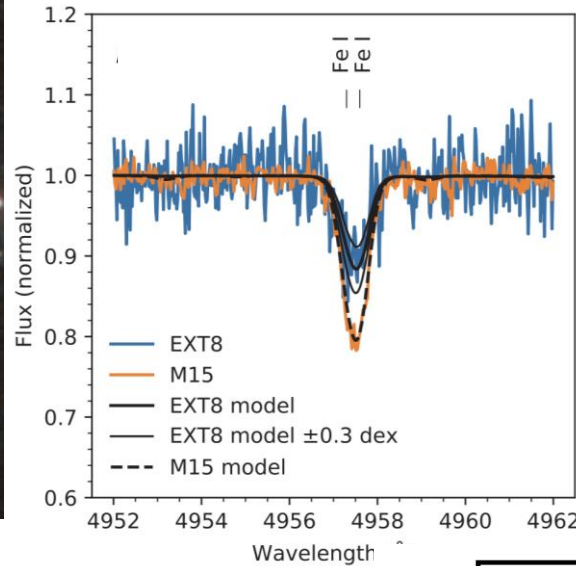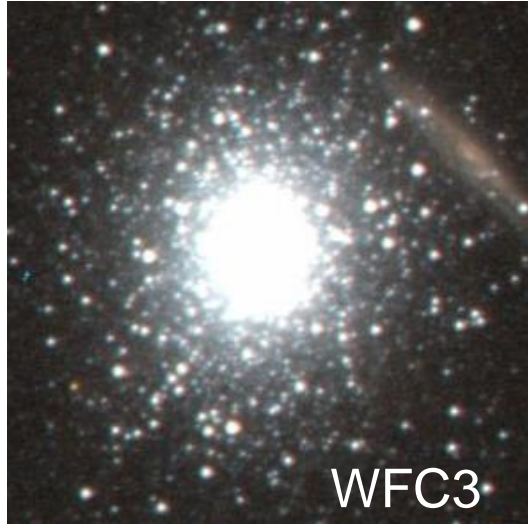
Larsen+20,21

$[Fe/H] = -2.91 \pm 0.04$

found serendipitously during Keck/HIRES chemical abundance studies of Local Group GCs, breaks "metallicity floor" of -2.5

