# The SAGA Survey:
# Building a Statistical Sample of Satellite Systems around Milky Way-like Galaxies


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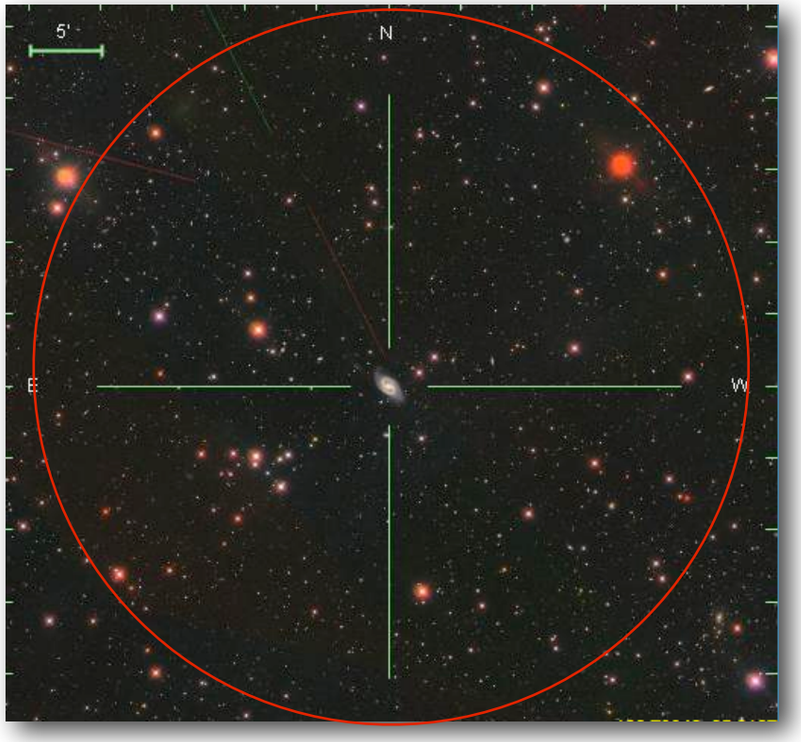
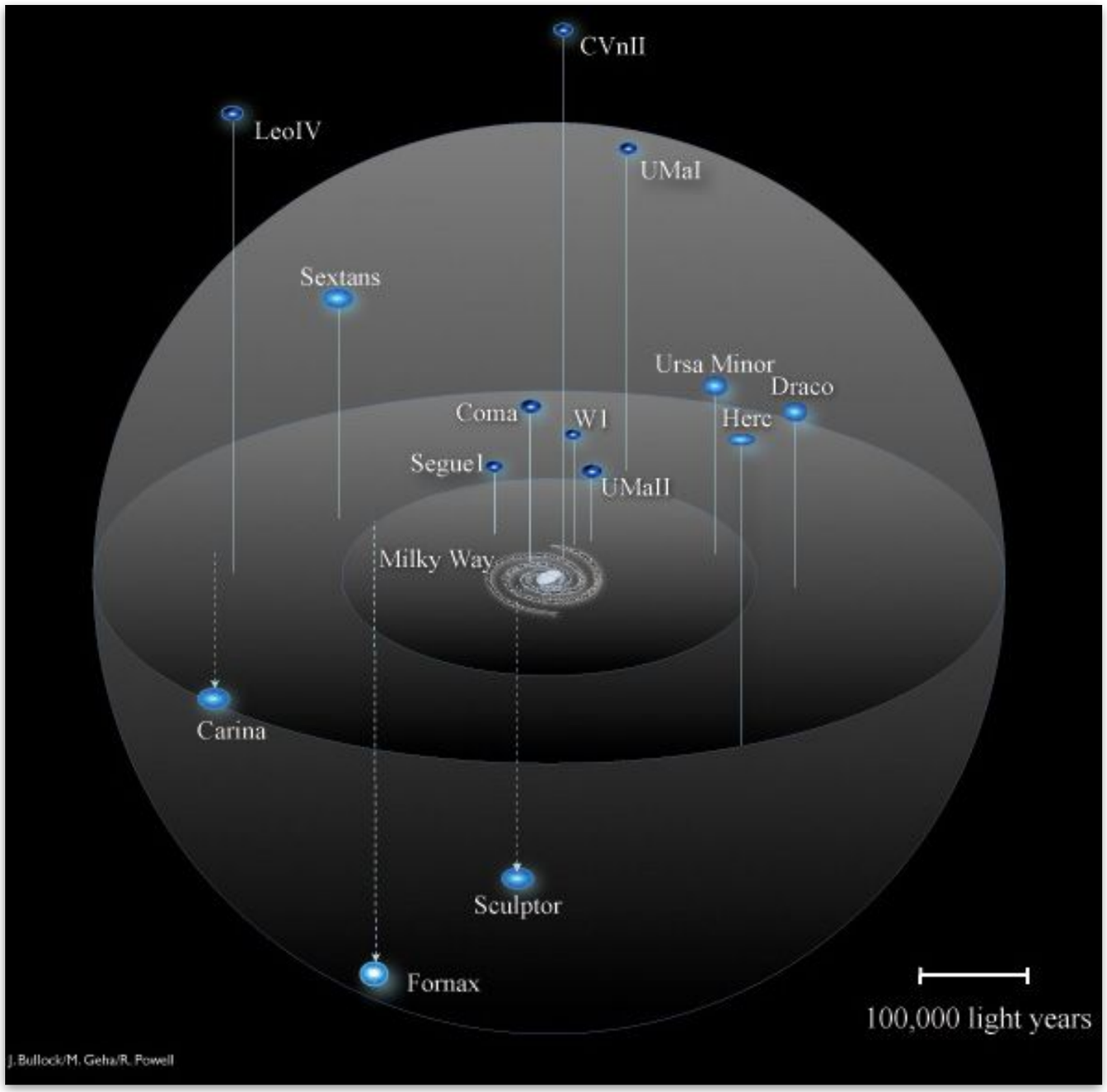



**sagasurvey.org**

# The Milky Way's Satellite Galaxy Population




There are currently 60 known satellite galaxies around the Milky Way.

Proximity allows for detailed study of the Milky Way's satellites.

These satellites provide strong tests of both cosmology and galaxy formation.

