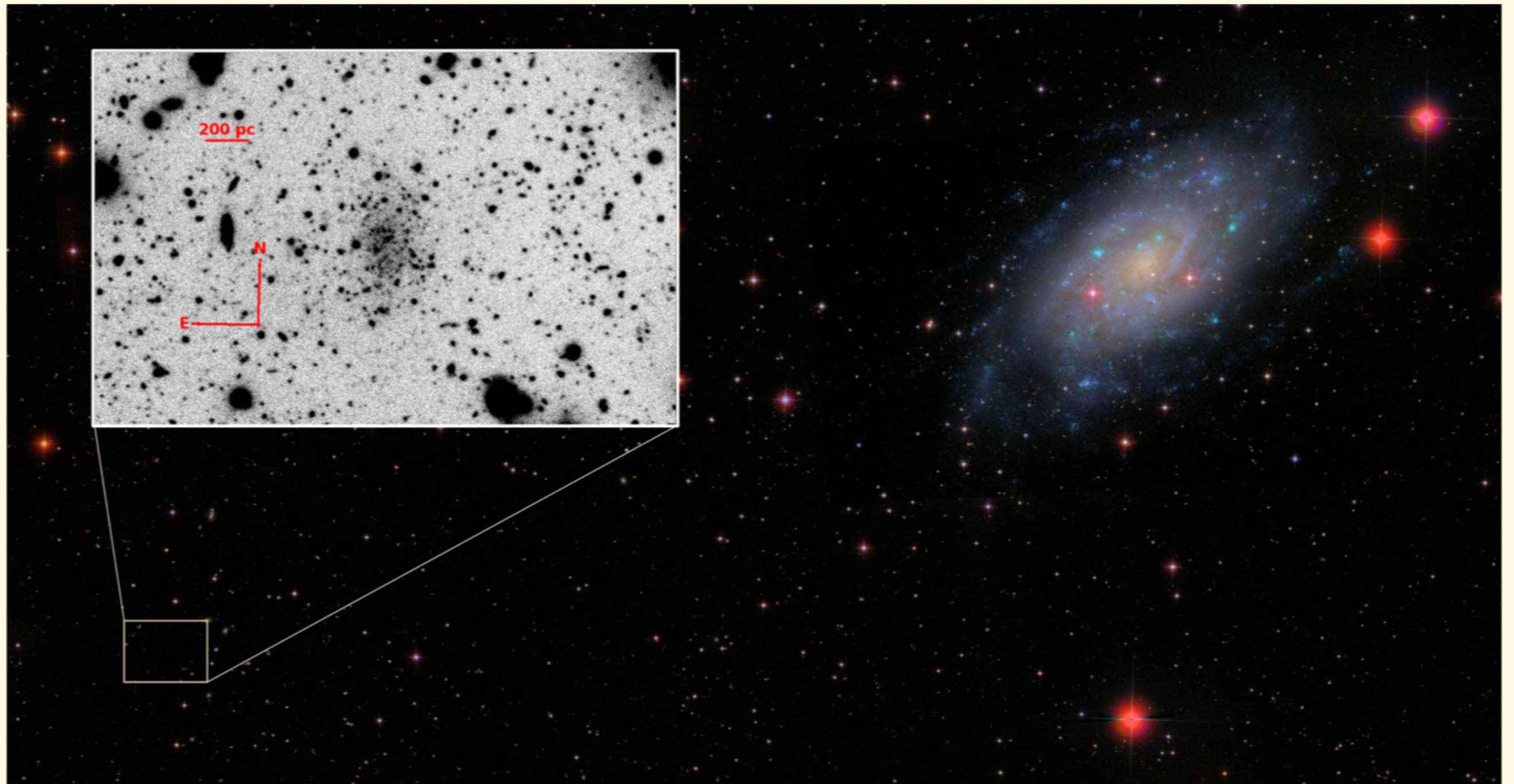


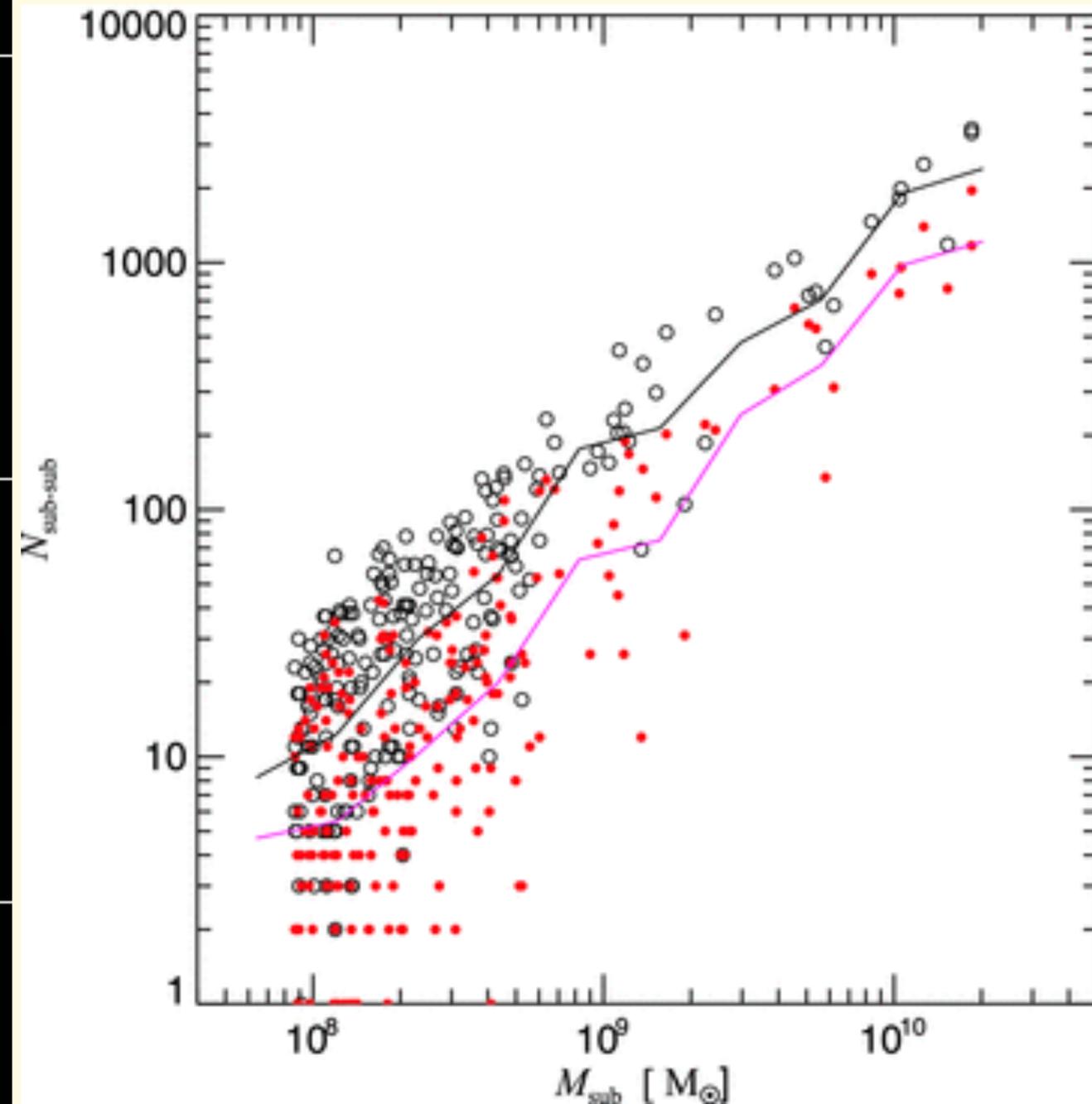
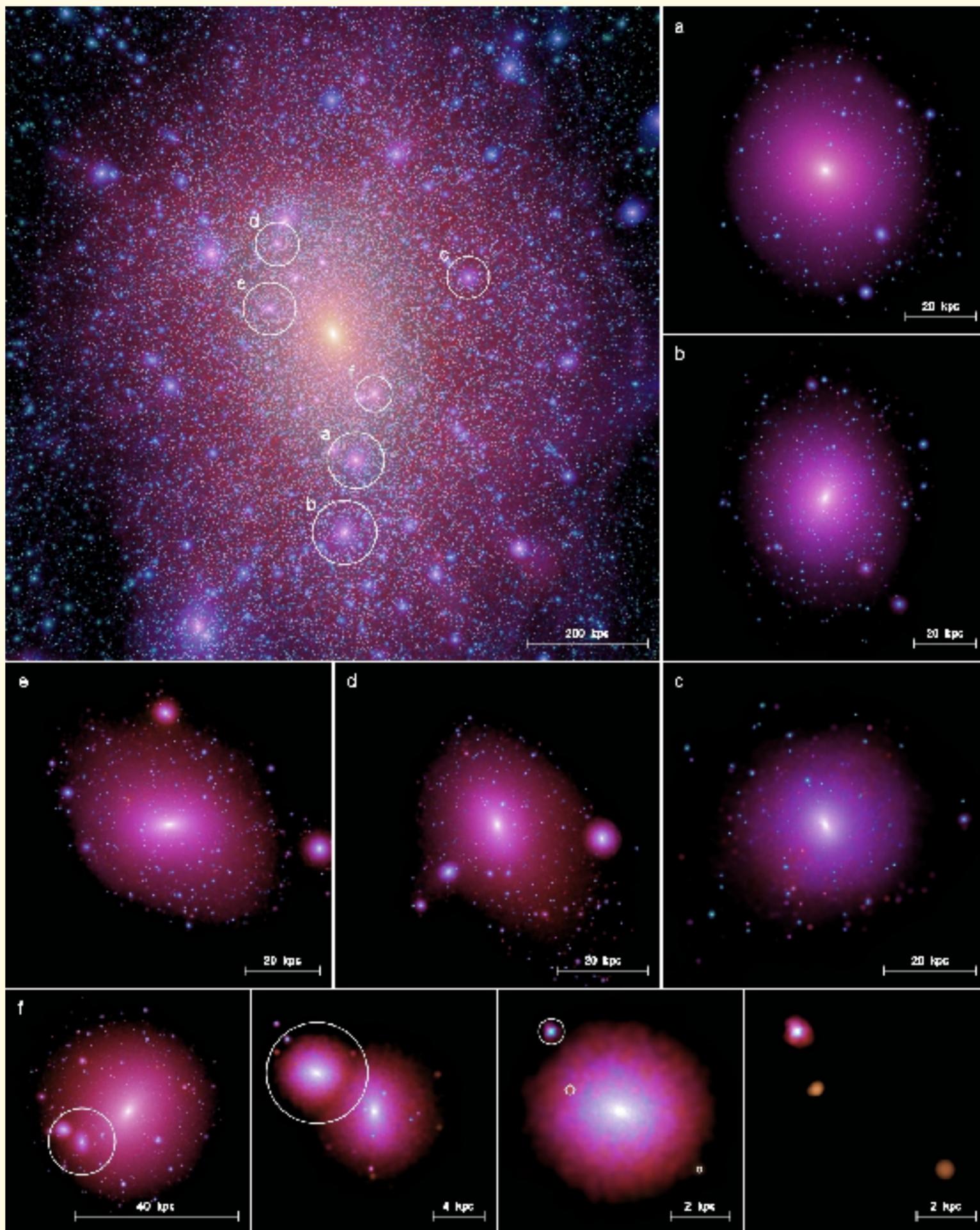
# Resolved Stellar Populations Around Local Volume LMC Stellar-Mass Galaxies



Jeff Carlin (LSST)

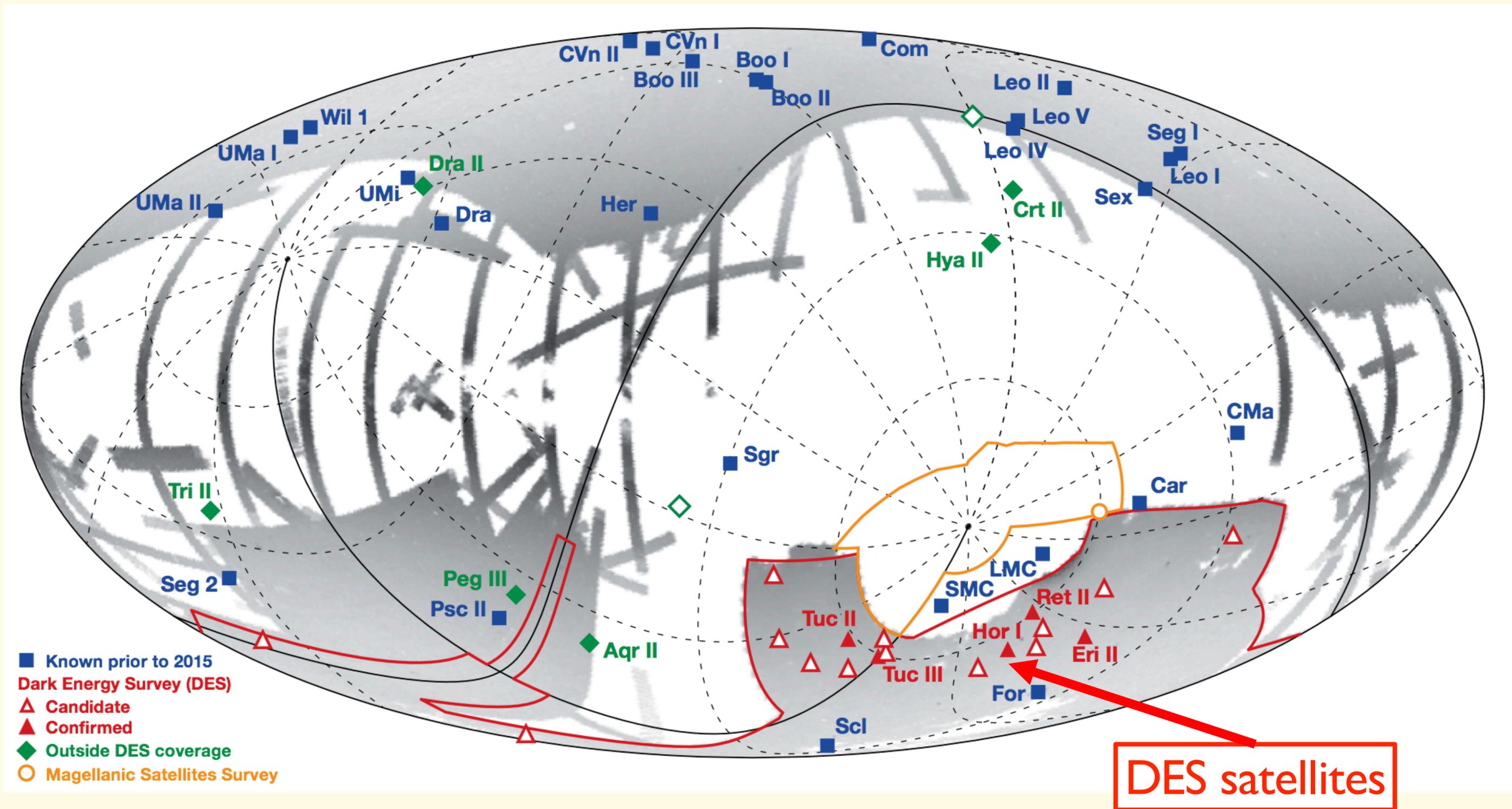
+ Keith Bechtol, Jean Brodie, [Denija Crnojević](#), Greg Dooley, Duncan Forbes, Ana Frebel, Jonathan Hargis, Ananthan Karunakaran, Evan Kirby, Robert Lupton, Ricardo Muñoz, Annika Peter, Paul Price, Ragadeepika Pucha, [Aaron Romanowsky](#), Dave Sand, Kristine Spekkens, Jay Strader, **Beth Willman**

(Sub)substructure – structure formation is essentially scale-free



# LMC/SMC satellites?

Satellites discovered in DES are not isotropically distributed  
→ associated with Magellanic Clouds?\*



\* see, e.g., Deason+2015; Drlica-Wagner+2015;  
Koposov+2015; Yozin & Bekki 2015; Jethwa+2016; Sales+2016

Do Local Volume ~SMC/LMC stellar mass dwarfs host their own dwarf galaxy satellites (and if so, what are their properties)?