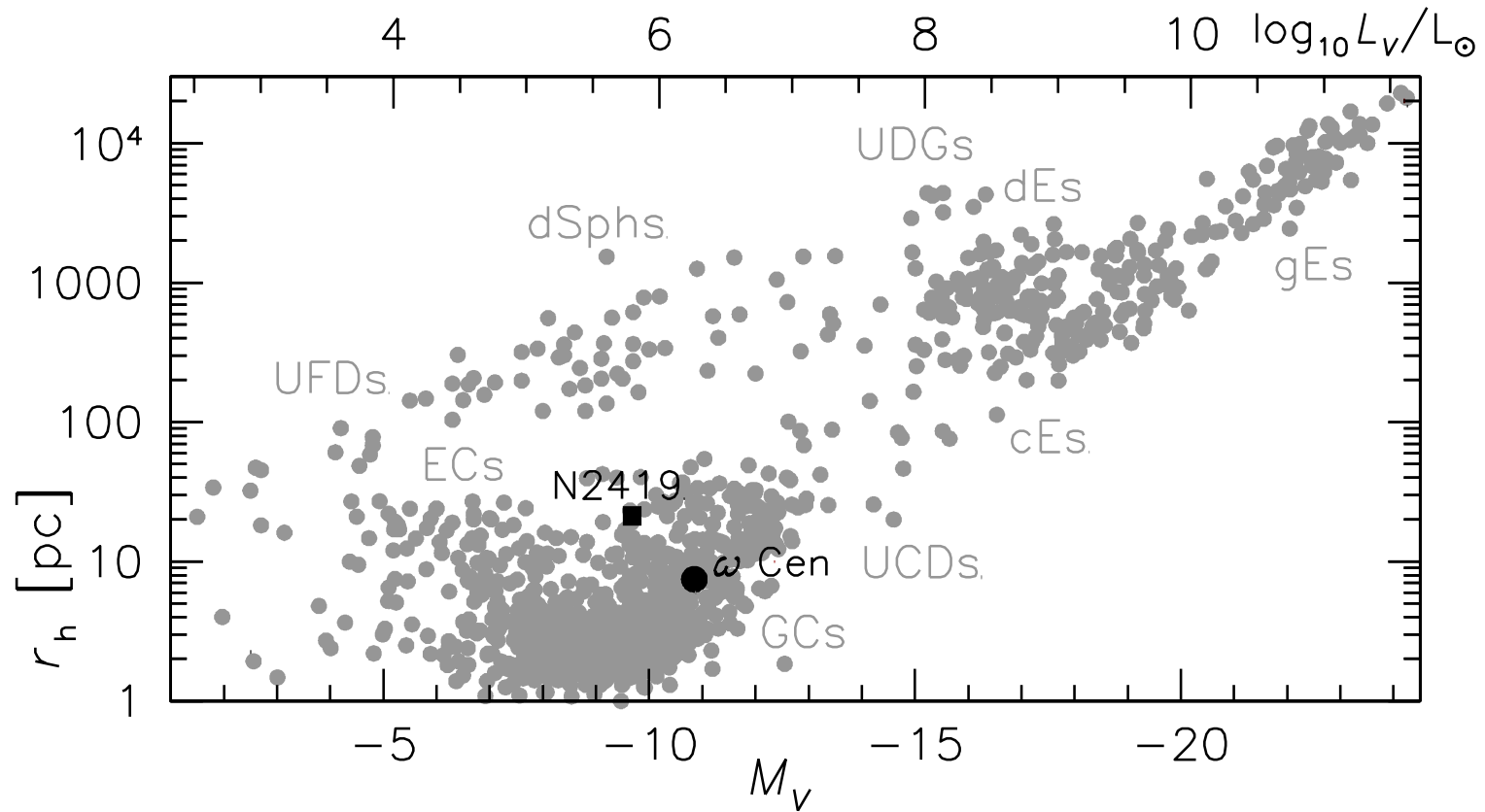$10^6 \, M_\odot$ mass challenges GC formation models: *requires high-mass host which couldn't have low metallicity*

forbidden zone

Inventory of the universe: galaxies and star clusters


quiescent stellar systems: the gaps are filling…

➢ **galaxies:** ultrafaint dwarfs, dwarf spheroidals, dwarf E/S0s, giant E/S0s

➢ **compact stellar systems:** extended clusters, globular clusters, hypercompact clusters, ultracompact dwarfs, compact ellipticals