# Satellite Galaxies as Useful Tools

1. **Cosmology**

***The Question:*** What is the nature of dark matter?

***The Tool:*** The ratio of low mass to high mass galaxies.

***The Observation:*** Count satellites around Milky Way-analogs, compare to both MW and to simulations.

2. **Galaxy Formation**

***The Question:*** What processes quench star formation in low mass galaxies?

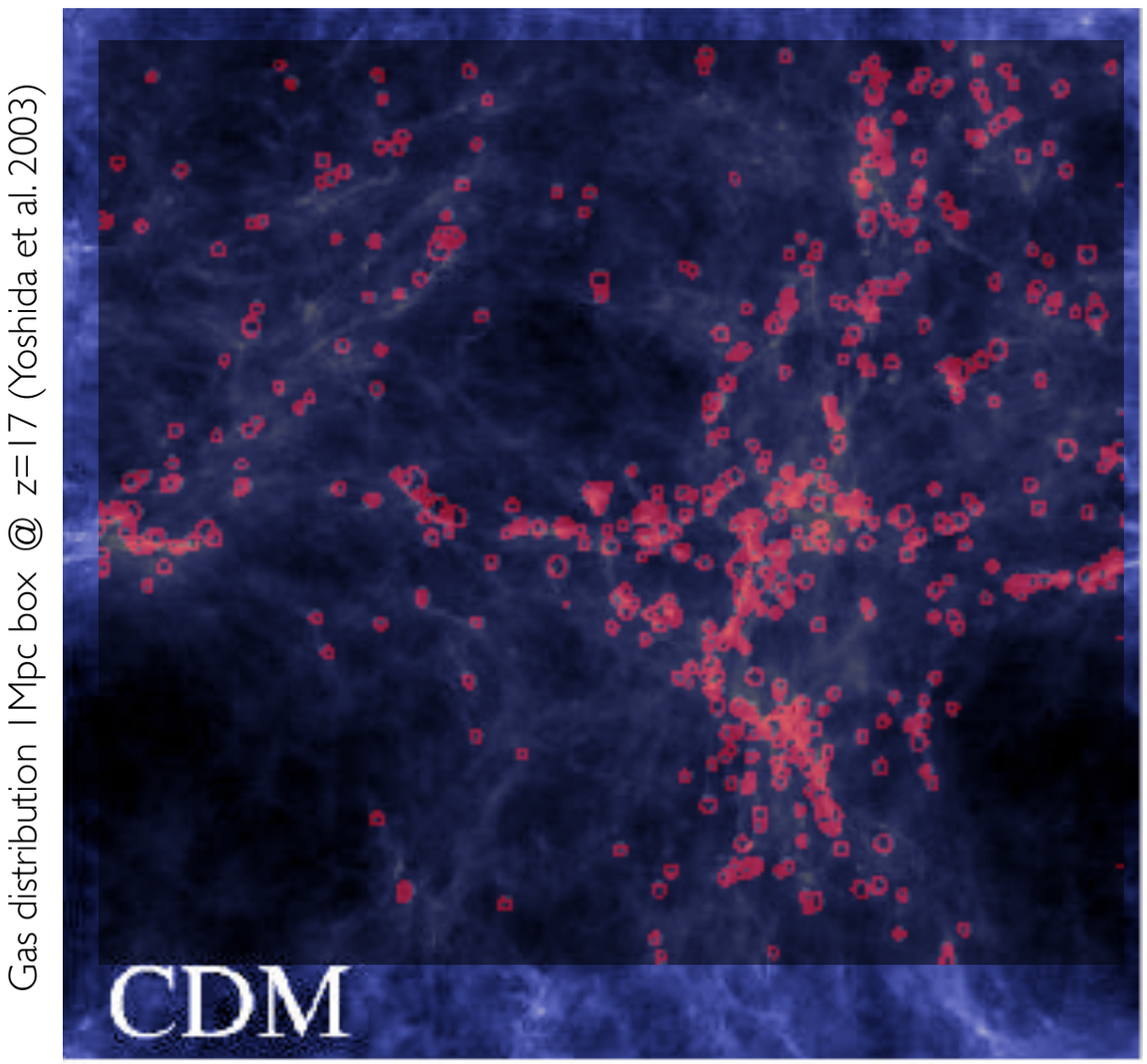
***The Tool:*** The ratio of star forming to quenched galaxies.

***The Observation:*** Determine quenched fraction of satellite galaxies, compare to both MW and to simulations.

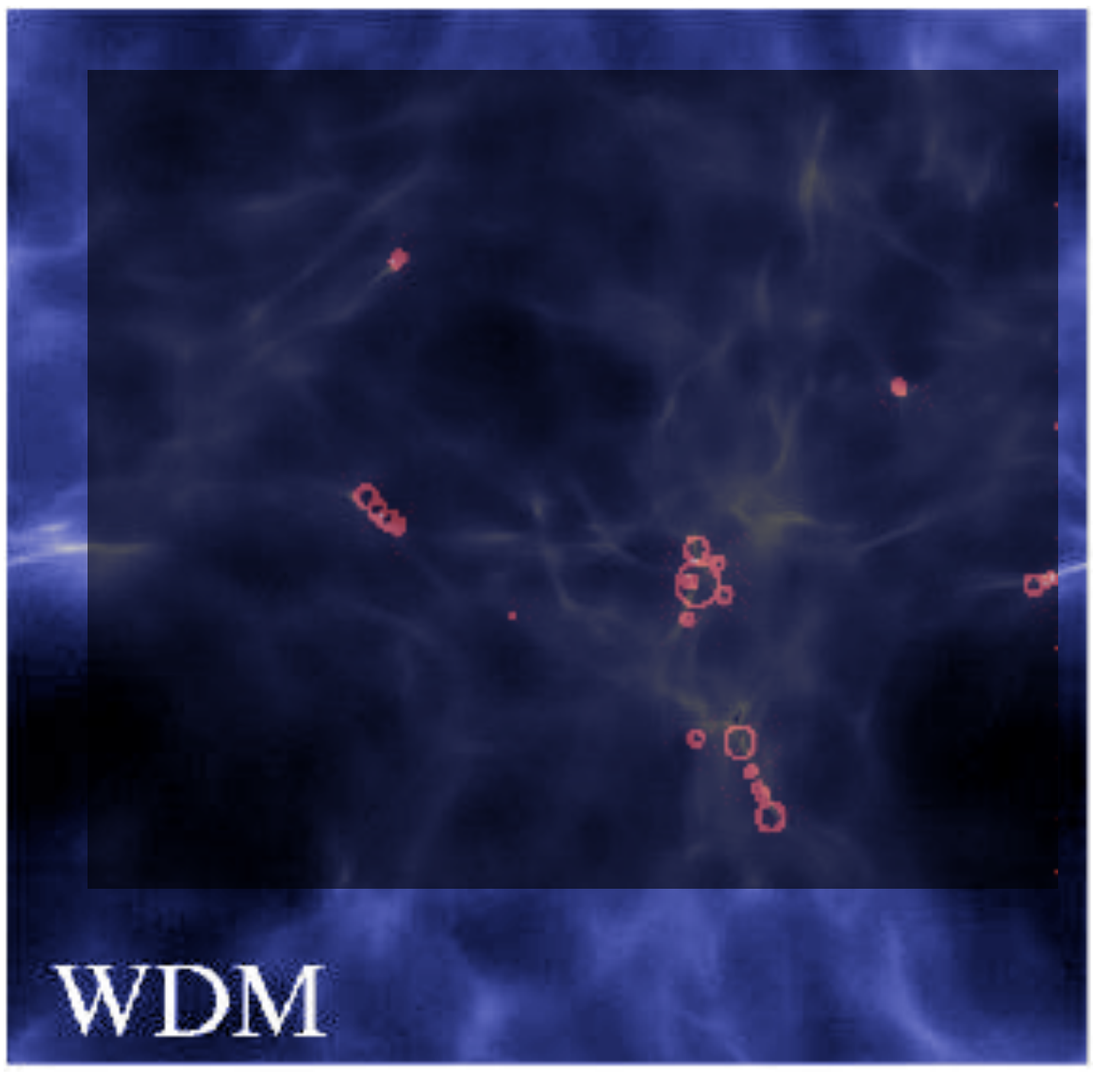
*Both of these tests have been done in the MW, but MW is a single realization of a MW-mass halo!*

# Satellite Galaxies as Probes of Cosmology

The number of low mass galaxies provide a strong constraint on the properties of dark matter.