NGC 3109 and NGC 2403 now have confirmed satellites – more soon!

What do dwarfs-around-dwarfs tell us about fundamental galaxy formation physics?

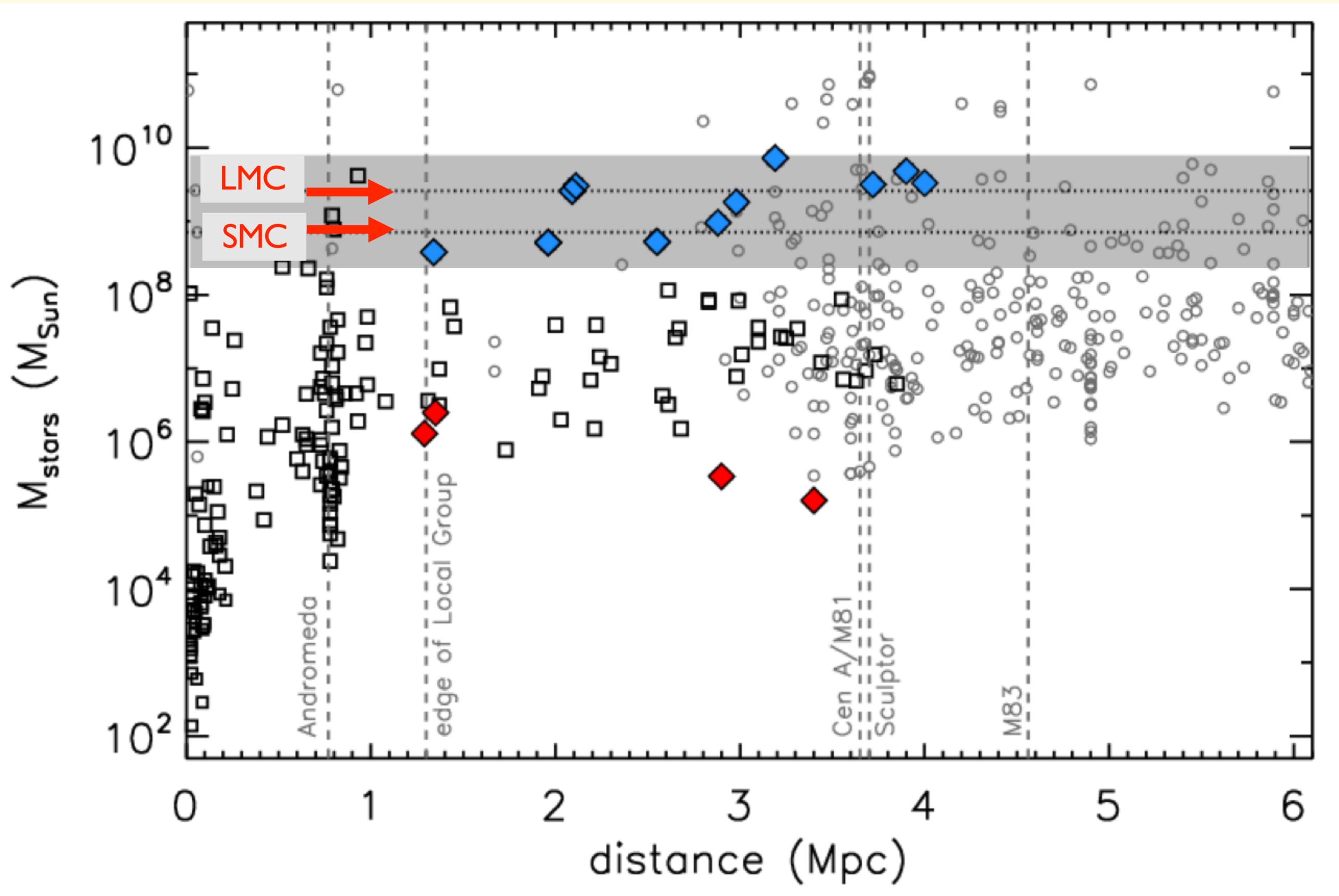
Number distribution and properties (luminosity function, total mass, metallicity, etc.) tell us about competing effects of galaxy formation efficiency, reionization, and environment.

What is the impact of environment on dwarf galaxy formation?

Do dwarf galaxies have stellar halos? Is there appreciable stellar substructure (i.e., satellite remnants) in the halos of LMC analogs?

*MADCASH survey observations of Local Volume galaxies will provide systematic measurements of stellar halos and dwarf satellites in sub-MW environments.*

# Stellar mass vs. distance; Local Volume galaxies



\*Data from Karachentsev+2013 Local Volume galaxies catalog, available at: <https://relay.sao.ru/lv/lvgdb/>, plus more recent MW dwarfs

# MADCASH observing program

Distant, > SMC

stellar mass

Galaxy	$M_*$ ( $10^9 M_{\text{Sun}}$ )	D (Mpc)
NGC 4214	1.0	2.9
<del>NGC 404</del>	<del>1.8</del>	<del>3.0</del>
NGC 300	2.6	2.1
NGC 55	3.0	2.1
NGC 247	3.2	3.7
NGC 4244	3.3	4.0
NGC 4449	4.8	3.9
NGC 2403	7.2	3.2

Subaru+HSC: 5/7 fields; ~69% of virial volume

Subaru+HSC: 3/7 fields; ~50% of virial volume

Subaru+HSC: 2/7 fields; ~45% of virial volume

Subaru+HSC: ~13 sq. deg.; 7/7 fields

sub-SMC

stellar mass

Galaxy	$M_*$ ( $10^8 M_{\text{Sun}}$ )	D (Mpc)
Sextans A	0.3	1.3
Sextans B	0.6	1.4
IC 1613	1.2	0.73
NGC 3109	3.7	1.3
IC 4662	4.9	2.4
IC 5152	5.2	2.0

CTIO+DECam: ~27 sq. deg.

CTIO+DECam: ~12 sq. deg.; 4/9 fields

Subaru+HSC: 4 fields; ~7 sq. deg., 6% of volume

CTIO+DECam: ~40 sq. deg.

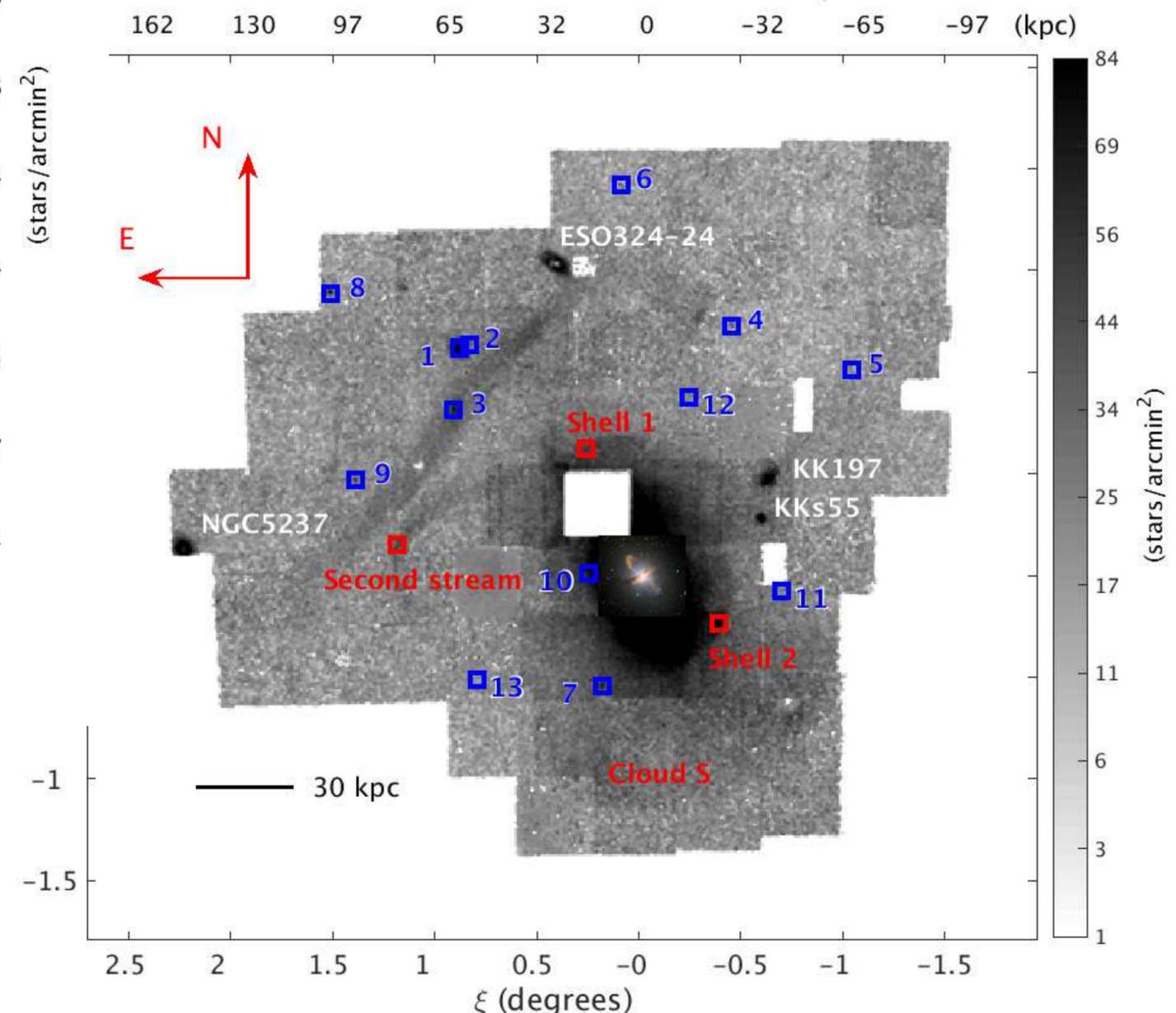
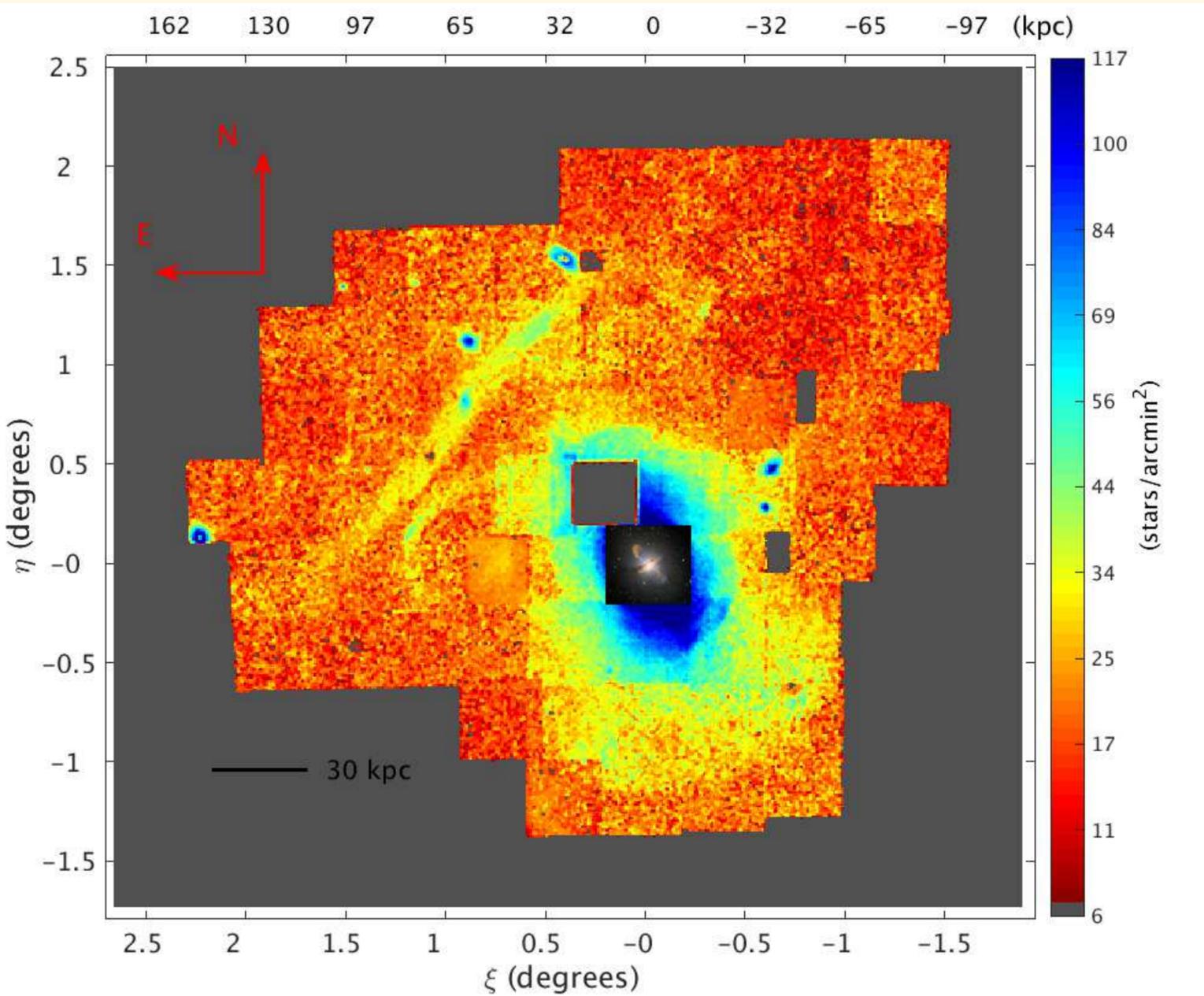
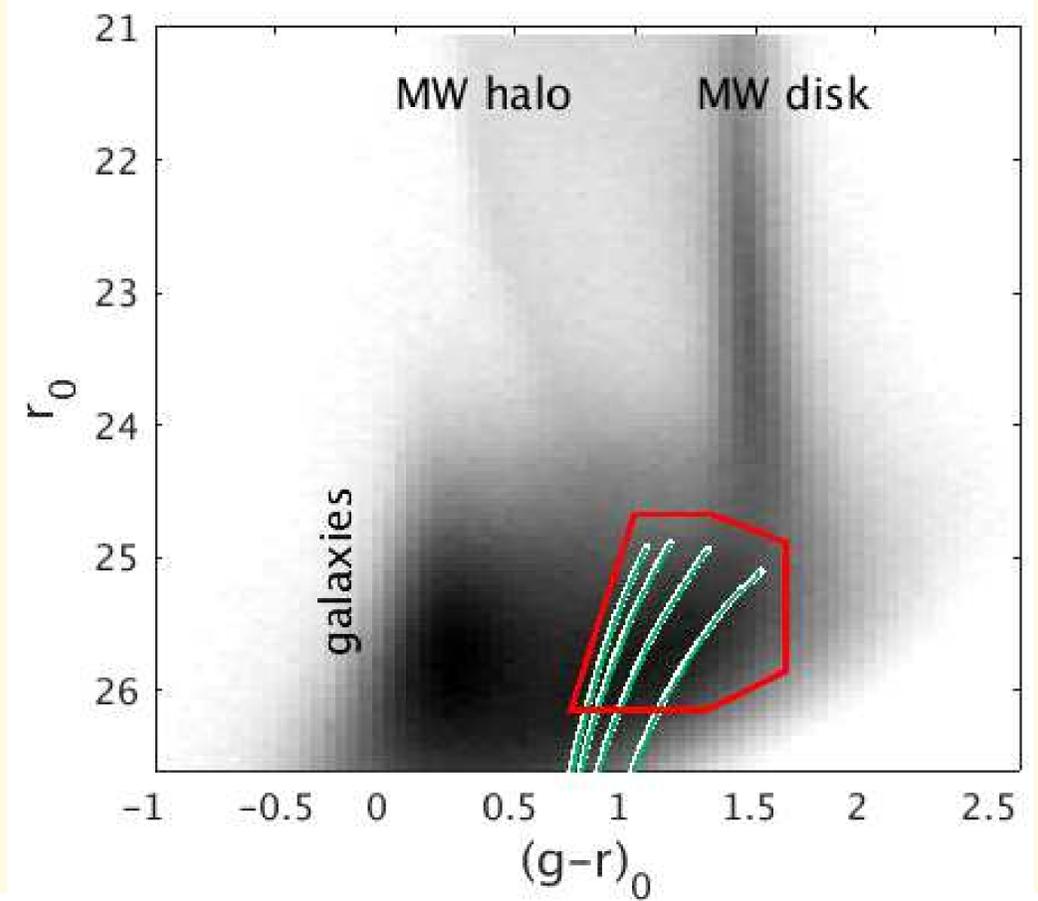
CTIO+DECam: ~18 sq. deg.; 6/7 fields