➢ little progress on explaining some of the novel categories

Puzzles about dwarfs in the field

high-mass dwarfs in the field ($M_\star \sim 10^{7-9}\ \mathbf{M_\odot}$)   should ~always be star-forming (e.g., Geha+12)
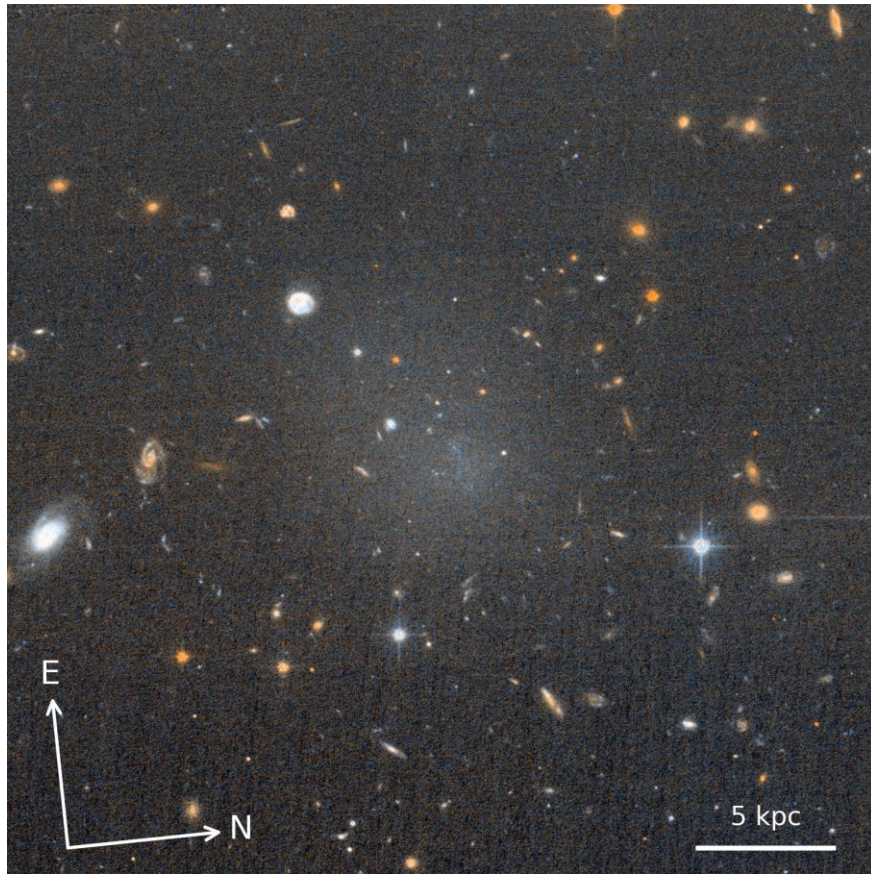

COSMOS-dw

2.5″
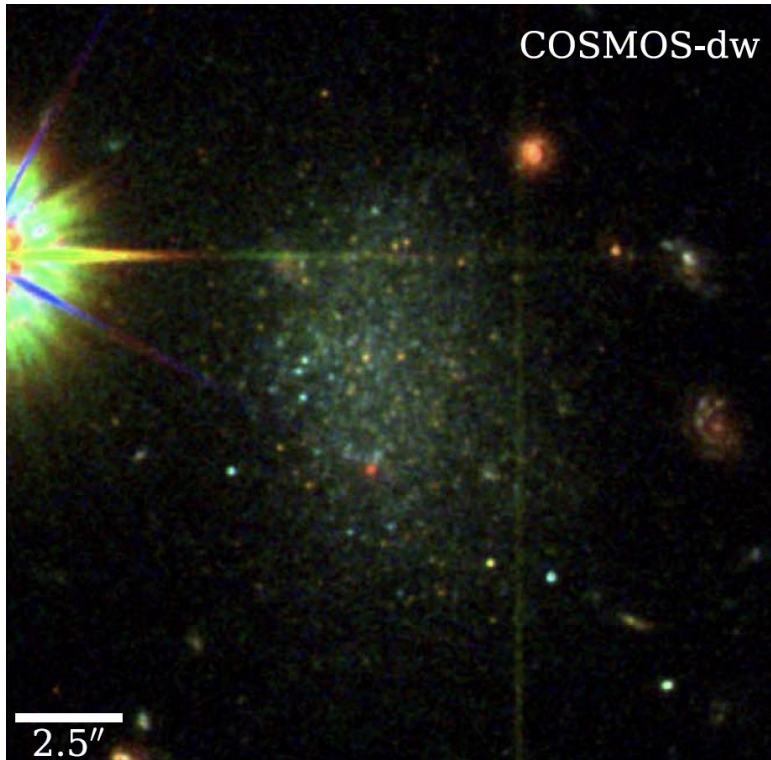
a few examples of quenched isolated dwarfs found (e.g., Polzin+21)

need another quenching mechanism:

➢ internal?