Cold Dark Matter simulation




Warm Dark Matter simulation

# Satellite Galaxies as Probes of Galaxy Formation

The Milky Way's two brightest satellites are actively forming stars (LMC/SMC), the rest ceased star formation 1 Gyr or more ago (quenched).

LMC: $M_r = -18.5$ SMC: $M_r = -17.1$ Sgr: $M_r = -13.8$ For: -13.7 Leo I: -12.3

In Milky Way, 2 of 5 brightest satellites are forming stars.

In M31, 3 of 9 brightest satellites are forming stars.

# Satellite Galaxies as Probes of Galaxy Formation

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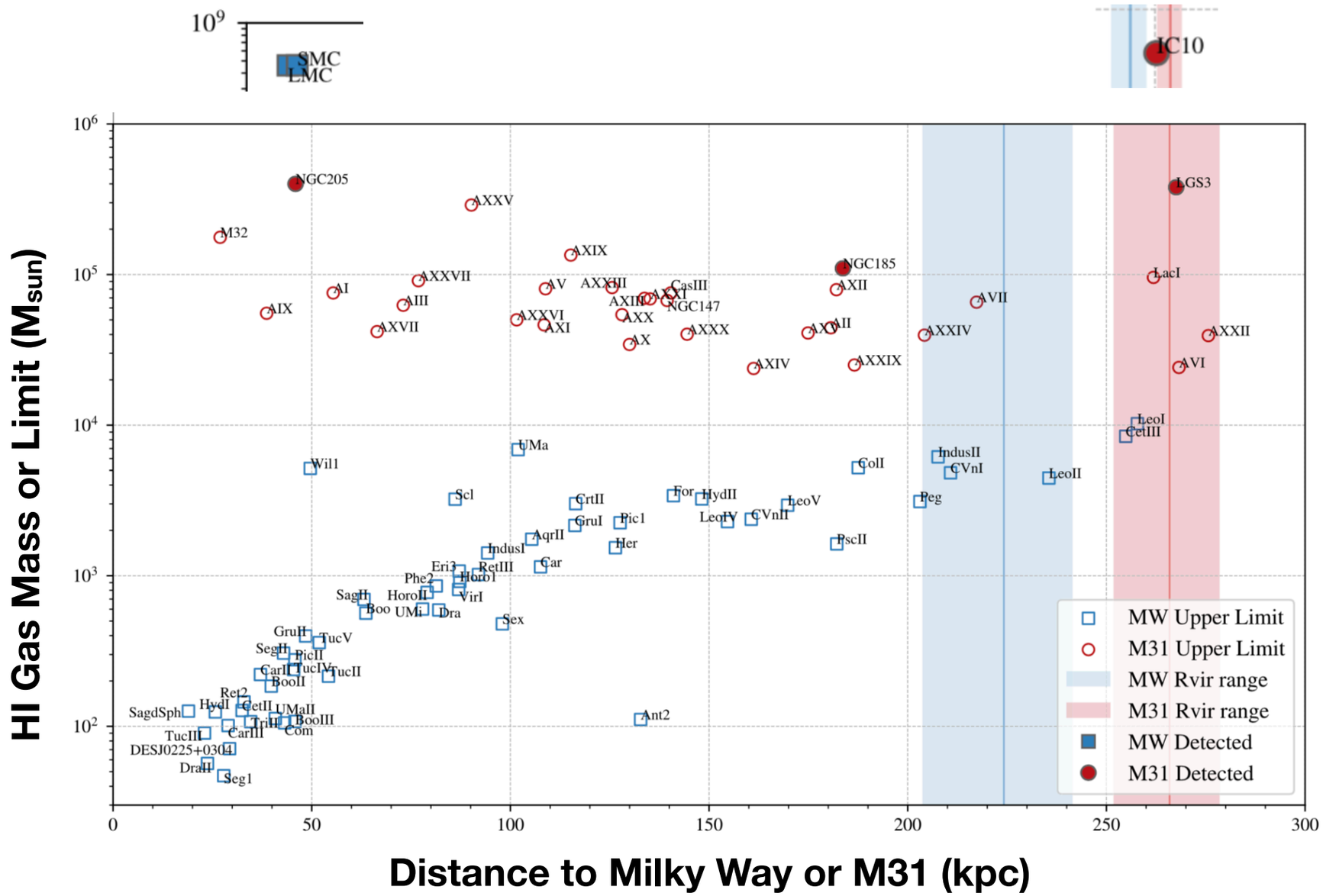
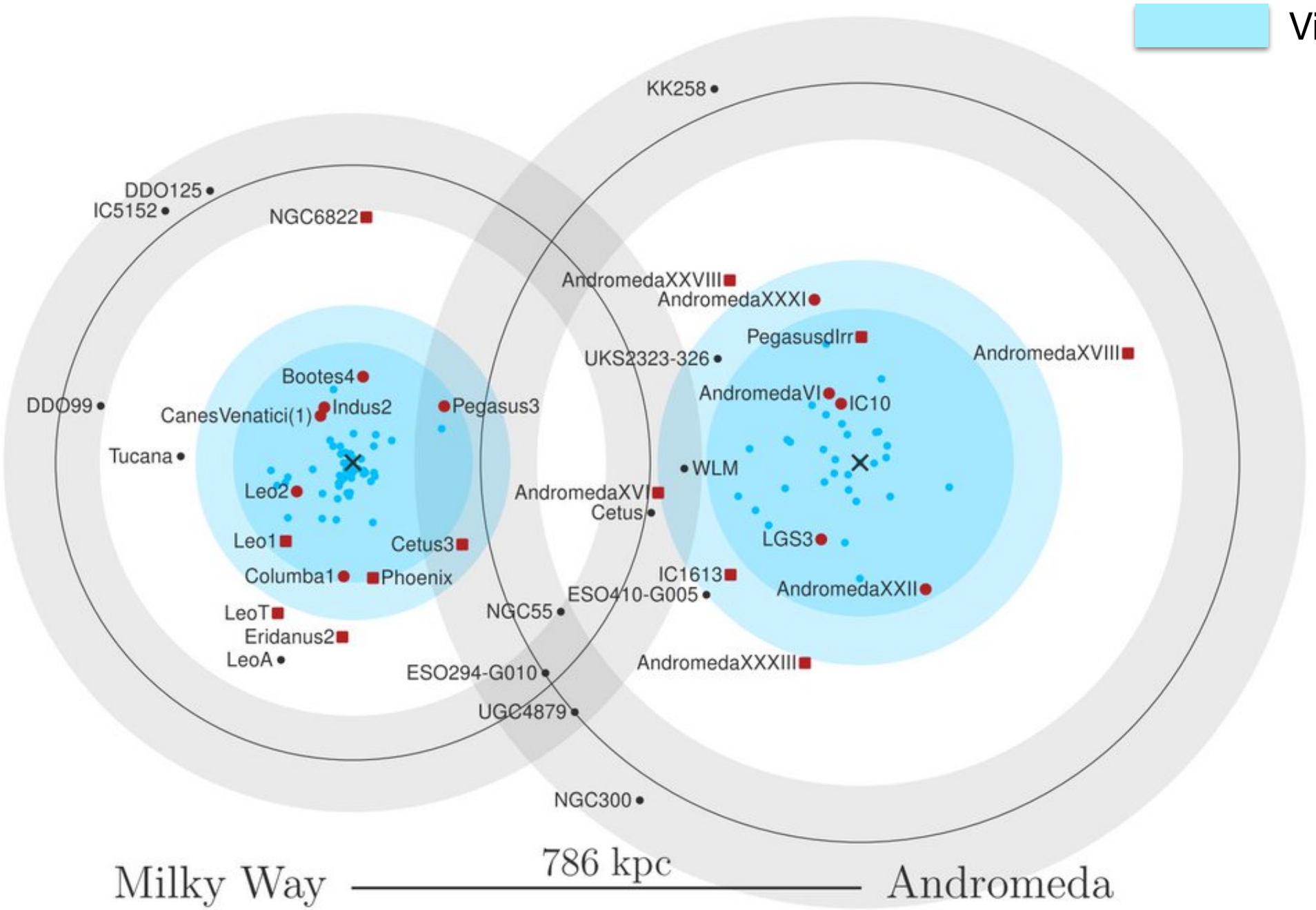