CTIO+DECam: ~6 sq. deg.; 2/7 fields

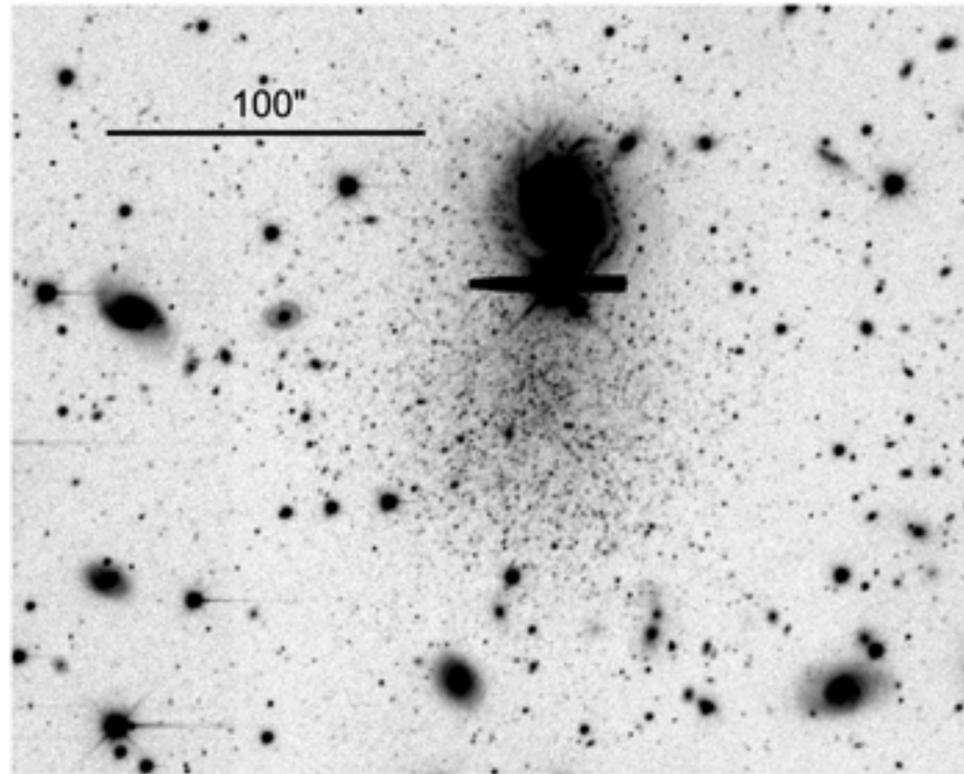
$$M_{*,\text{LMC}} \sim 2.6 \times 10^9 M_{\text{Sun}} ; M_{*,\text{SMC}} \sim 7.1 \times 10^8 M_{\text{Sun}}$$

# Stellar substructure (tidal remnants) in PISCeS:

Resolved substructure around Centaurus A  
( $D \sim 3.7$  Mpc): Crnojević+2016, *ApJ*, 823, 19



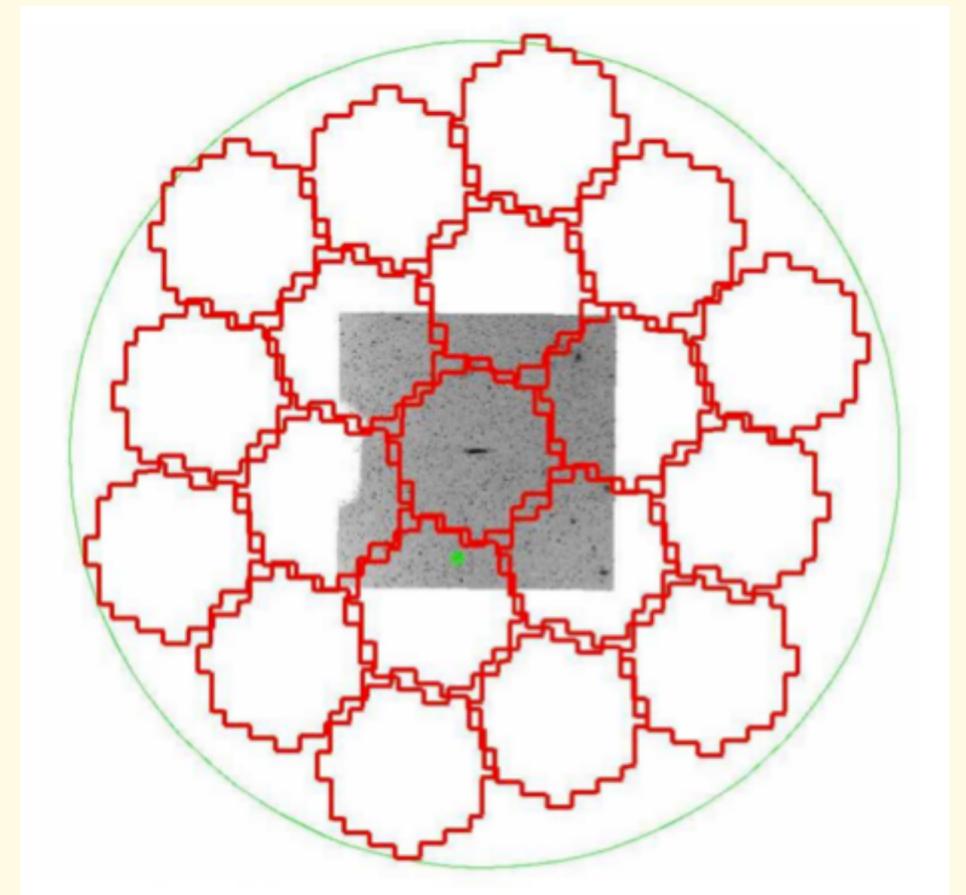
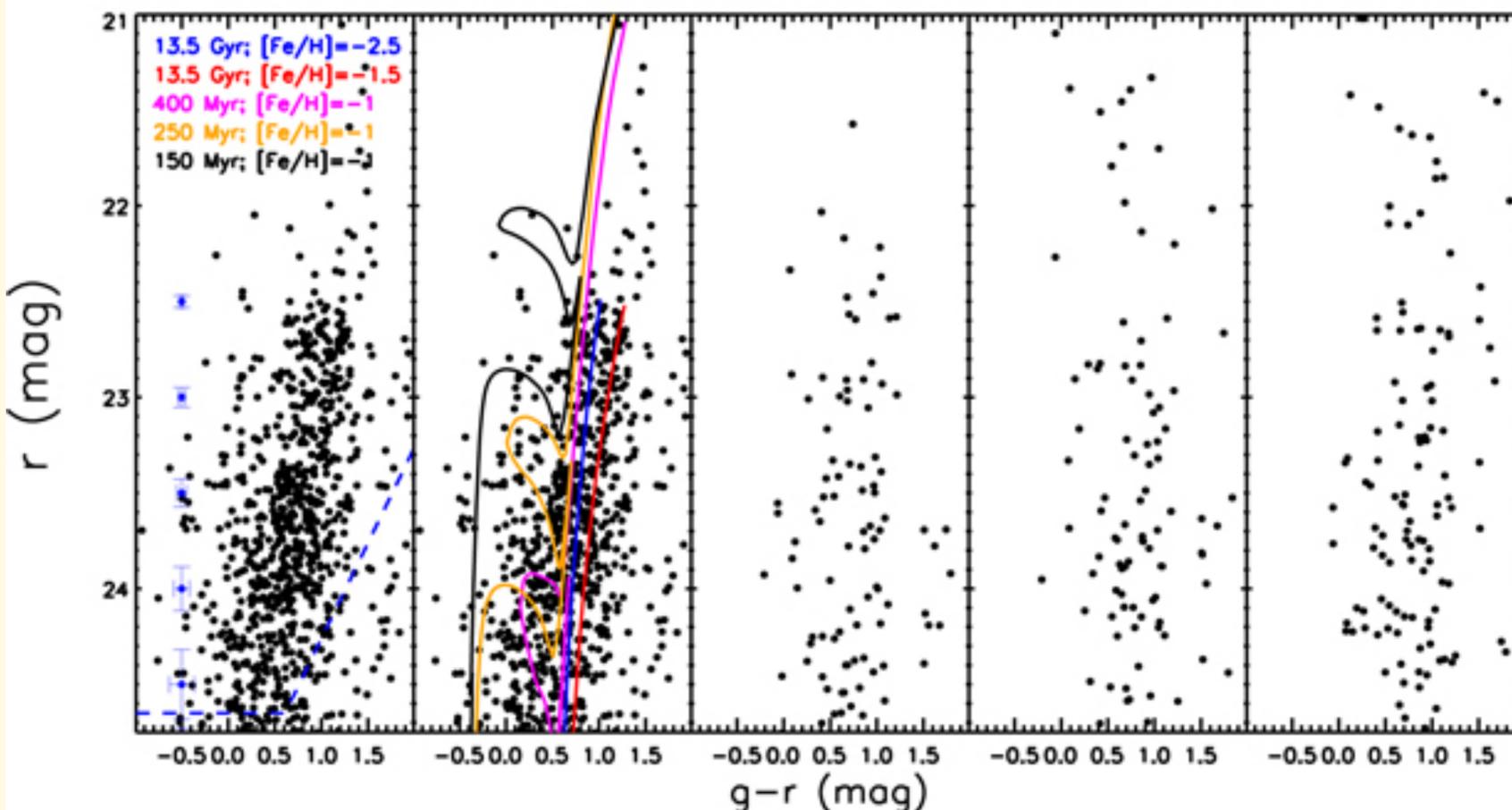
# Dwarfs around dwarfs with CTIO/DECam: NGC 3109



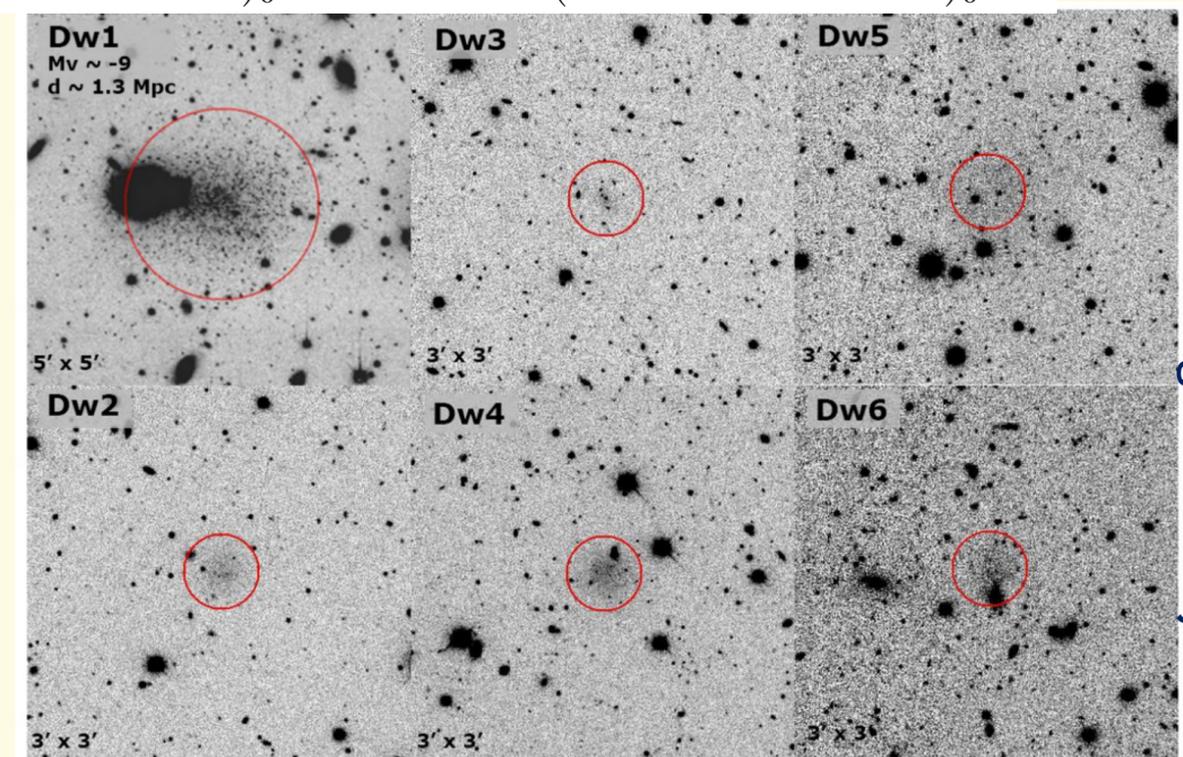
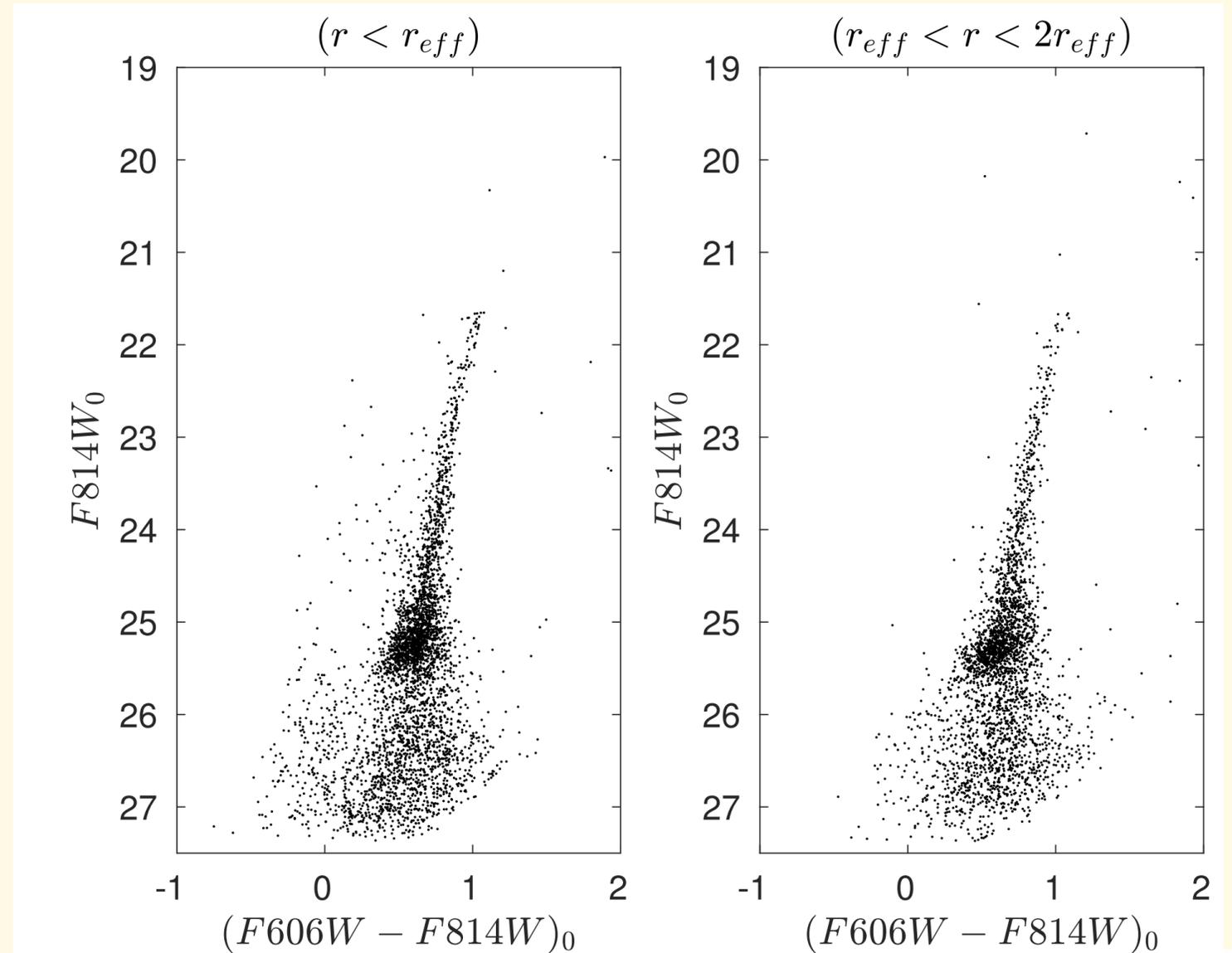
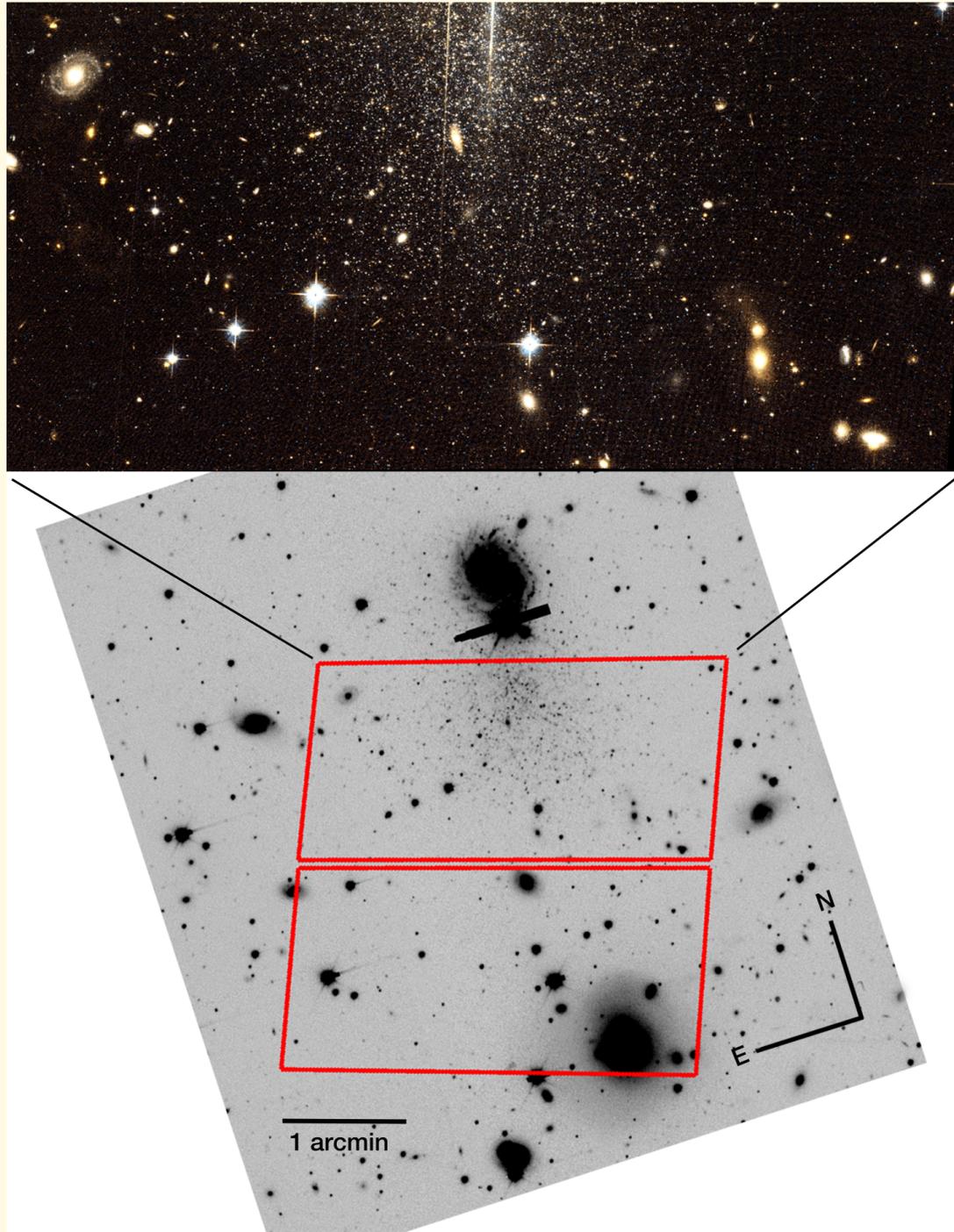
NGC 3109:  $M_V \sim -15$  dwarf  
( $M_{\text{star}} \sim 3 \times 10^8 M_{\text{sun}}$ ) at 1.3 Mpc