➢ stripping/quenching by cosmic web/sheets?
  (Benítez-Llambay+13; Pasha+22)

if large numbers of such dwarfs missed by surveys, would have implications for abundance matching in ΛCDM (Klypin+15; Sardone+24)
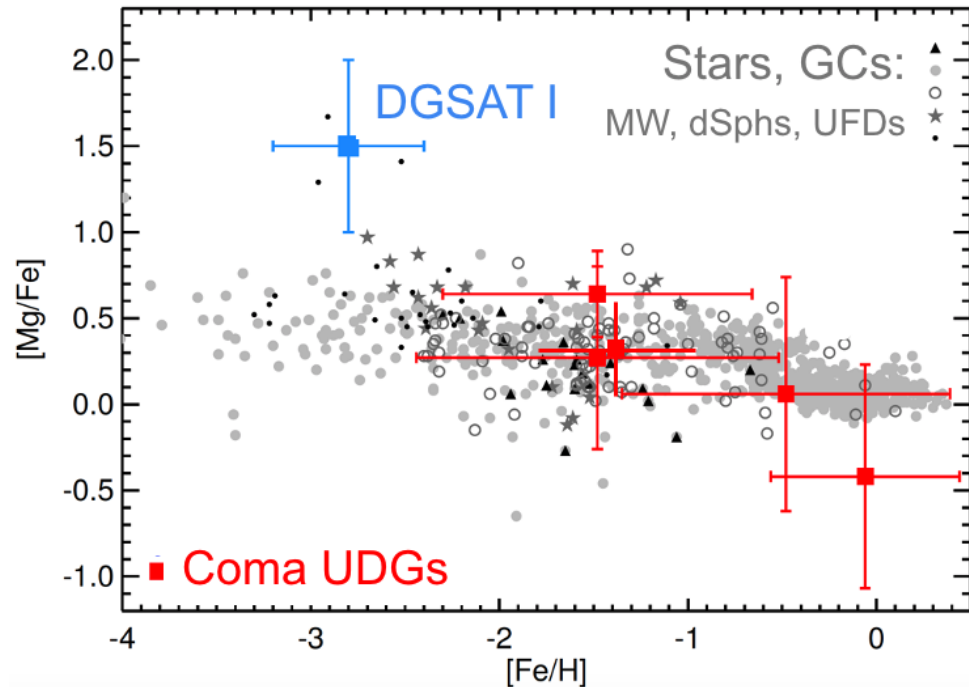
DGSAT I: peculiar ultra-diffuse galaxy

discovered accidentally in search for M31 satellites (Martínez-Delgado+16)

HST + *Spitzer* study (Janssens+22): $M_\star$ ~ 3×10^8 $M_\odot$, $R_e = 4$ kpc,   high mass fraction in globular clusters, isolated and quenched