Putman et al. (2021)

# How to Define a Milky Way Analog?




Diemer (2020)

# How to Define a Milky Way Analog?

<u>Milky Way Analog Definition:</u>

**Stellar mass:**

$-24.6 < M_K < -23$

**Environment:**

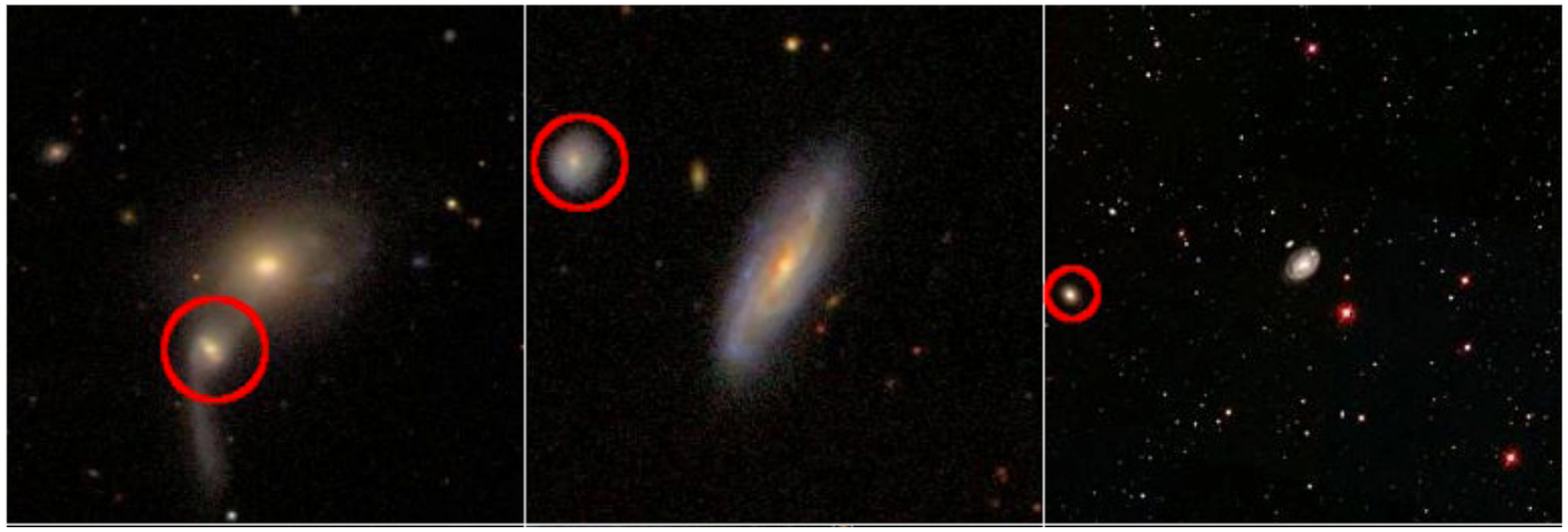
Outside of 2MASS group

No bright galaxy ($M_K < -23$) within viral radius

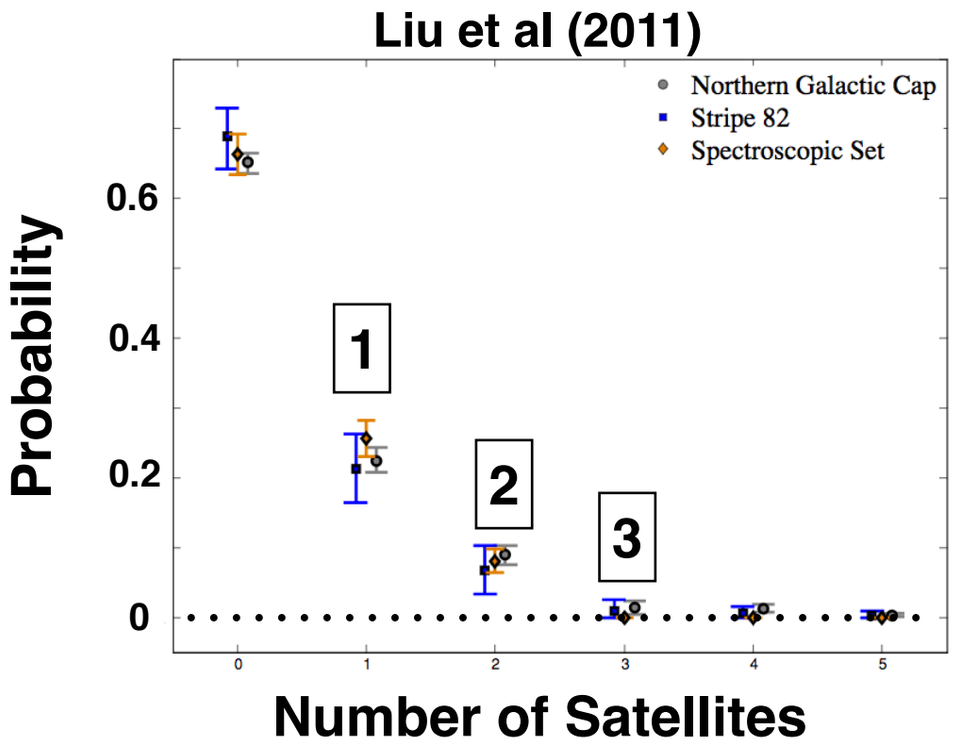
# Satellites Around Milky Way Analogs

SDSS spectroscopic survey allows identification of LMC/SMC satellites around Milky Way-like hosts out to 200 Mpc.