Discovery of a new dwarf  
galaxy, **Antlia B:**

- $M_V \sim -9.7$ ,  $r_{\text{half}} \sim 270$  pc  
(Sand+2015, ApJL, 812, 13)



# Dwarfs around dwarfs with CTIO/DECam: NGC 3109

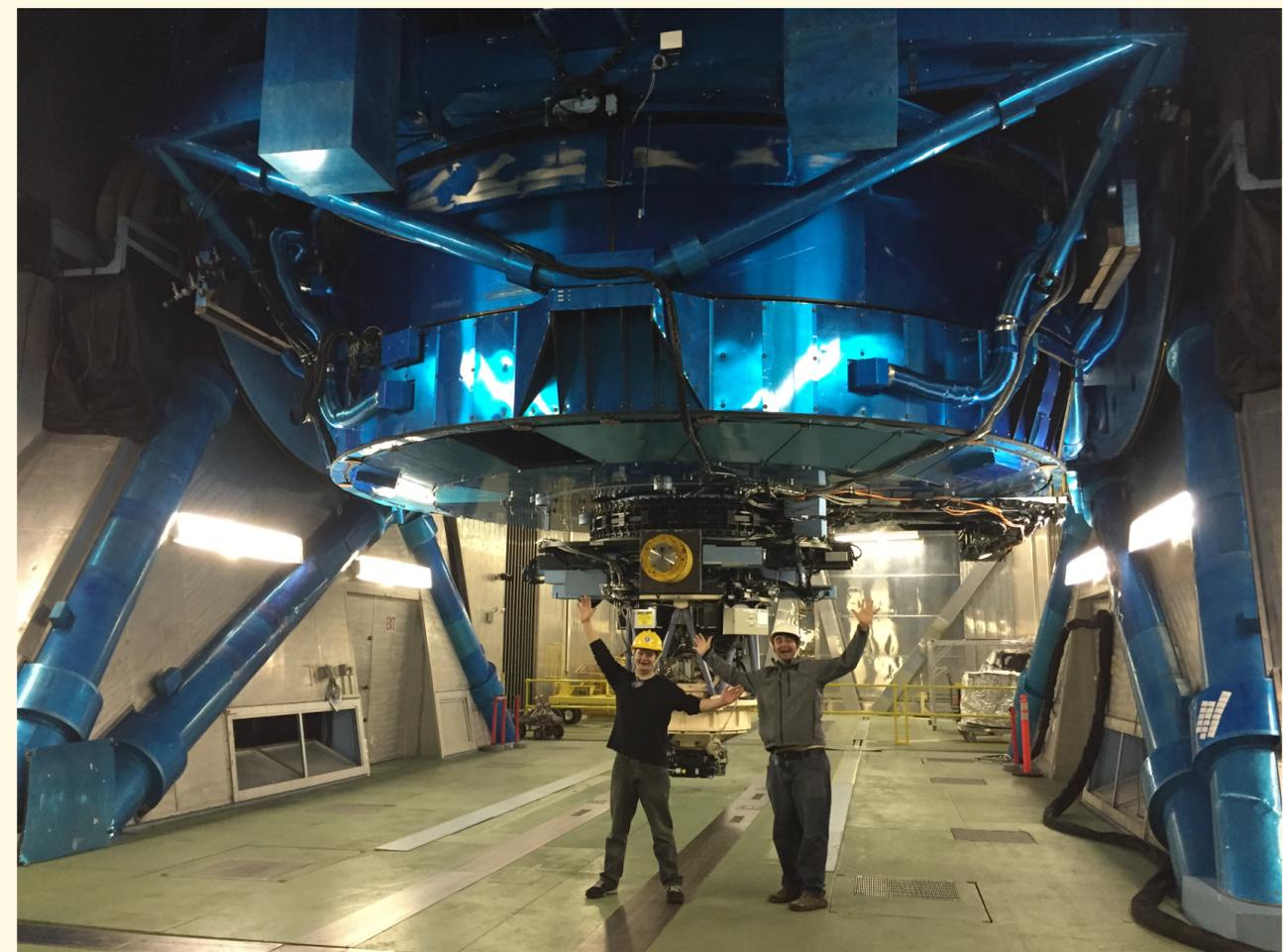


Several candidate  $M_v \sim -6$  dwarfs, a confirmed  $M_v \sim -9$  dwarf (Antlia B, Sand+15), and a candidate stream. HST Cycle 23 analysis ongoing (PI: J. Hargis).

Image: D. Crnojevic

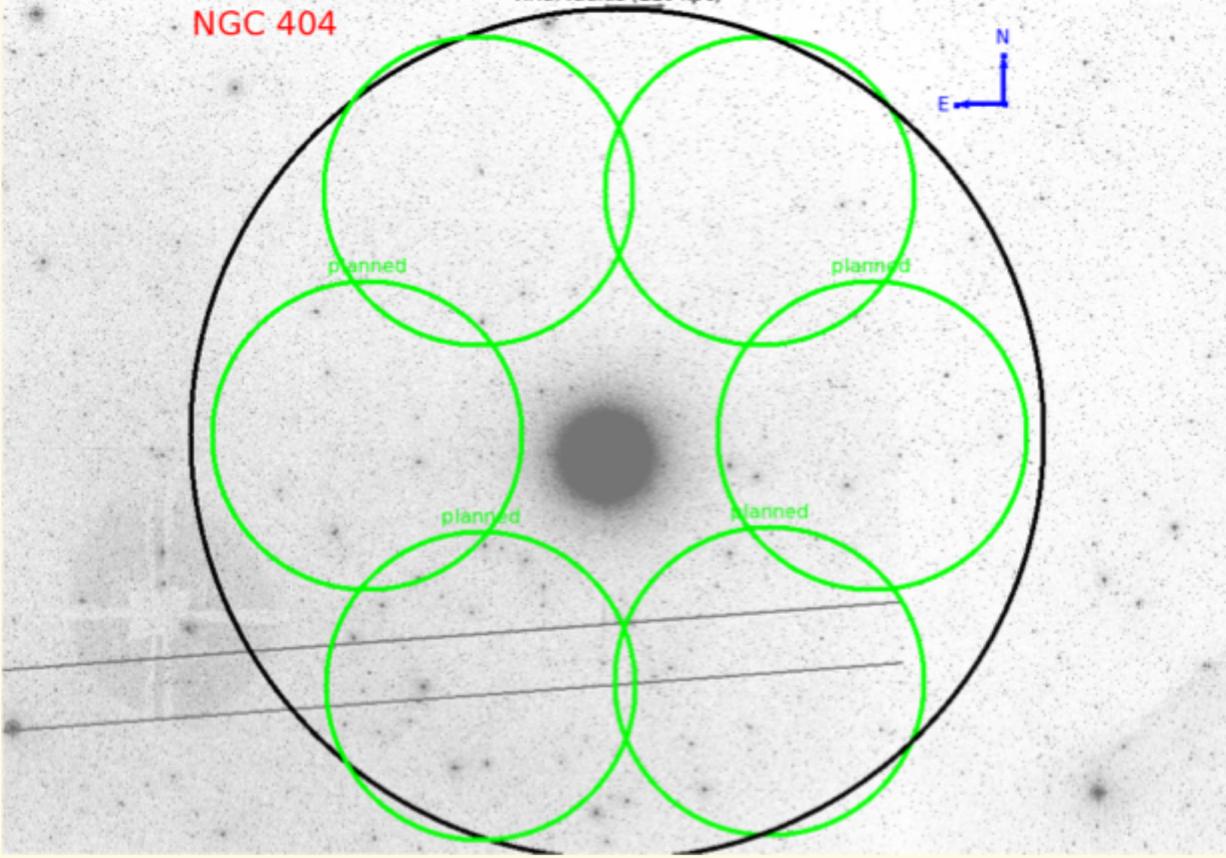
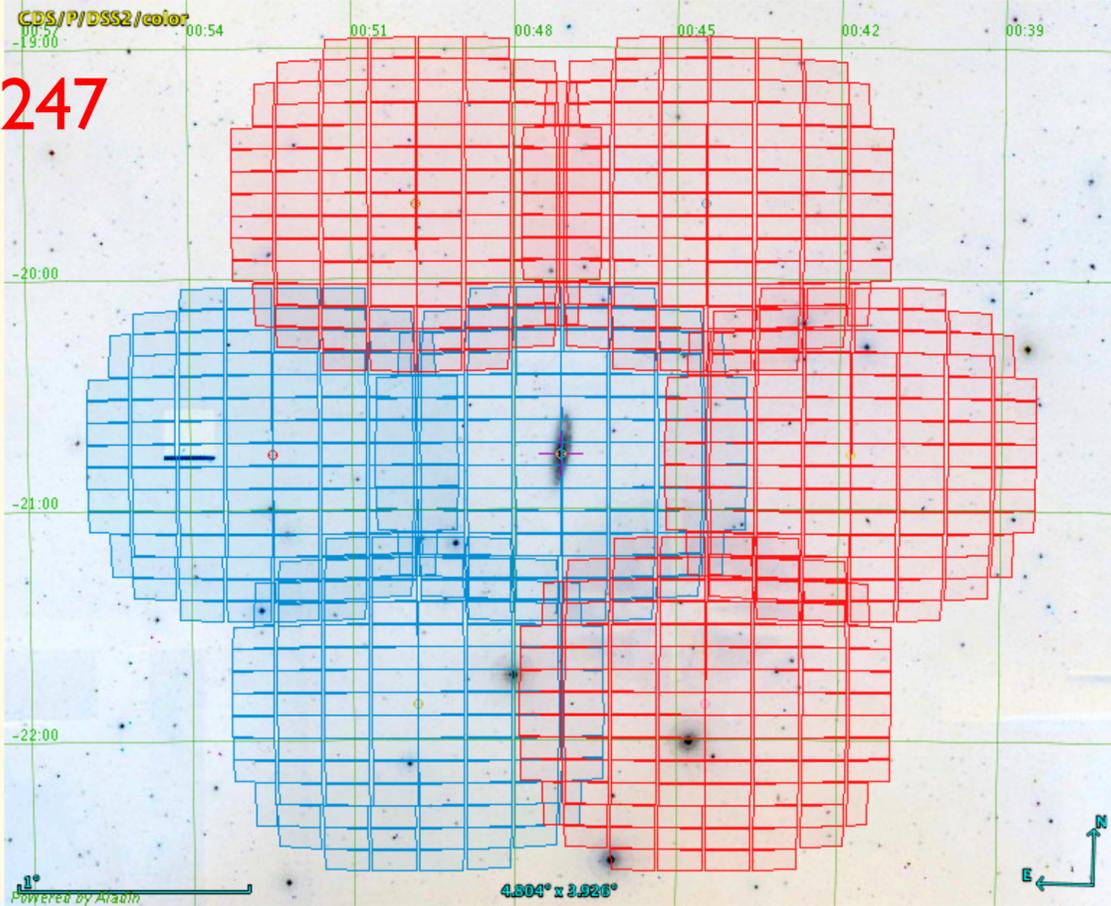
# Magellanic Analog Dwarf Companions And Stellar Halos (MADCASH) survey:

- Ongoing Subaru+HyperSuprimeCam (HSC) and DECam program
- 7 galaxies with  $\sim$ LMC stellar mass ( $M_{\text{star}} = 1-7 \times 10^9 M_{\text{Sun}}$ ) between 2-4 Mpc of MW
- 6 sub-SMC stellar mass galaxies at  $D < 2.5$  Mpc
- $5\sigma$  point source depths:  $g \sim 27.4$ ,  $i \sim 26.2$  ( $\sim 1.5$  mags below the TRGB at 3.2 Mpc)