bizarre abundance pattern
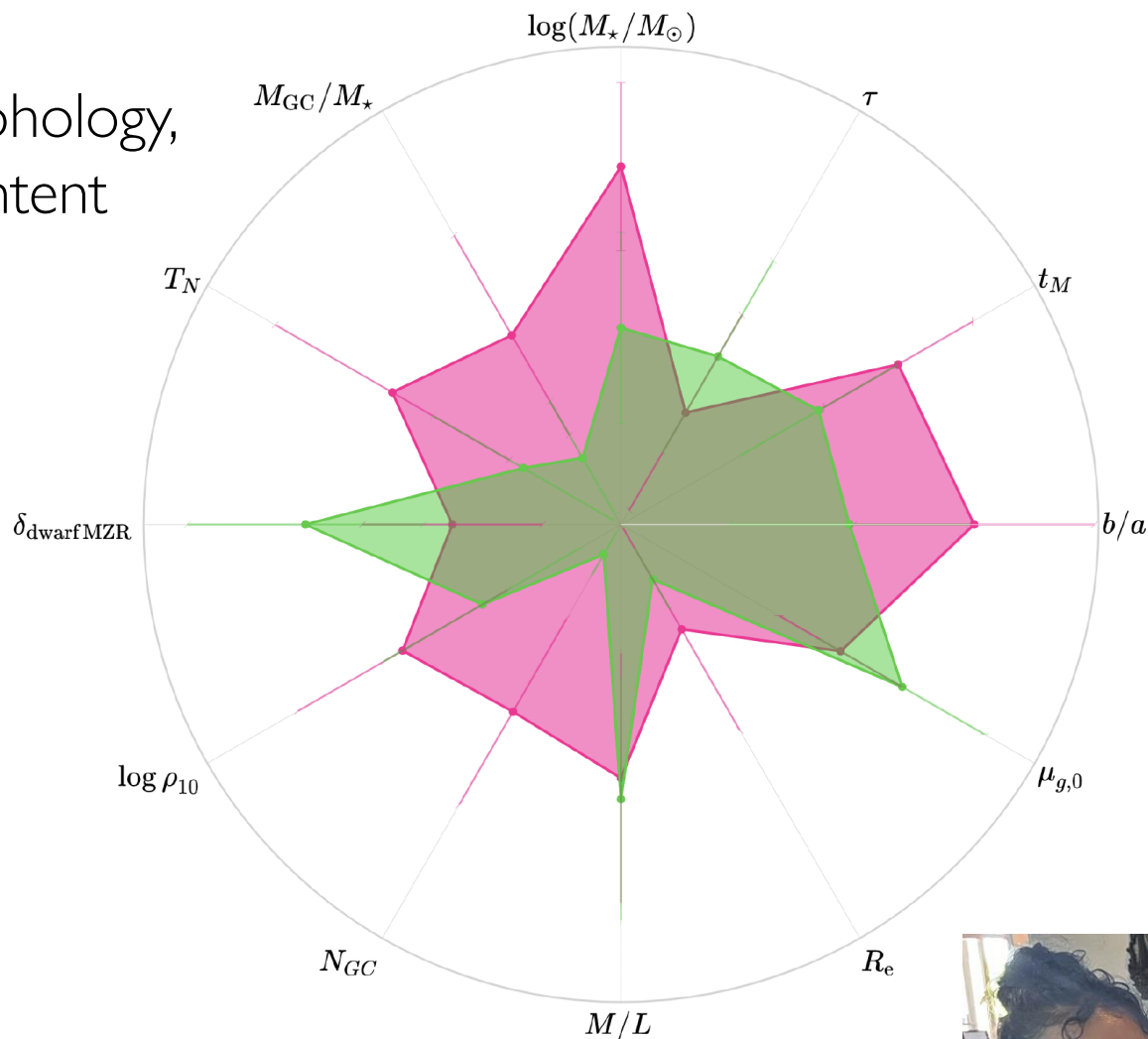[Fe/H] ~ −2.8, [Mg/Fe] ~ +1.5
(Martín-Navarro+19)

Systematic study of UDG subpopulations

Kmeans clustering in multi-dimensional space of morphology, stellar populations, GC content (Buzzo+24a,b)

two classes with
silhouette score = 0.7

☞ support for two families of UDGs
(puffed-up normal dwarfs; failed galaxies)
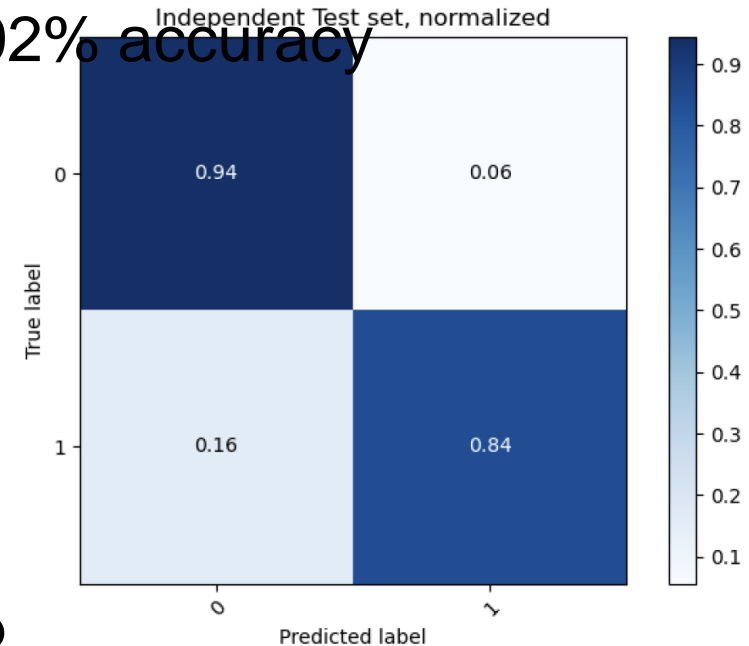