(Liu et al 2011, Tollerud et al 2011, Guo et al 2011, Wechsler & Strigari 2012)



**Liu et al (2011)**

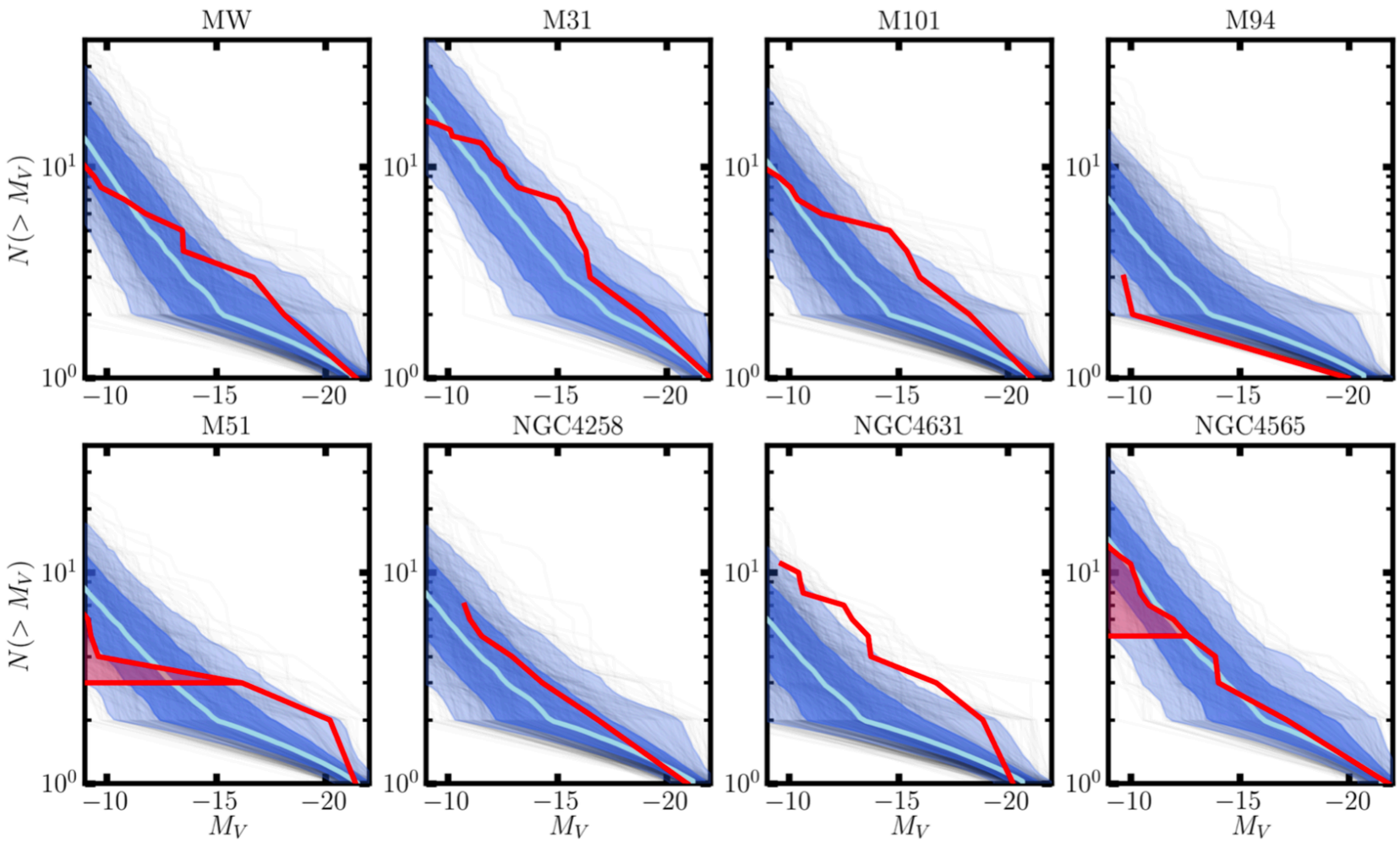



SDSS suggests LMC/SMC are unusual for a MW-mass halo, but not uncomfortably so (~4%).

# Satellites Around Milky Way Analogs

Local volume surveys identify satellites using semi-resolved star techniques.

Carlsten et al (2021): Luminosity functions for 6 Milky Way analogs to $M_v$ = -9




Cumulative satellite number

DMO+SAM models

Crnojevic+ 2019, Smercina+ 2018, Danieli+2017, Bennet+2020

*How many MW analogs are needed to quantify scatter in luminosity function?*

# Satellites Around Milky Way Analogs

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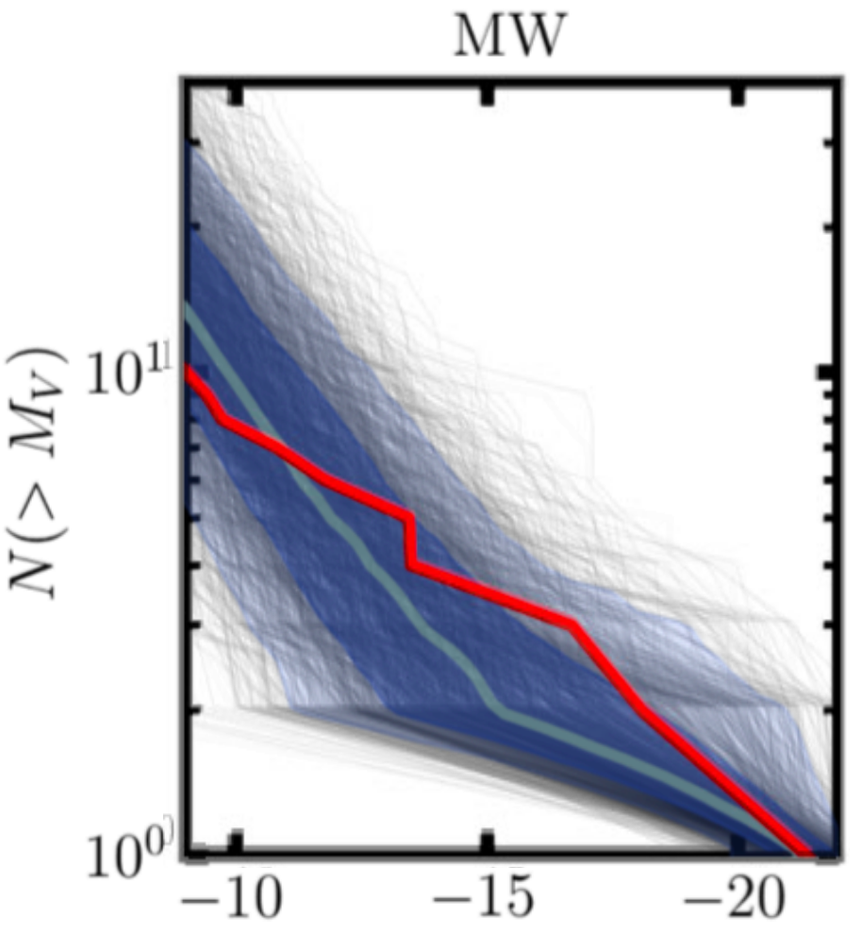



*How many MW analogs are needed to quantify scatter in luminosity function?*

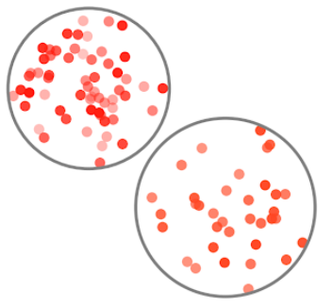
To characterize satellite luminosity functions need around **100** Milky Way analogs.