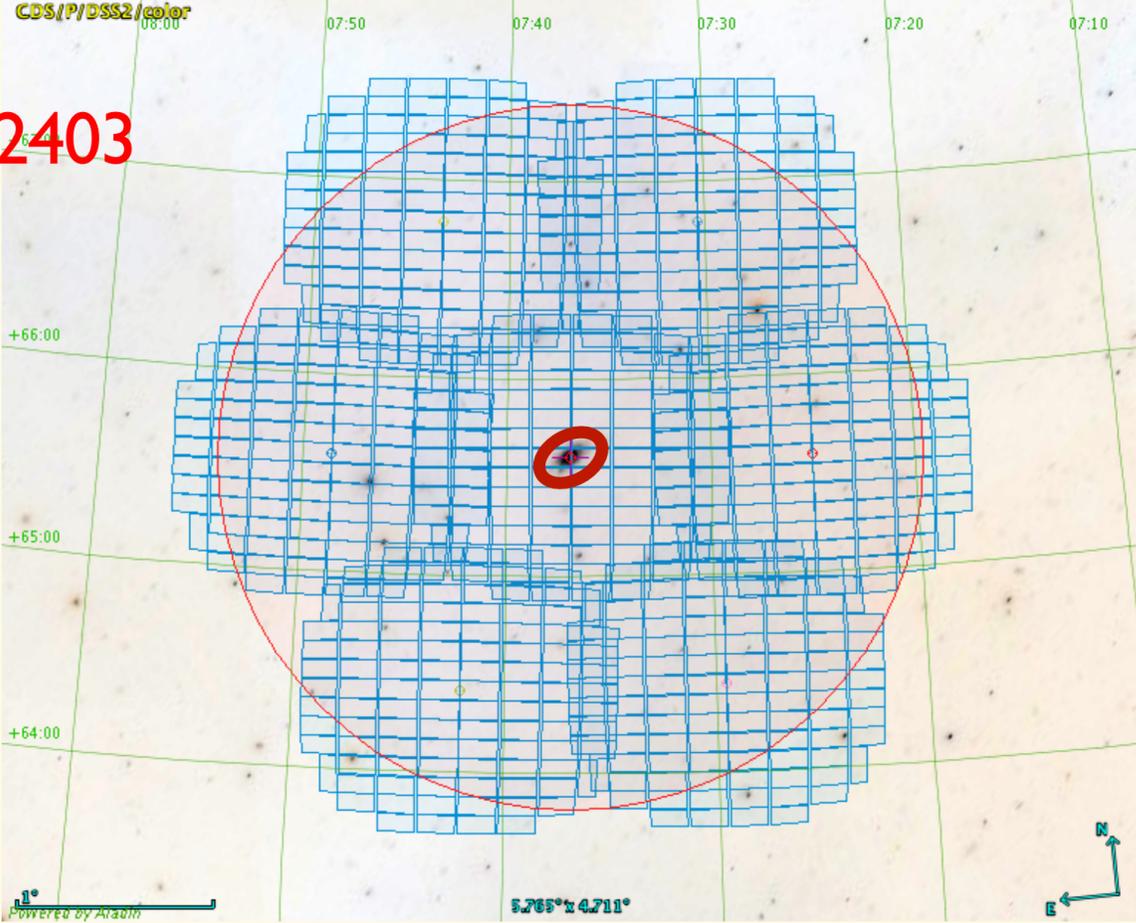


# Subaru/HSC observing plans/progress

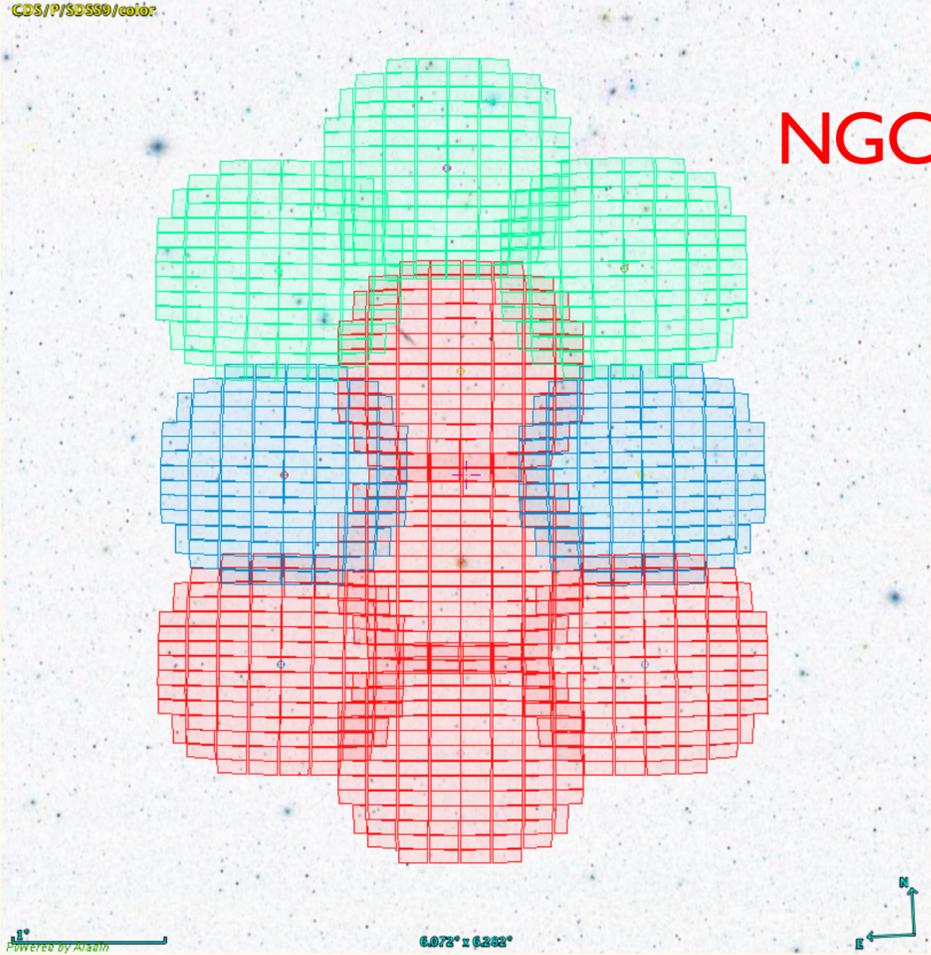
NGC 247



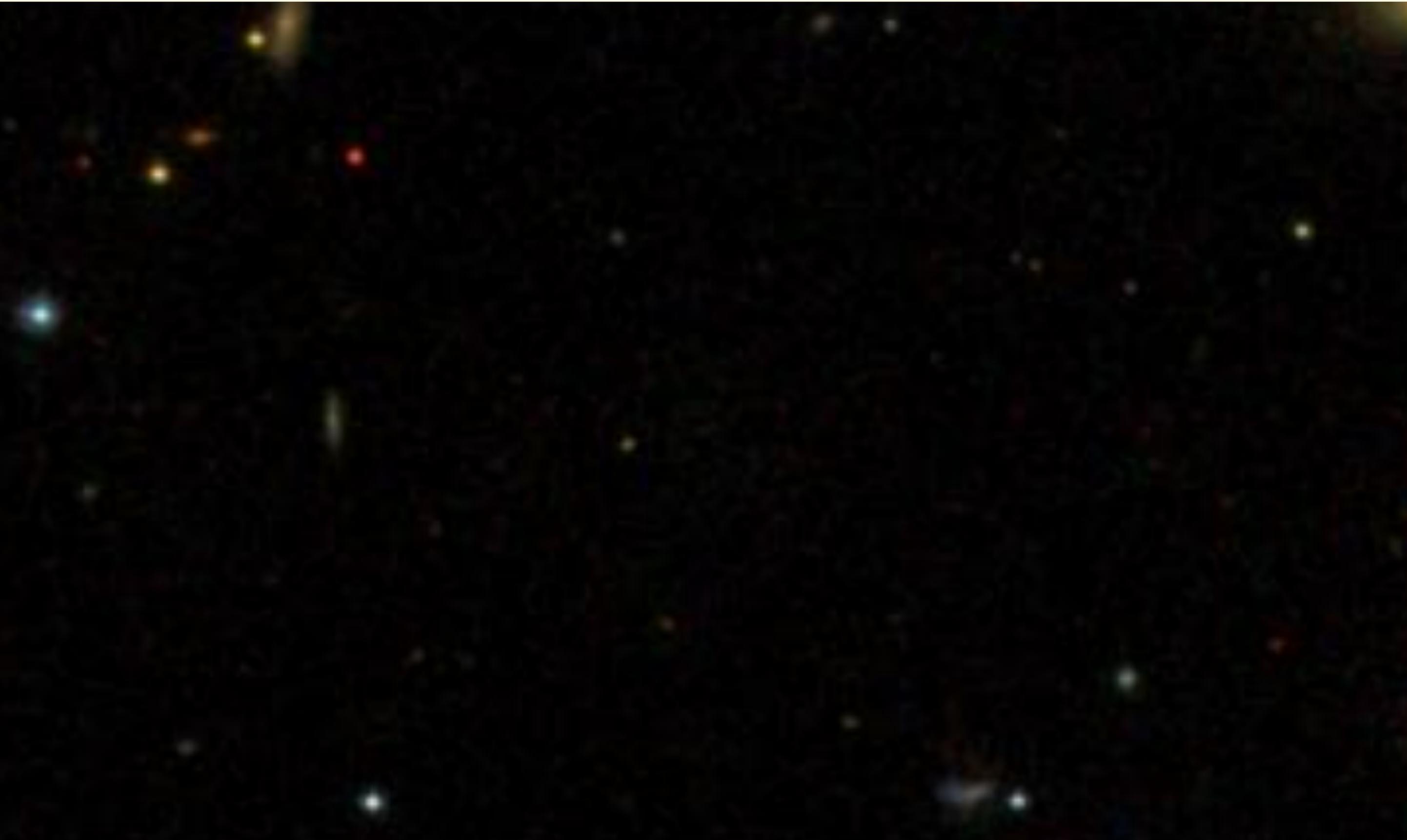
NGC 2403



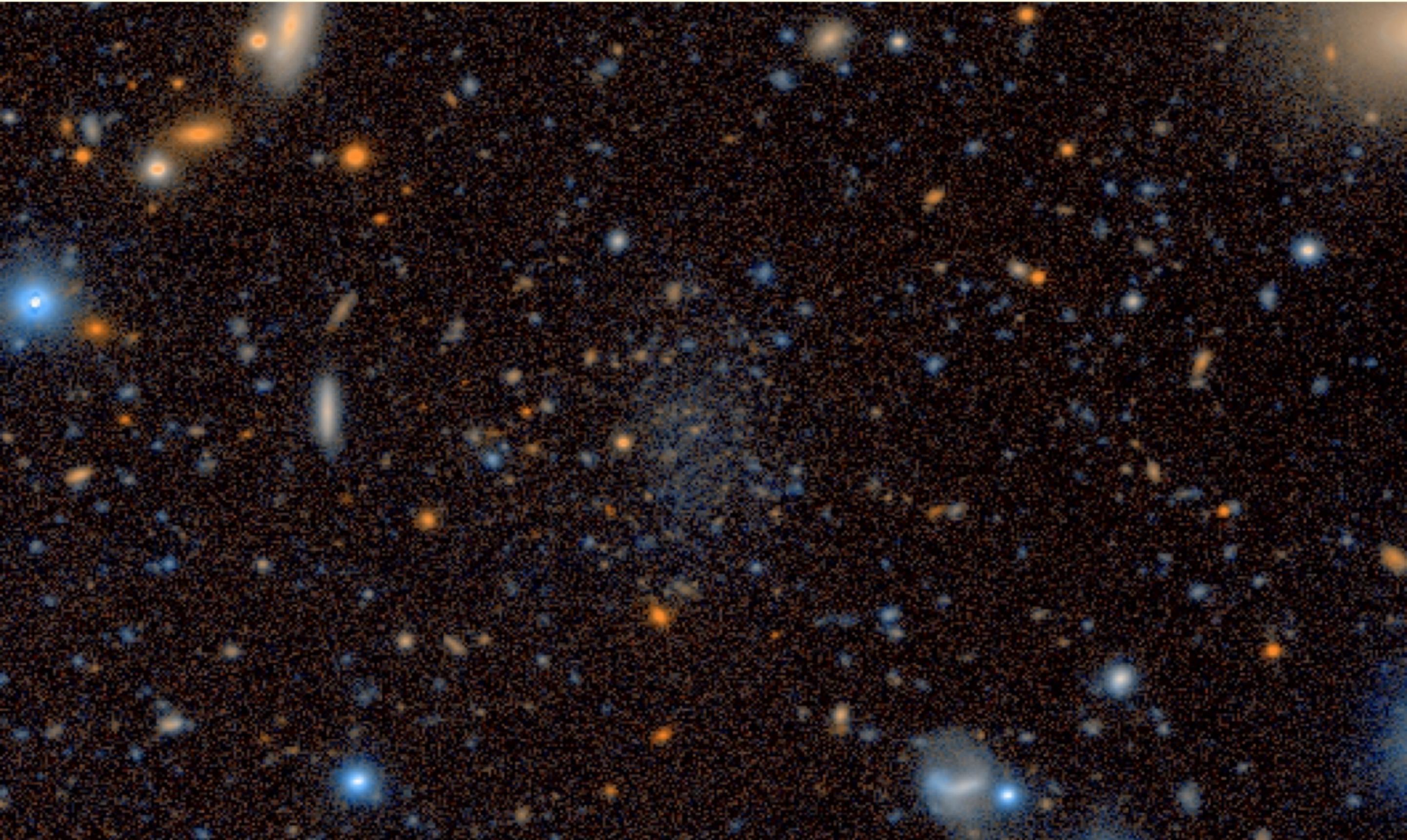
NGC 4214/4244



# SDSS vs. HSC

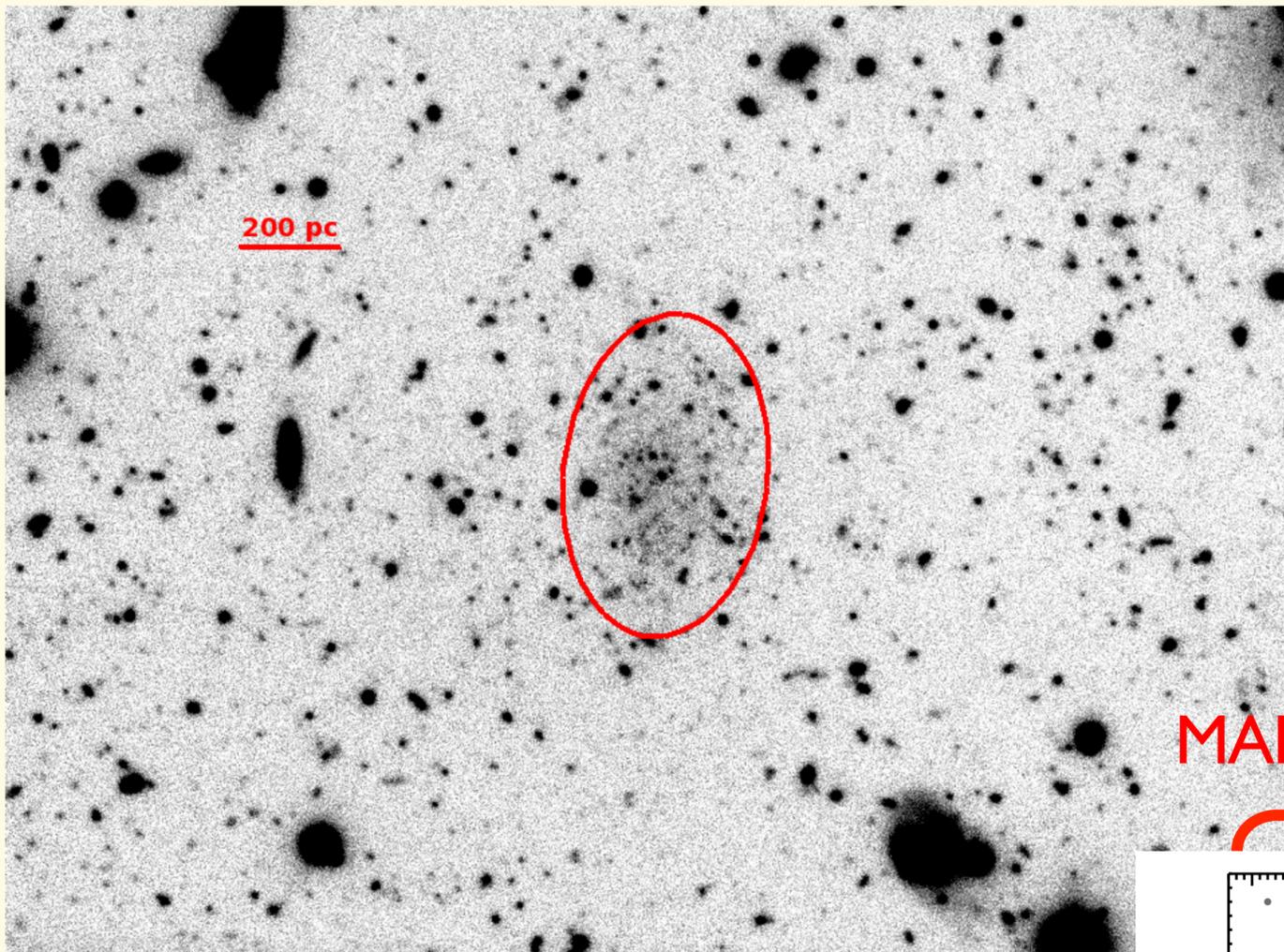


# SDSS vs. HSC



# New dwarf galaxy near NGC 2403

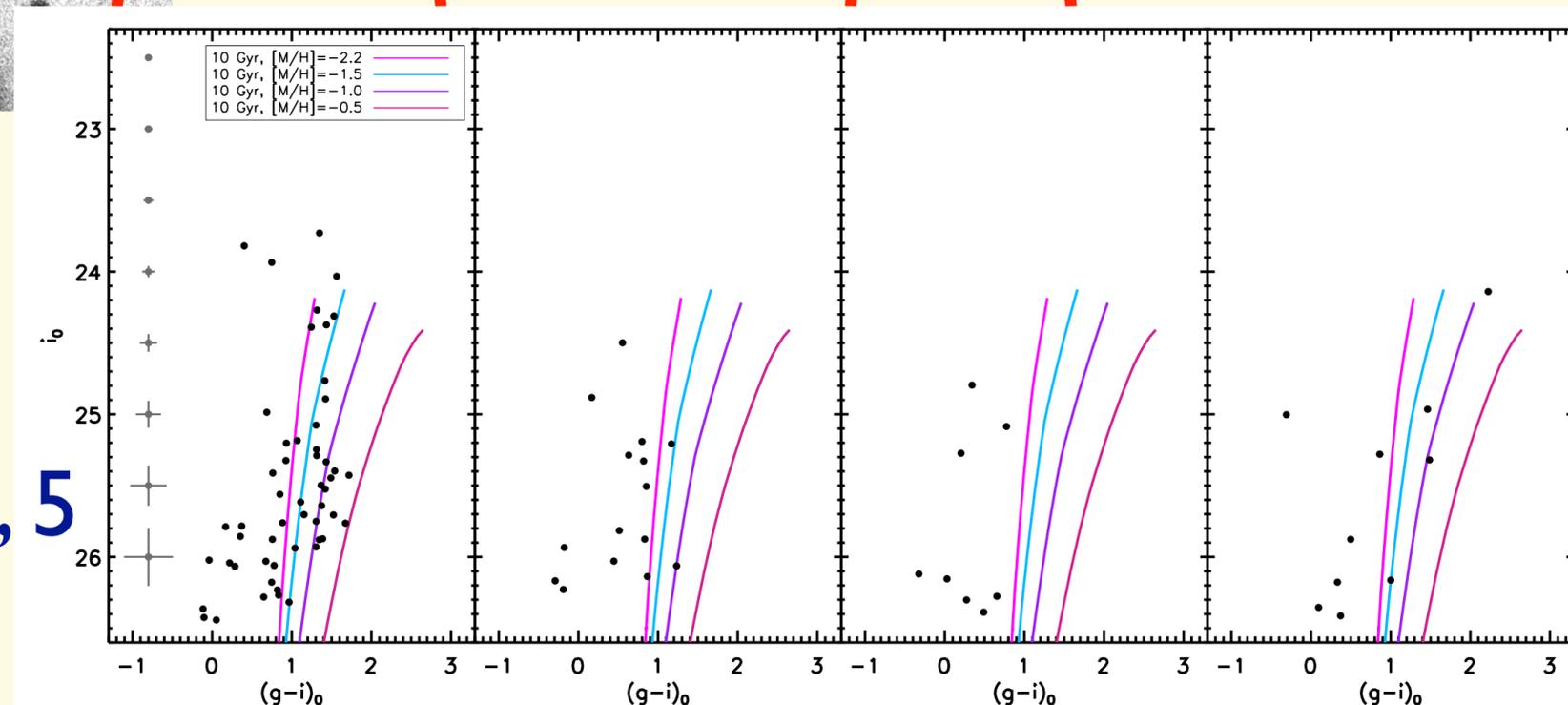
( $D \sim 3.2$  Mpc,  $M_* \sim 7 \times 10^9 M_{\text{Sun}}$ ;  $\sim 2.5 M_{*,\text{LMC}}$ )



**MADCASH J074238+652501-dw**  
 $M_V \sim -7.7$   
 size:  $\sim 200 \times 70$  pc  
 $R \sim 35$  kpc from NGC 2403

MADCASH-dw1

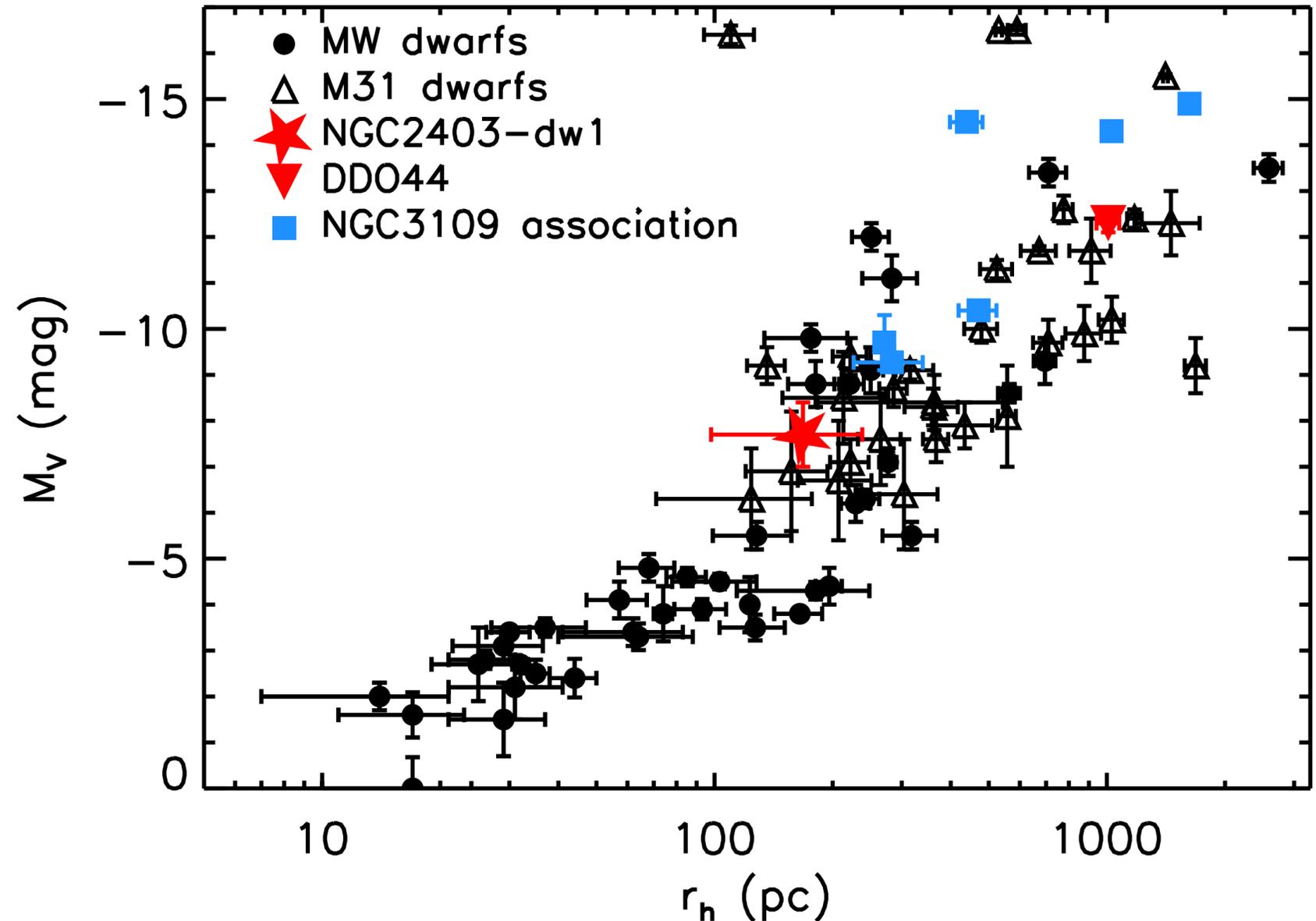
background



\* Carlin et al. (2016), ApJL, 828, 5

# Properties of MADCASH-1 in comparison to Local Group dwarfs

Parameter	Value