new work w/DESI
(L. Kenoly poster)

Classifying Perseus cluster dwarfs w/SDSS

Perseus dwarfs

background

- SDSS images encode color, morphology info
- training set of Perseus dwarfs and contaminants (Wittmann+19 deep imaging; SDSS spectroscopy)
- simple search for galaxies requires much data cleaning
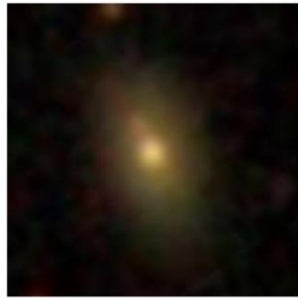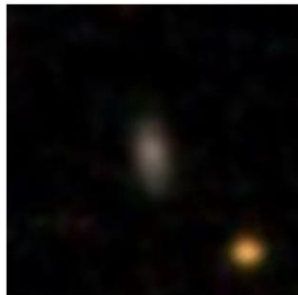- ResNet-50 CNN on SJSU "Spartan" HPC
- independent test set: 92% accuracy

bad sky   "GALAXY"

Jason Pruitt

Pruitt & Romanowsky, in prep

Independent Test set, normalized
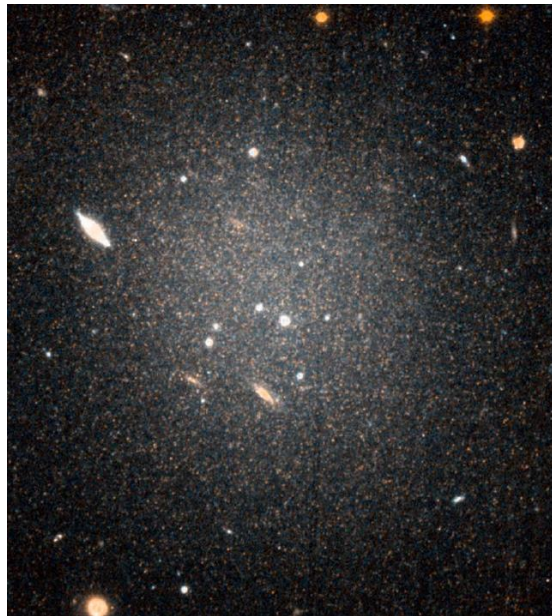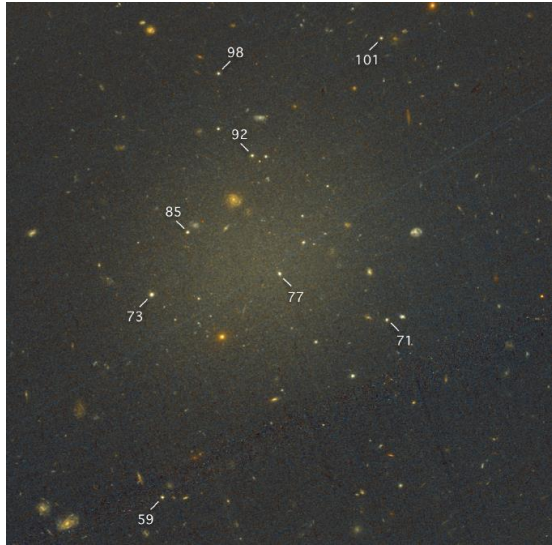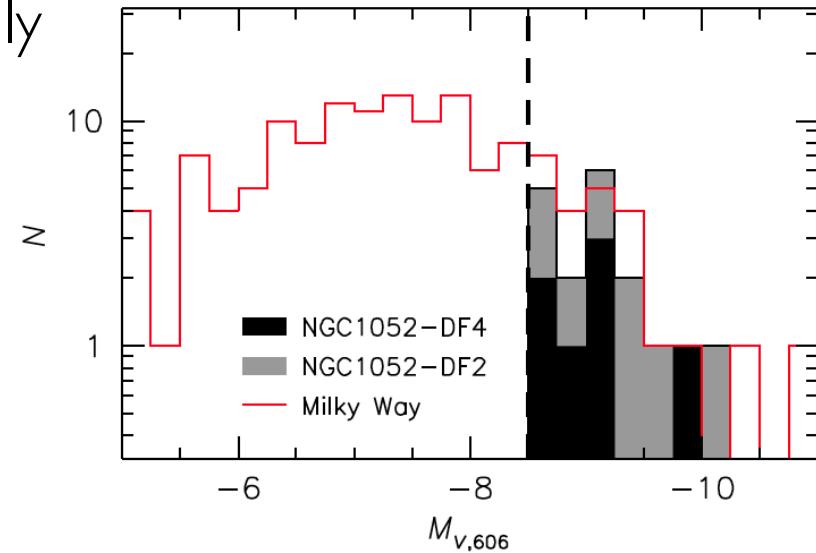
UDGs with no dark matter