This requires a survey volume beyond the range of SBF/TRGB methods.

# Satellites Around Milky Way Analogs

## Local Group

e.g., Drlica-Wagner+2020
McConnachie+2012
and MANY more!

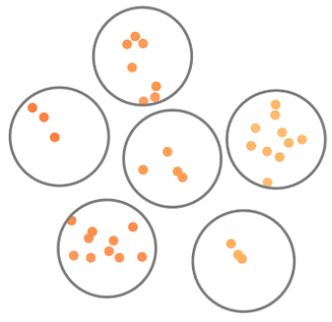


**Resolved stars**

MW ~60 sat.
M31 ~30 sat.

## Local Volume
## < 20 Mpc

e.g., Carlsten+2020
Danieli+2018

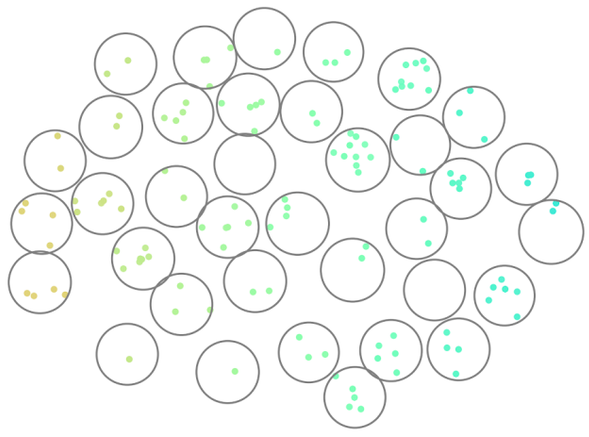


**TRBG/SBF**

~ 5-8 satellites per hosts

## **The SAGA Survey**
## 25 – 40 Mpc

**MG+2017, YYM+2020**

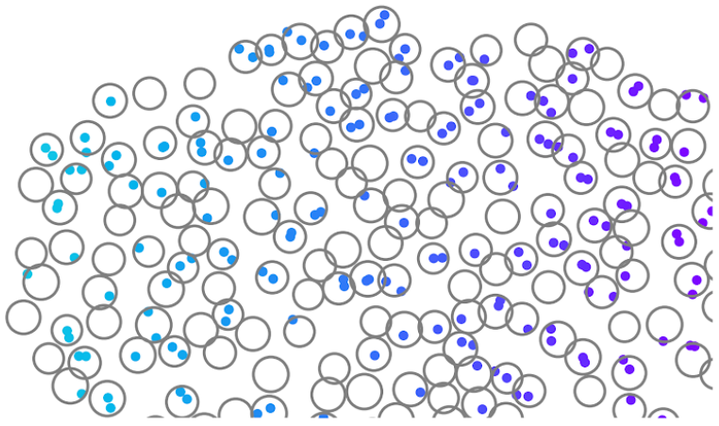


**Targeted spectroscopy**

**~ 3-5 satellites per host**

## SDSS (Main Galaxy Sample)
## Up to ~200 Mpc

e.g., Sales+2013: r < 17.77;



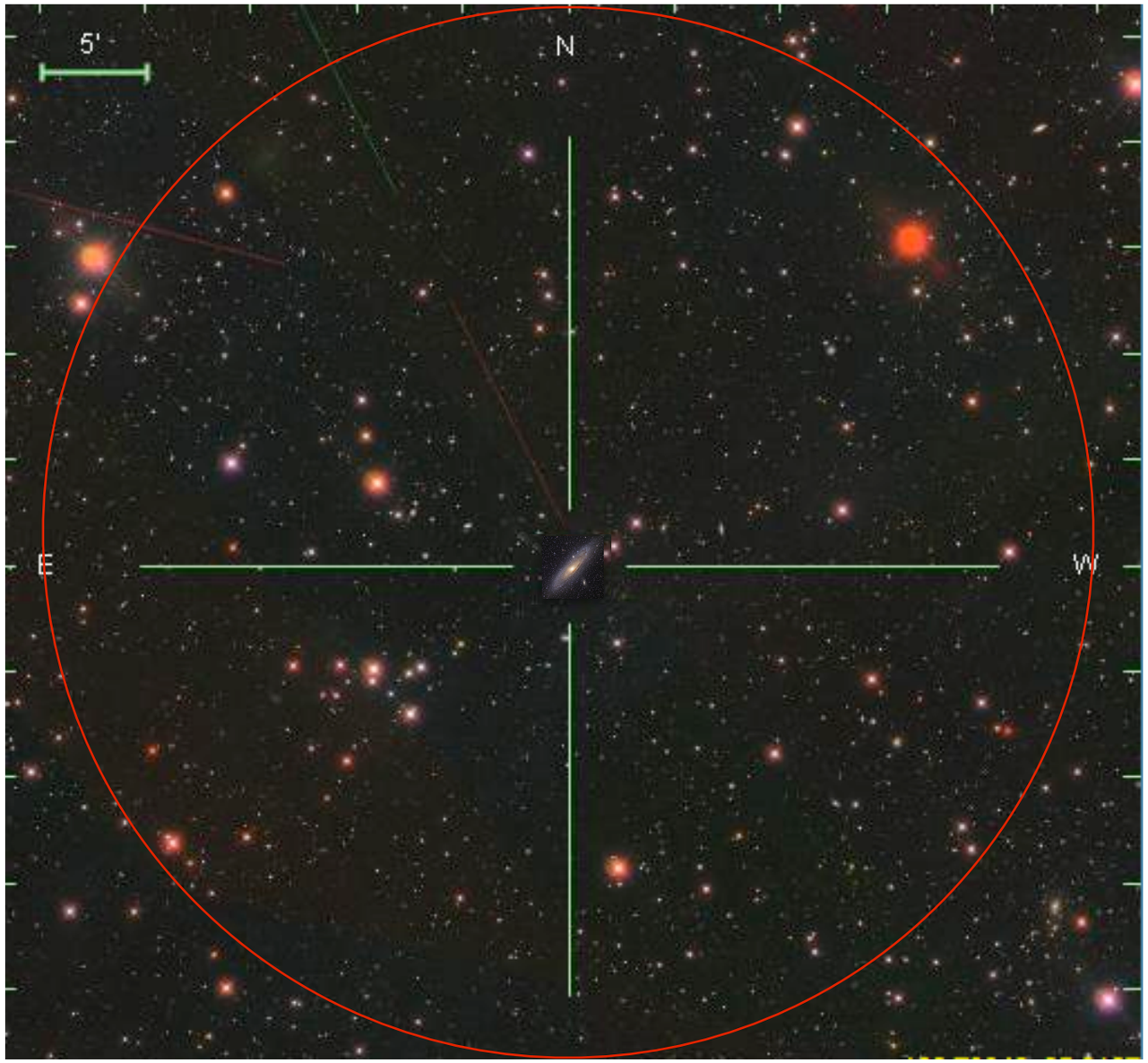
**Complete spectroscopy**

~ 1 sat. per host

**Satellites Around Galactic Analogs (SAGA) Survey goal:**
Characterize satellite populations around
~100 MW analogs to $M_r$ ~ -12.3 ($M_{stellar}$ ~ $10^7$ $M_{sun}$).