RA (hh:mm:ss)	07 : 42 : 38.887 $\pm$ 2.6''
Decl (dd:mm:ss)	+65 : 25 : 01.89 $\pm$ 3.2''
$m - M$ (mag)	27.65 $\pm$ 0.26
$D$ (Mpc)	3.39 $\pm$ 0.41
$M_g$ (mag)	-7.4 $\pm$ 0.4
$M_V$ (mag)	-7.7 $\pm$ 0.7
$r_h$ (arcsec)	10.2 $\pm$ 3.0
$r_h$ (pc)	168 $\pm$ 70
$\epsilon$	< 0.42 (68% CL)
$\theta$ (deg.)	29° (unconstrained)
$\mu_0$ (mag arcsec <sup>-2</sup> )	25.9 $\pm$ 0.7
$M_{\text{star}} (M_{\odot})$	$\sim 1 \times 10^5$
$M_{\text{HI}}/L_V (M_{\odot}/L_{\odot})$	< 0.69
$M_{\text{HI}} (M_{\odot})$	< $7.1 \times 10^4$
SFR ( $M_{\odot}/\text{yr}$ )	$\leq 4.4 \times 10^{-6}$

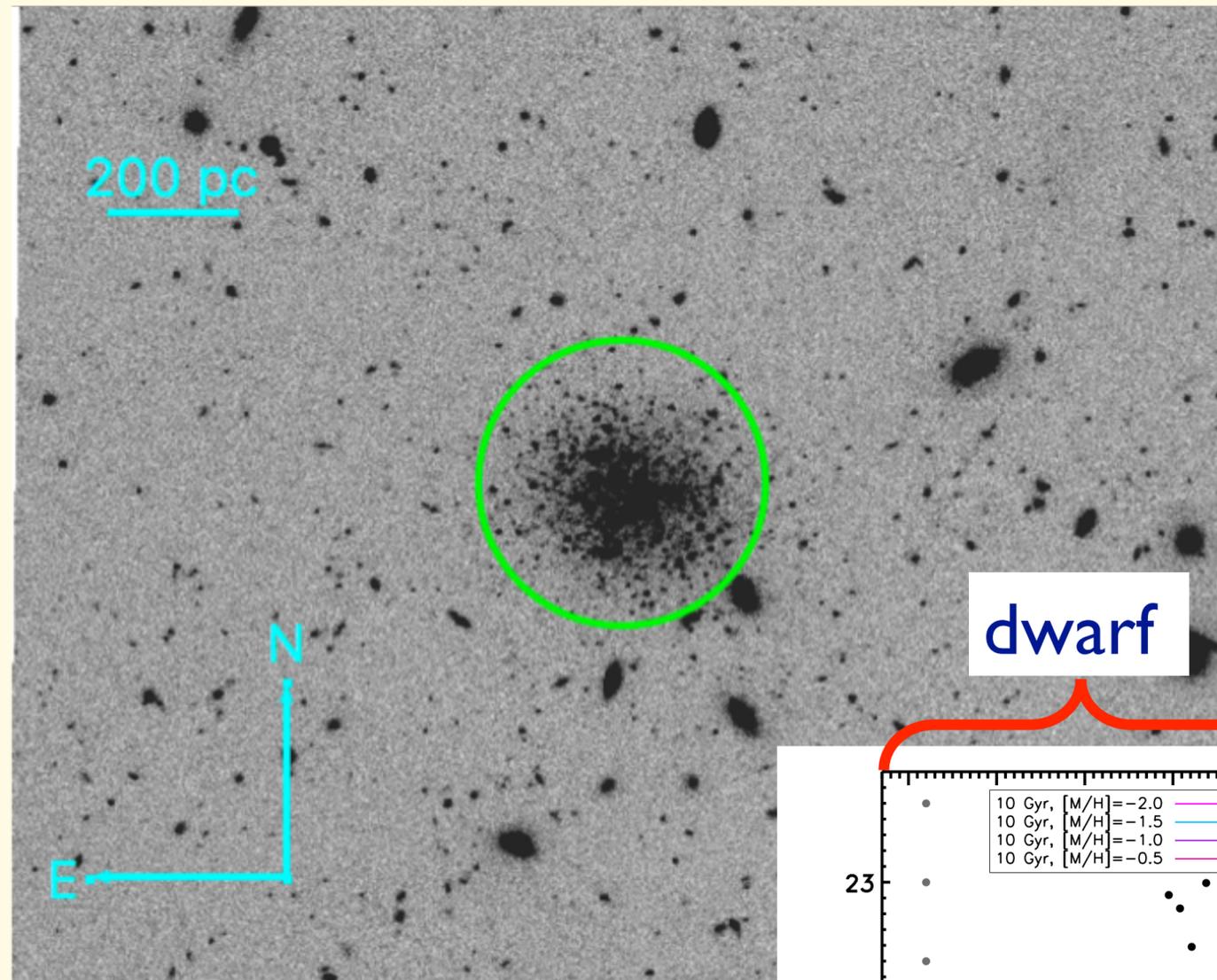


**Faint ( $M_V \sim -7.7$ ) companion of LMC analog NGC 2403, with old ( $> 10$  Gyr), metal-poor ( $[M/H] \sim -2$ ) stellar pops, no appreciable HI or UV emission**