NGC 1052-DF2, DF4 at ~20 Mpc :
no dynamical indication of DM from stars or GCs
(van Dokkum+18,19; Danieli+19,20; Shen+23)

**GCs** are unusually luminous, large, monochromatic (Shen+21; van Dokkum+22b)

both galaxies part of linear "trail" structure
☞ best explanation is "bullet dwarf" collision
(Silk 19; van Dokkum+22a; Lee+24; Tang+24)

are there more examples in the nearby Universe?

Searching for more dark matter-free dwarfs

bullet-dwarf descendants could be marked by unusual GC systems

DF2 (Legacy)

(model)
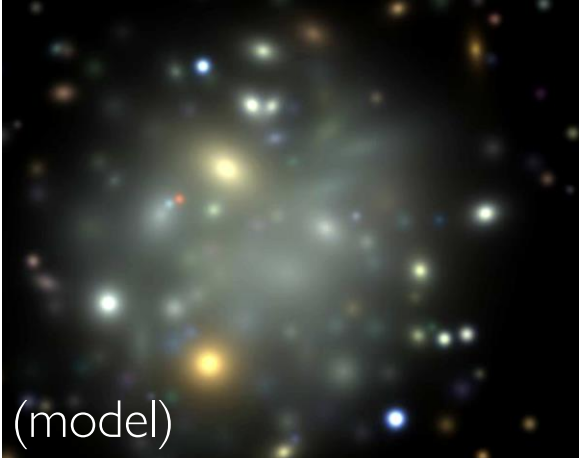
Legacy searche complicated by shredding (Bains, O'Brien posters)

visual inspection of 24,000 LSB galaxies from DES (Tanoglidis+21)
found clumpy candidates (E. Cabrera)

GCs confirmed using *HST* and Keck; DM TBD (Tang+24b; Buzzo+24c)

Lessons learned from extreme searching

- "dirty" data can hamper finding rare gems
- beware of invisible selection effects from catalog incompleteness
- consider unexplored areas of parameter space
- value from human inspection of images
- take spectra of "everything"
- challenges of converting rare gems from curiosities to conveyers of important stories
- exploit multiple dimensions of data to identify new classes of objects