# The SAGA Survey:  Survey Design

To observe 100 Milky Ways, need to survey a volume out to ~30 Mpc.




At 30 Mpc,
the virial radius (300 kpc)
is equivalent to diameter of 1 degree

At 30 Mpc,
$M_r$ = -12.3 is equivalent to $r_o$ = 20.75

Within 1°, there are a few thousand
galaxies down to $r_o$ = 20.75

# The SAGA Survey In a Nutshell

## Photometric catalogs (DES/LS/SDSS)

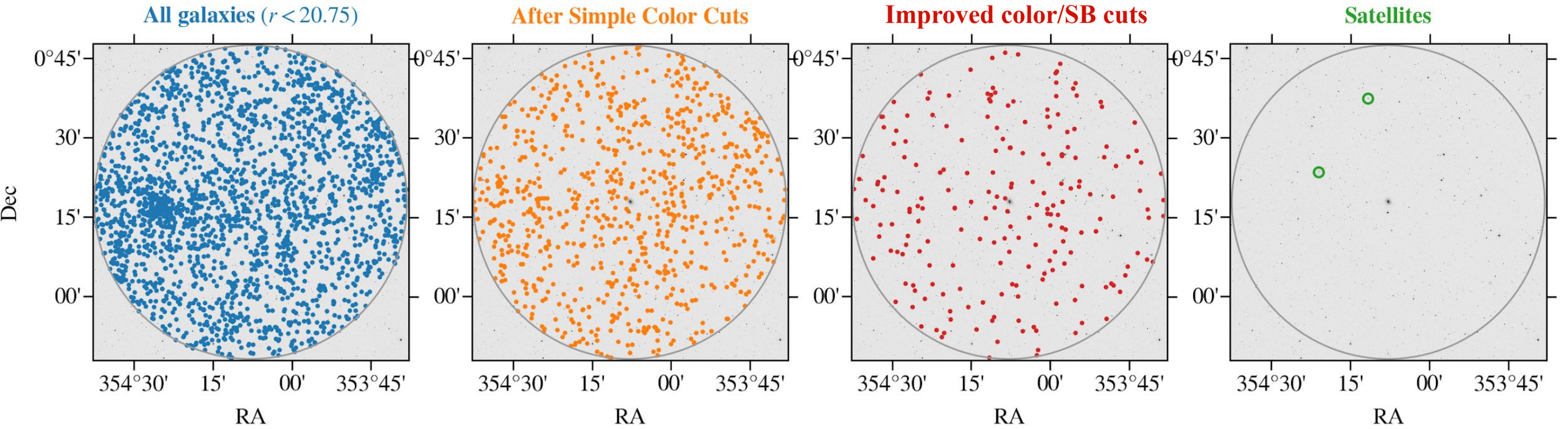
## Stage I

### Geha et al (2017)

## Stage II

### Mao et al (2020)

## Spectroscopically Confirmed Satellites

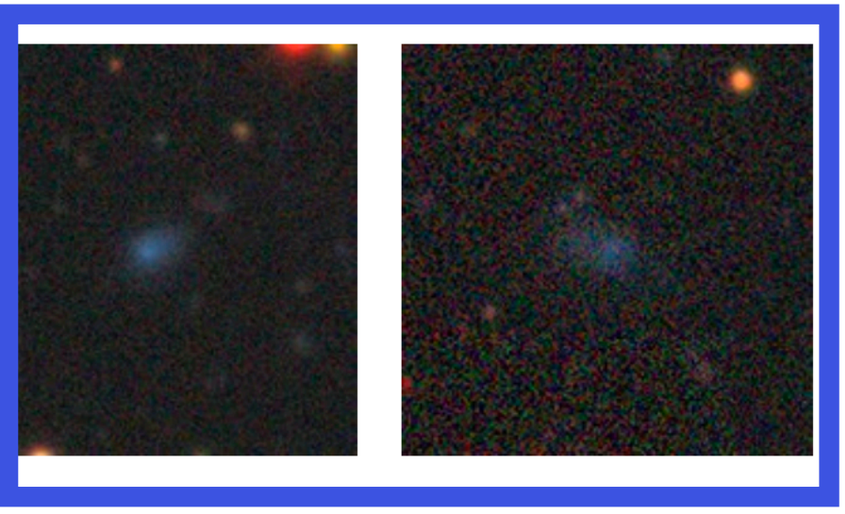



~ 2,500 / sq. deg.

~ 1,000 / sq. deg.

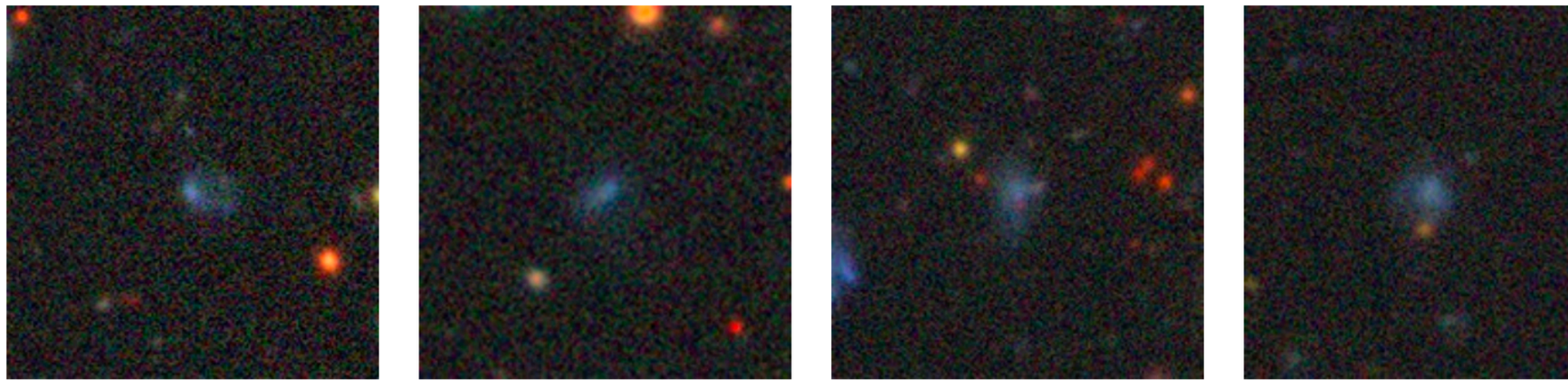
~ 200 / sq. deg.