\* Carlin et al. (2016), *ApJL*, 828, 5

# New dwarf galaxy near NGC 4214?

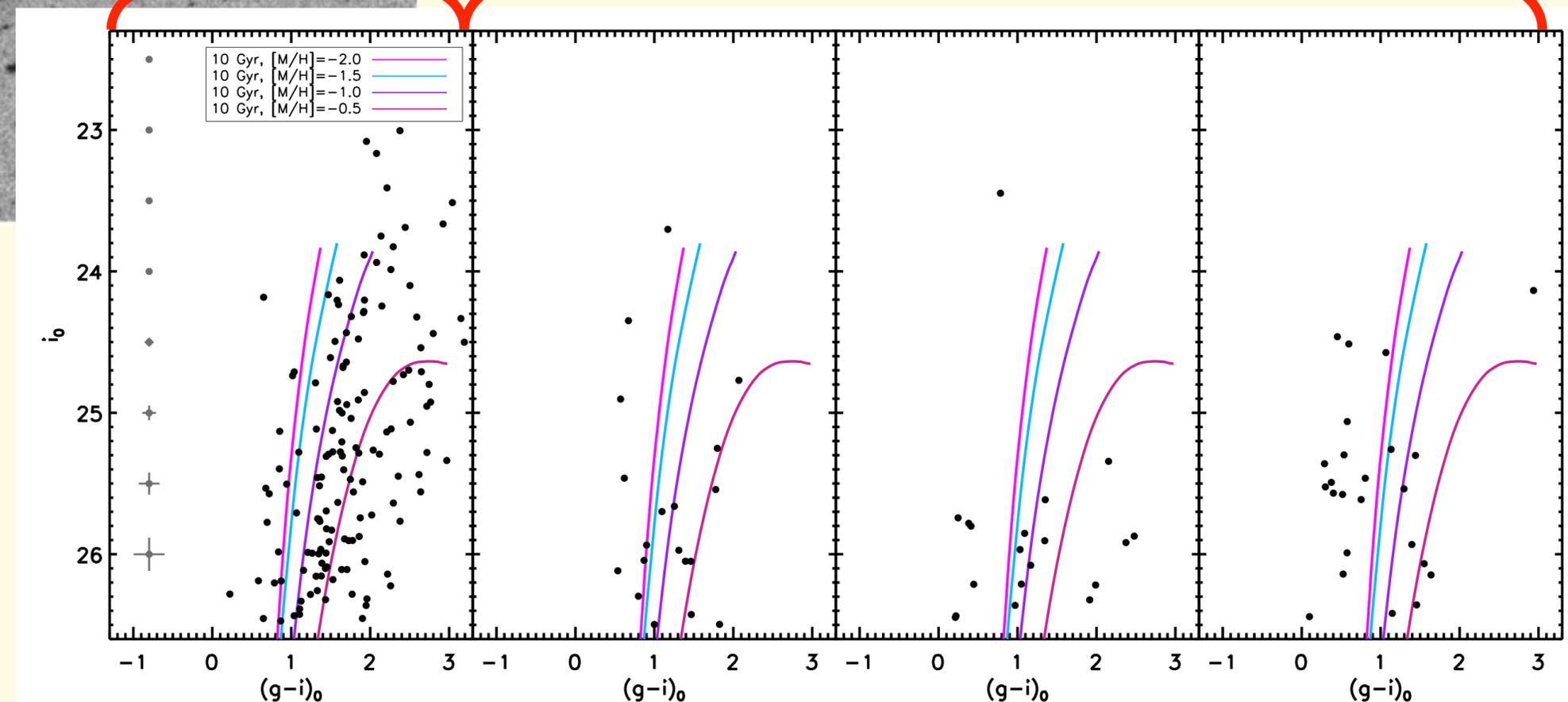
( $D \sim 2.9$  Mpc,  $M_* \sim 1 \times 10^9 M_{\text{Sun}}$  ;  $\sim 0.4 M_{*,\text{LMC}}$ )



dwarf

**MADCASH Jxxxxxxx+xxxxxxx-dw**  
 $M_V \sim -8.5(?)$   
 $r_{\text{half}} \sim 200$  pc  
 $R_{\text{proj}} \sim 70$  kpc from NGC 4214

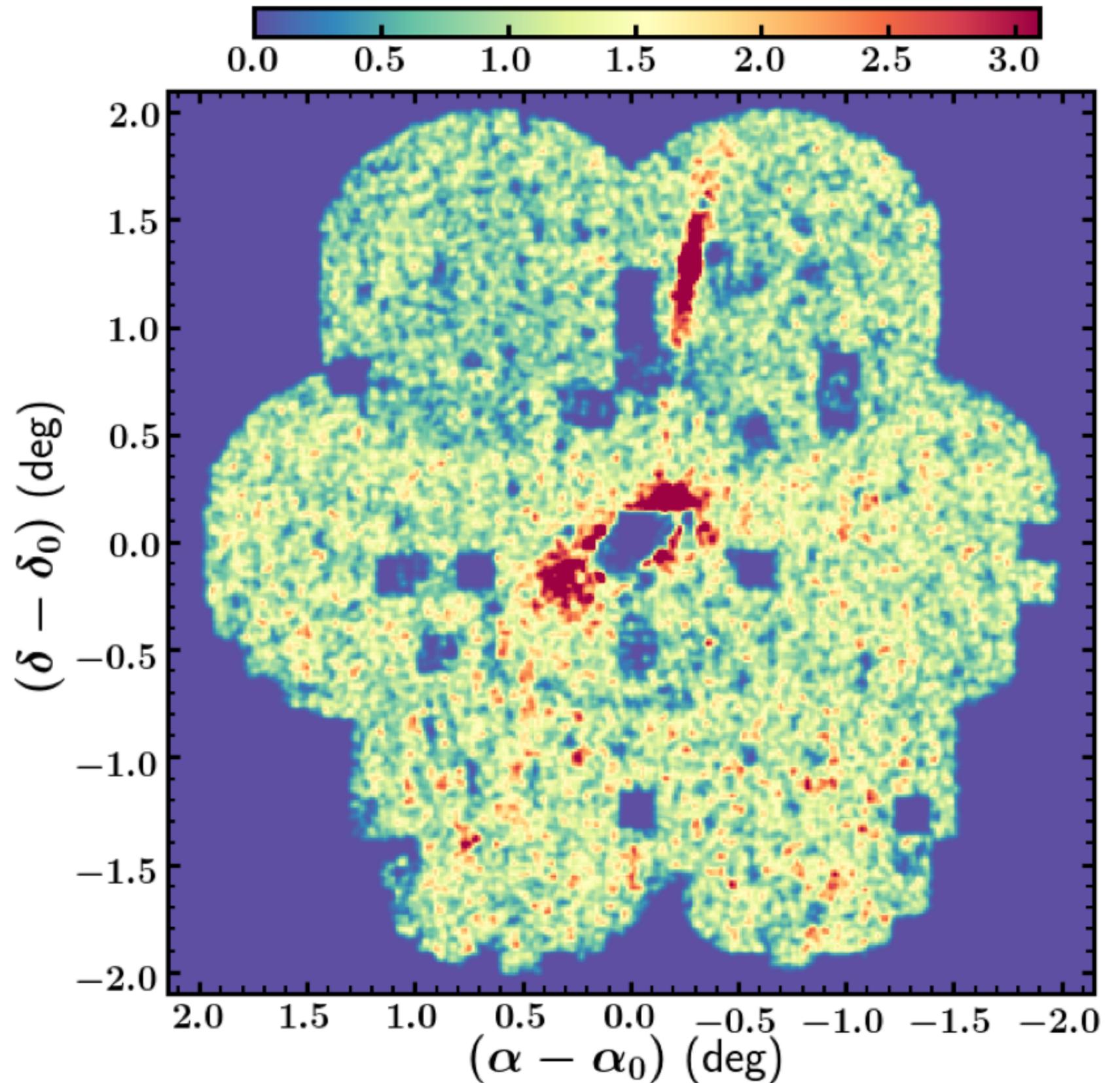
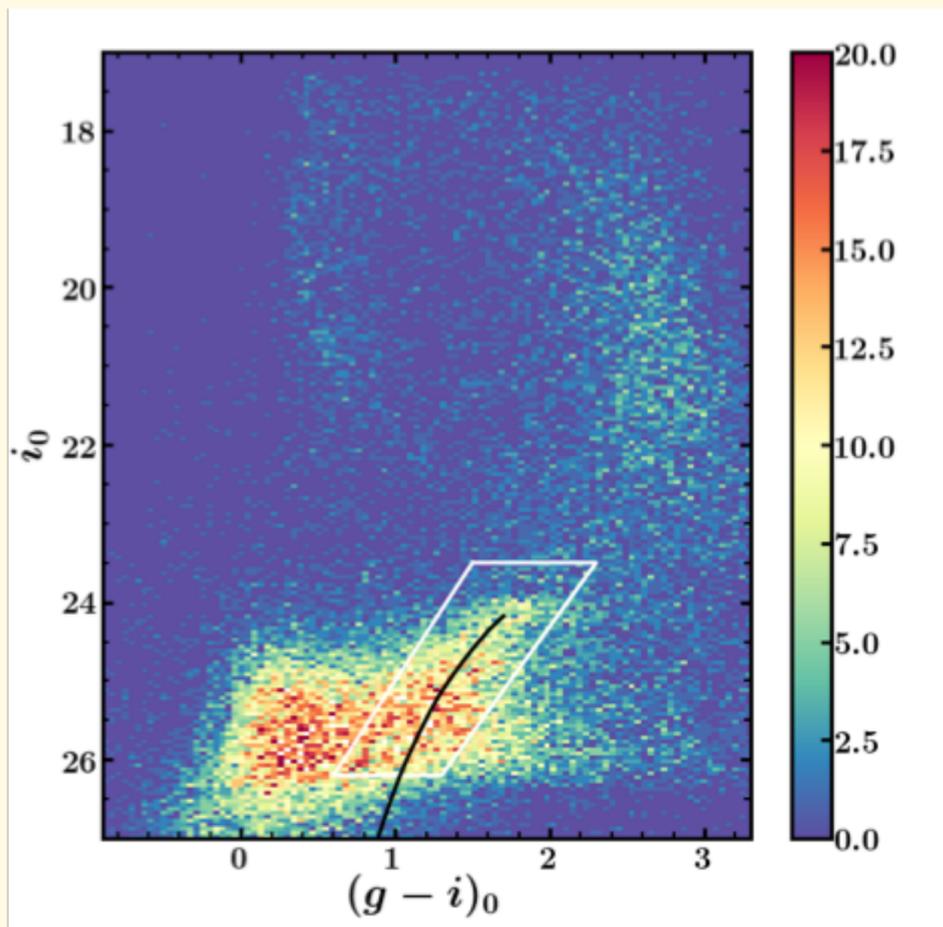
background



\*\*\* preliminary

# Density of RGB stars around NGC 2403

-- Disrupting dwarf satellite with Leo I-like luminosity



Carlin+2018, *in prep.*

\*\*\*preliminary!

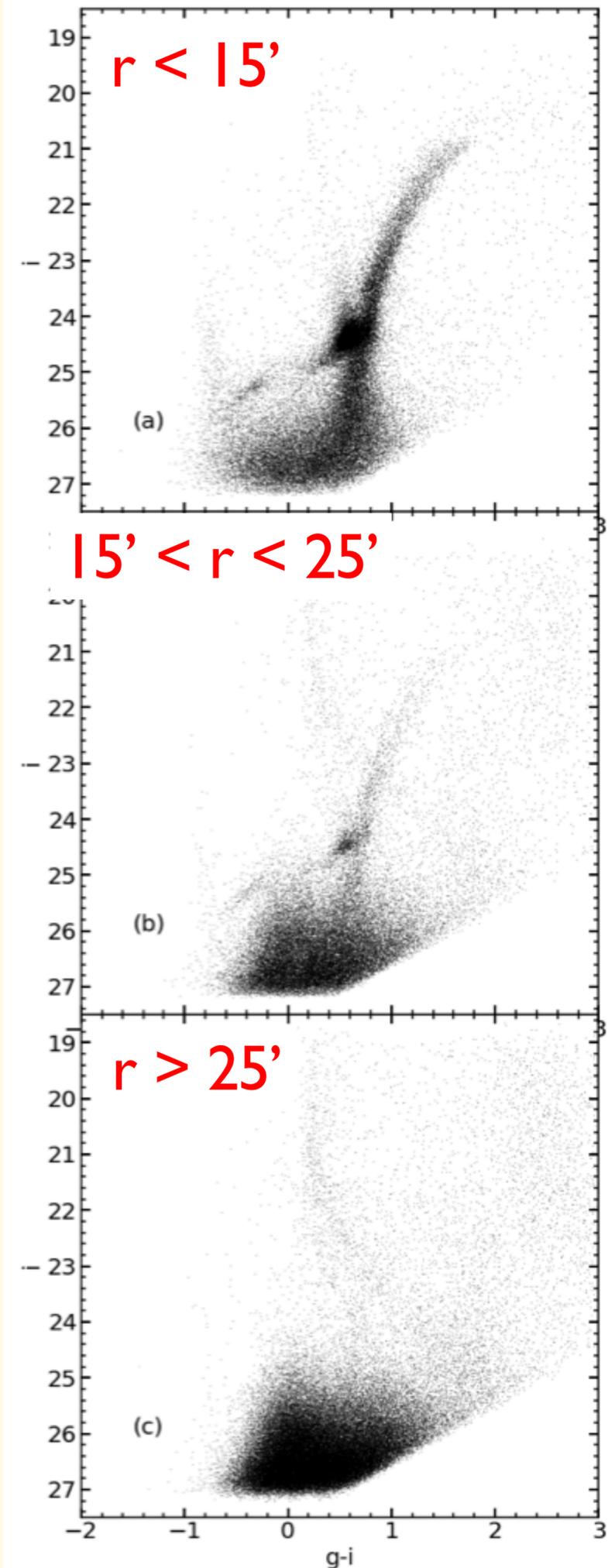
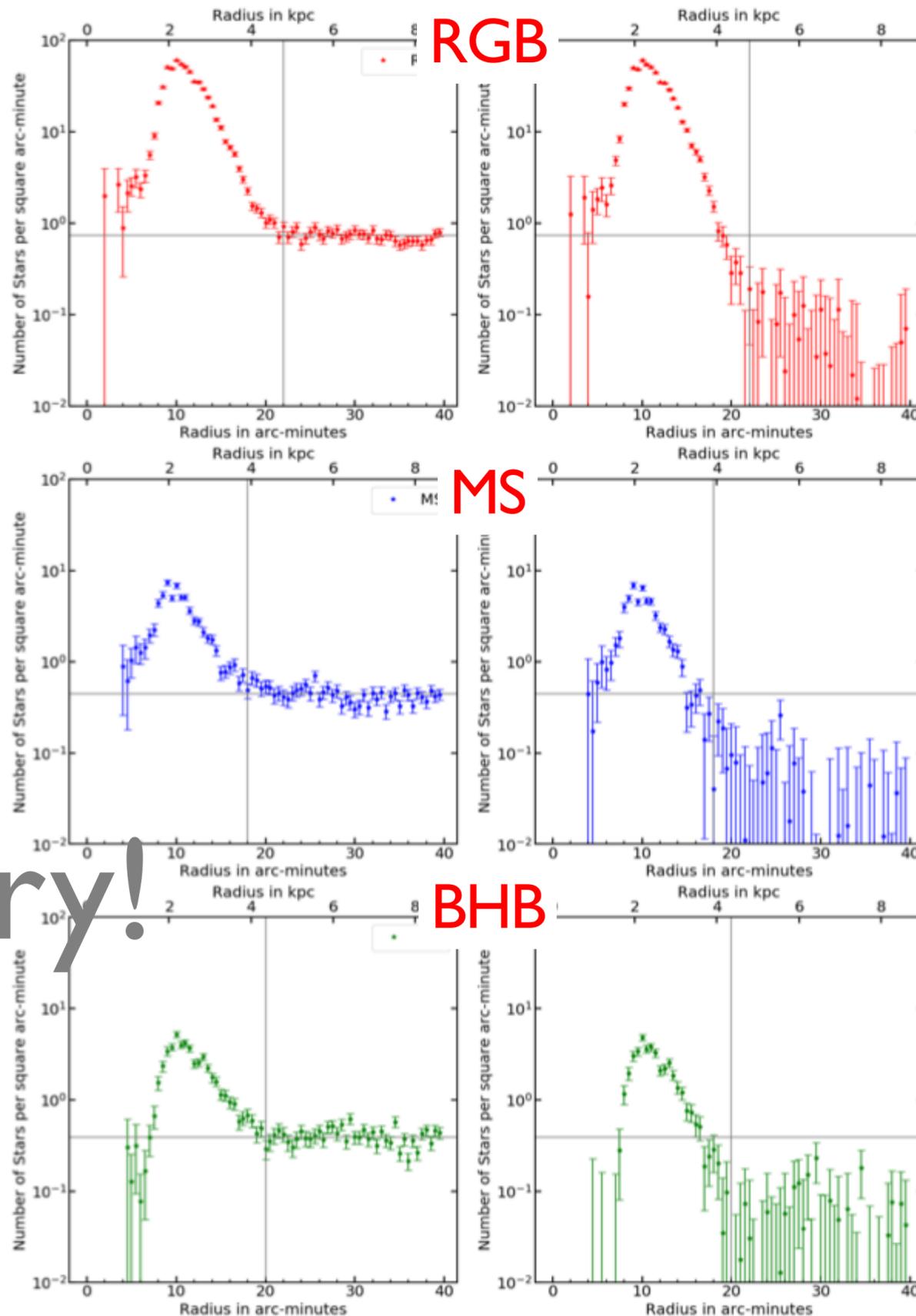
# IC 1613:

$M_* \sim 0.5 M_{*,\text{SMC}}$ ;  $d \sim 730$  kpc

Evidence of  
an extended  
stellar  
component

preliminary!

\*work by Ragadeepika  
Pucha et al.; in prep.

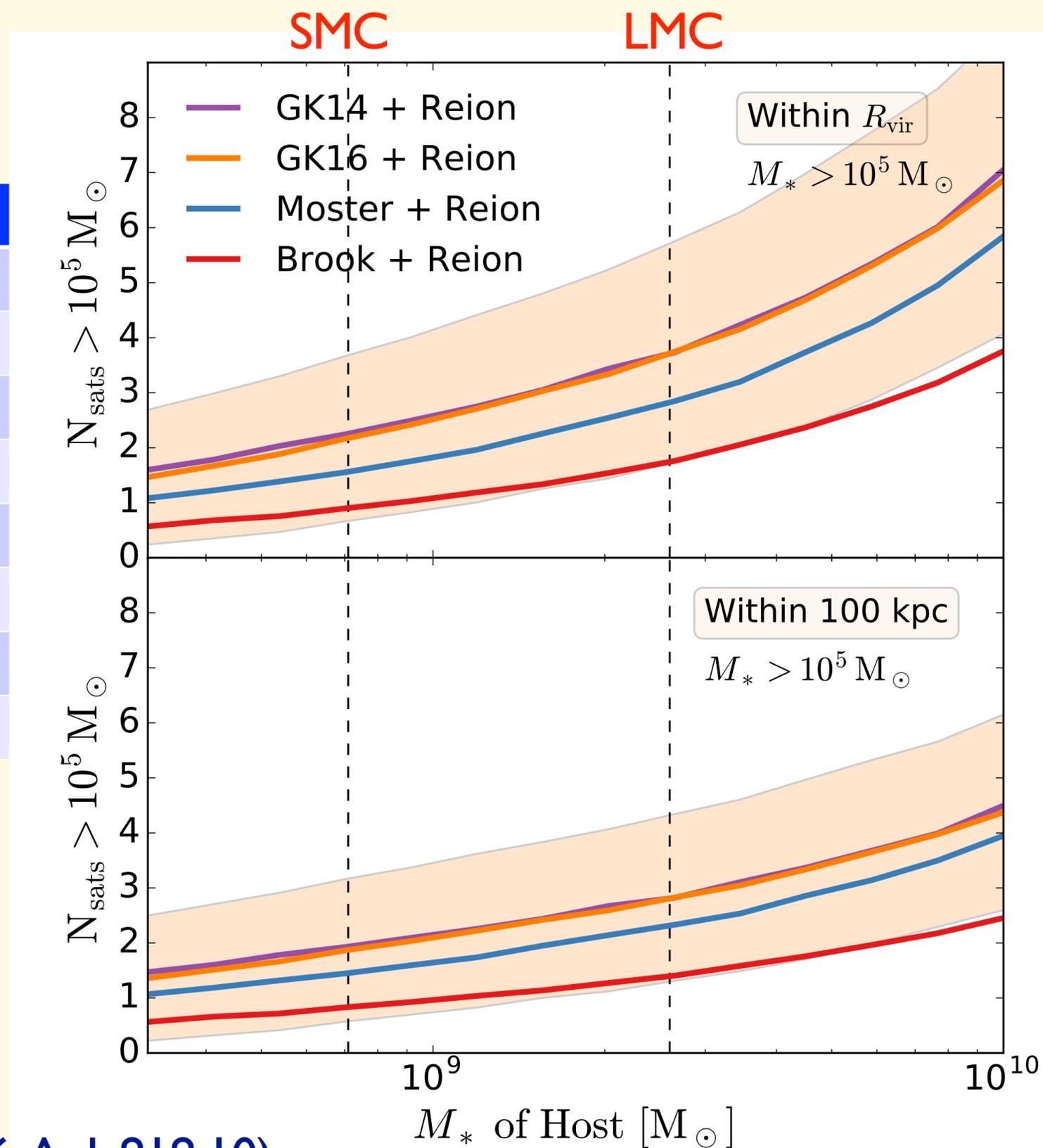


# How many satellites do we expect to find around isolated LMC/SMC stellar-mass galaxies?

[Dooley+2017(MNRAS, 471, 4894)]

Galaxy	$M_*$ ( $10^9 M_{\text{Sun}}$ )	$N_{\text{sat}}$ ( $> 10^5 M_{\text{Sun}}$ )
***SMC***	0.7	1-3
NGC 4214	1.0	1-4
NGC 404	1.8	2-5
NGC 300	2.6	2-5
***LMC***	2.6	2-5
NGC 55	3.0	2-6
NGC 247	3.2	2-6
NGC 2403	7.2	4-8

Note:  $M_* = 10^5 M_{\text{Sun}} \rightarrow M_V \sim -7.2$



see also Dooley+2017 (MNRAS, 472, 1060);  
based on Caterpillar simulations (Griffen+2016, ApJ, 818, 10)

# How many satellites do we expect to find around M33 ( $M_* \sim M_{*,\text{LMC}}$ )?

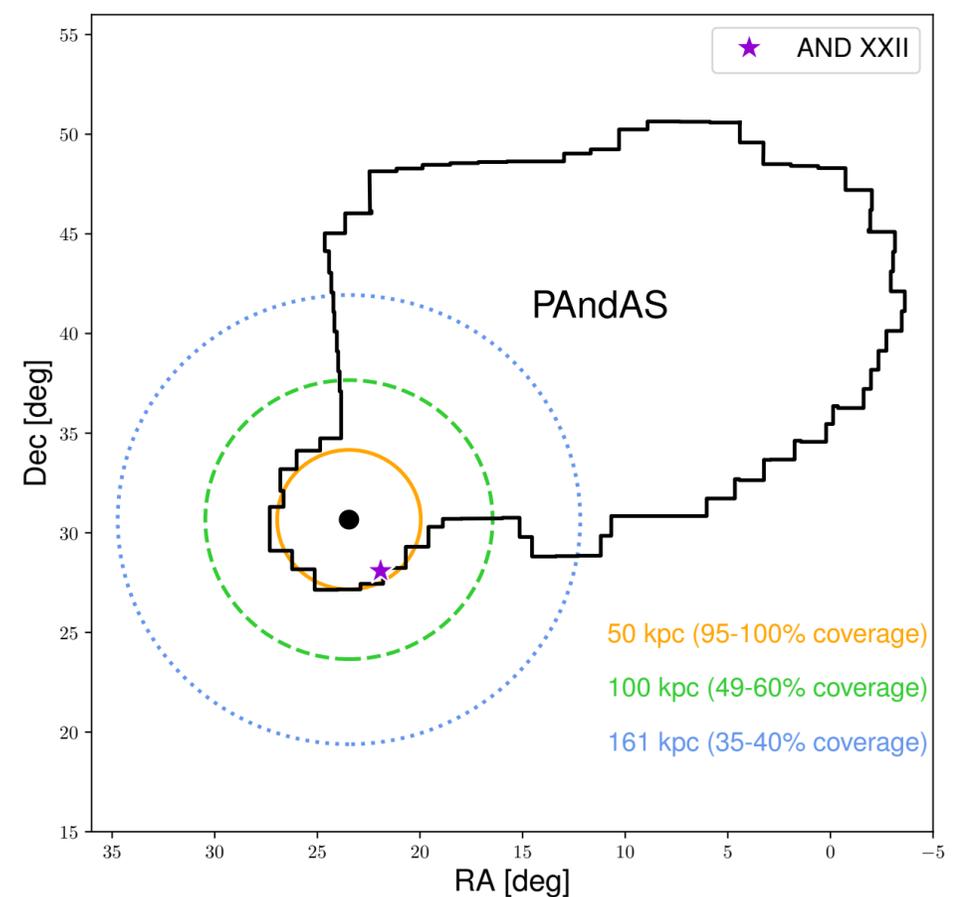
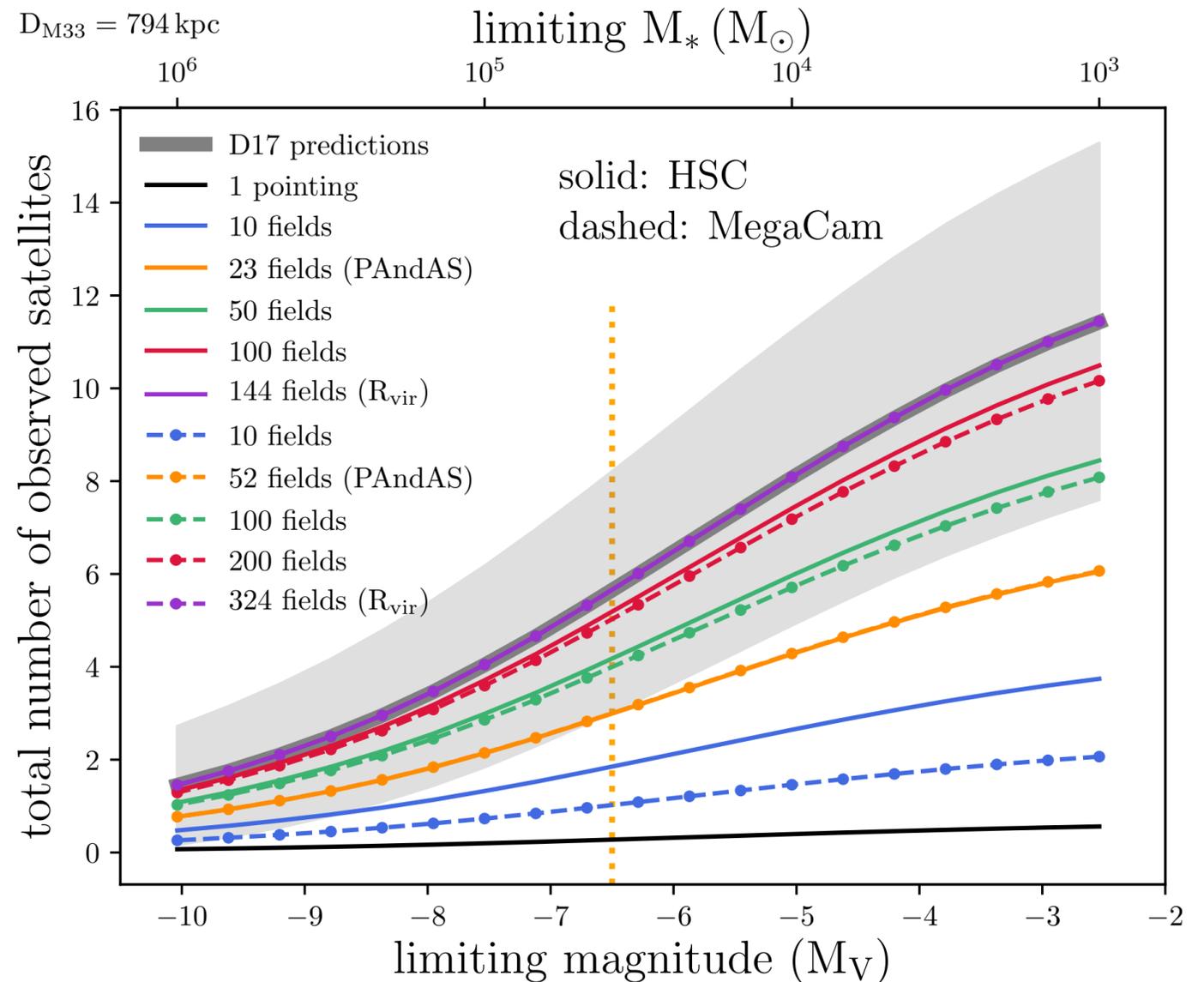
Patel+2018 (MNRAS, *submitted*):

$\Lambda$ CDM predictions:

~4 satellites with  $M_* > 10^5 M_{\text{Sun}}$ ,  
and ~11 with  $M_* > 10^3 M_{\text{Sun}}$

(only 1 possible M33 sat. known – And XXII;  $M_* \sim 4 \times 10^4 M_{\text{Sun}}$ )

Using method of Dooley+2017 (MNRAS, 471, 4894)



# The Large Synoptic Survey Telescope

will again revolutionize our picture of our own cosmic backyard



The LSST system will include:

- (i) an 8.4-meter optical telescope, a 3.5-degree diameter field-of-view, a 3.2 billion pixel camera, and 6 broad-band, optical filters that **will observe more than half the sky hundreds of times over 10 years**
- (ii) a data facility that will process, archive, and distribute survey images, associated transient alerts, and calibrated catalogs.

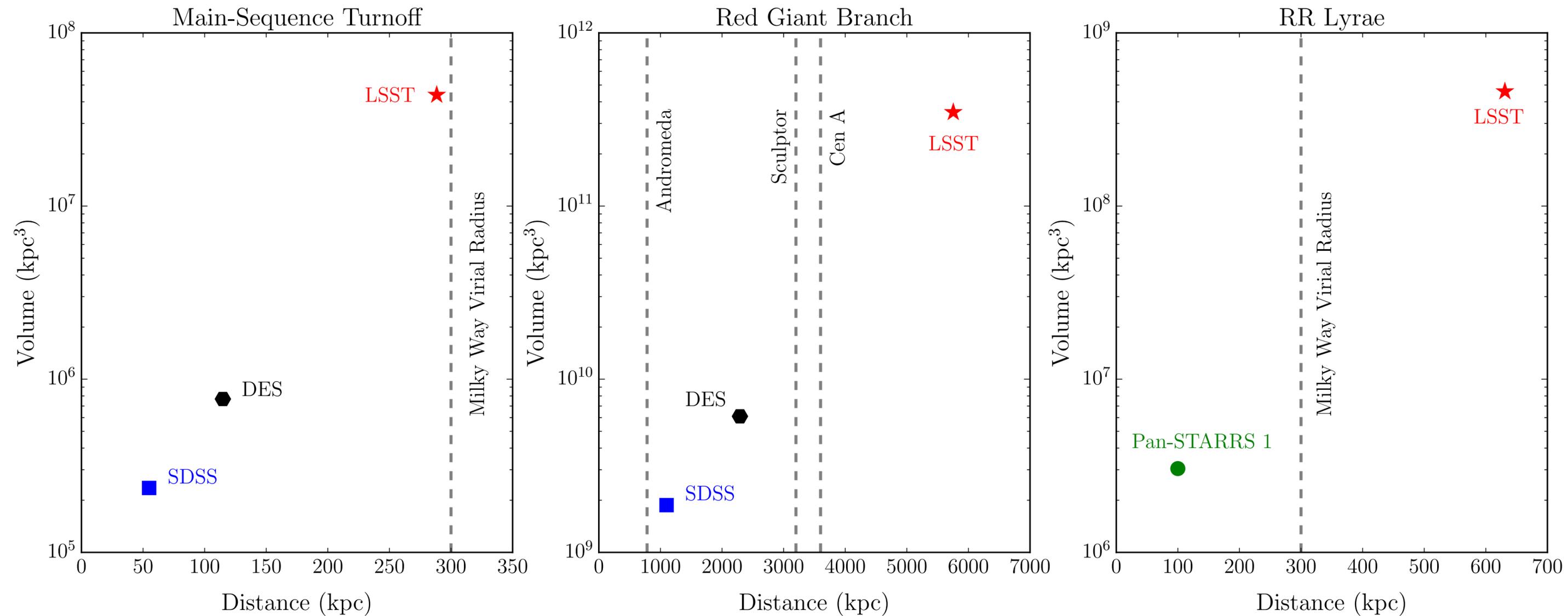


Figure: Keith Bechtol

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

# Summary -- Magellanic Analog Dwarf Companions and Stellar Halos (MADCASH):

We (Carlin et al. 2016) have discovered the faintest dwarf galaxy companion of an LMC-mass host in the Local Volume -- MADCASH J074238+652501-dw.

Many more dwarfs-around-dwarfs are likely to be discovered soon.

## Still to come:

- Systematic search for overdensities of resolved RGB stars in LMC-mass galaxy halos
- (Resolved) surface brightness maps, halo density profiles
- Explore as a function of environment
- Interpret in context of predictions from cosmological models
- LSST!