~ 4 / sq. deg.



z~ 0.008

(Dist = 35 Mpc)



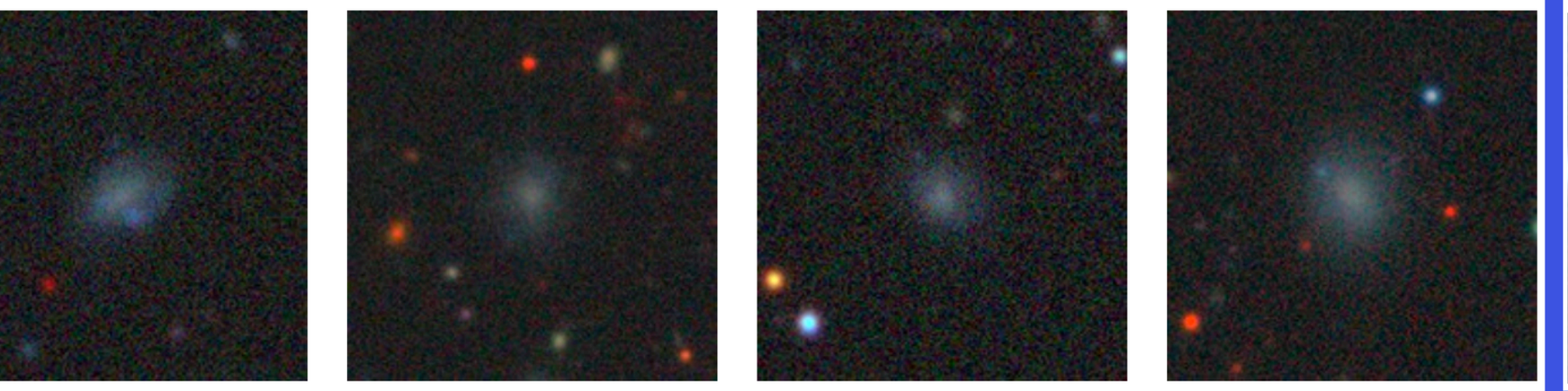
0.06 < z < 0.1

(Dist = 250-500 Mpc)

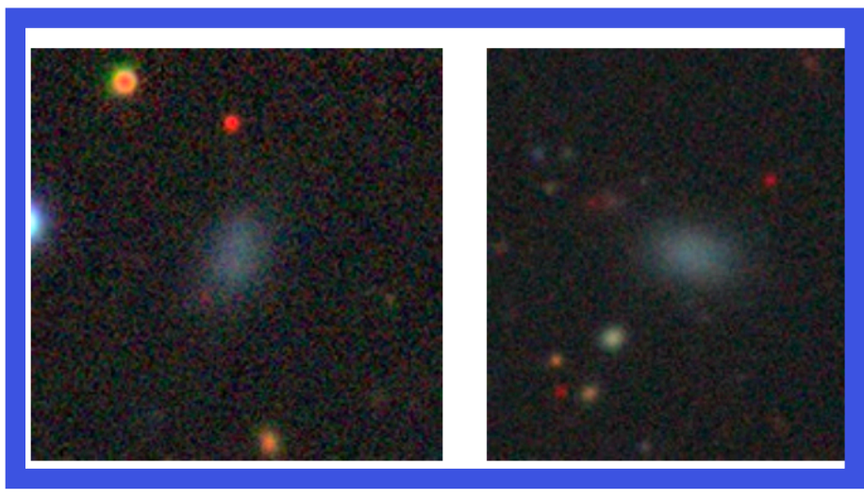
Why is this so difficult?

Guess which of these is a satellite galaxy.

0.05 < z < 0.1



z~ 0.008



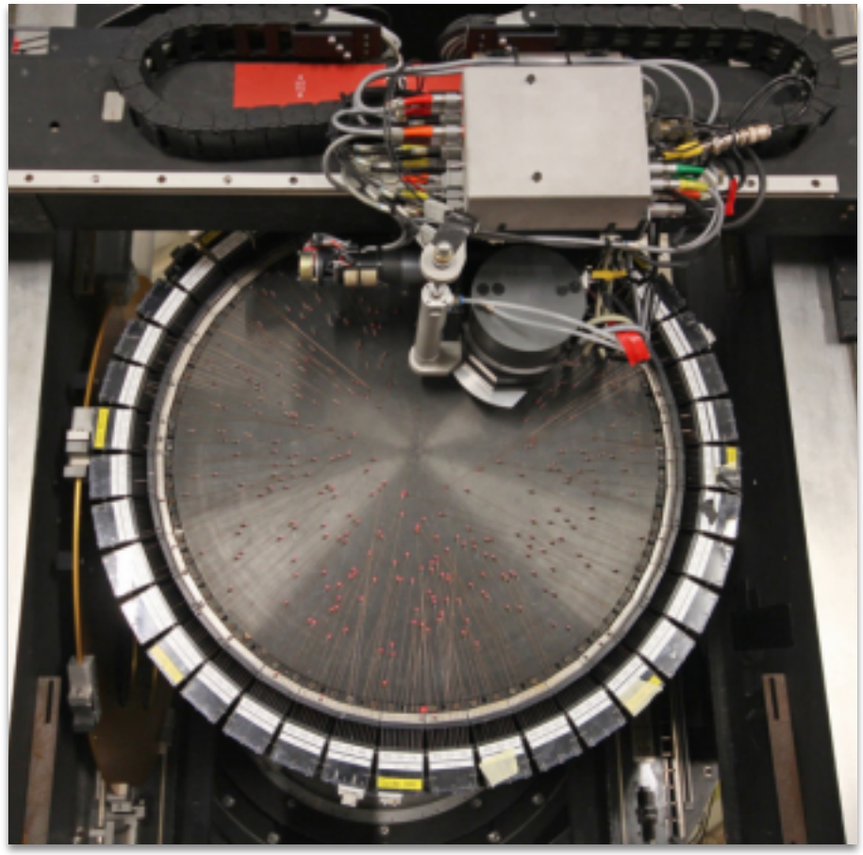
# The SAGA Survey: Spectroscopic Follow-up

Given lack of reliable galaxy distances (photo-z),
we require spectroscopy to identify satellites.

Need large FOV, multi-object spectrographs:

- **AAT/AOmega+2dF** (2 deg, 400 fibers)
- **MMT/Hectospec** (1 deg, 300 fibers)

AAT/2dF



Follow-up multi-fiber work with single-slit spectroscopy (**Palomar/DBSP, SALT/RSS**)
to ensure redshifts of lowest surface brightness targets.

SAGA hosts selected in distance range 25 Mpc < Dist < 40 Mpc.

# The SAGA Survey:  Towards 100 Milky Ways

**SAGA Observational Goal:**
Characterize the satellite populations down to $M_r = -12.3$ around 100 Milky Way-like galaxies.

✔ **Stage 1:** Build complete sample of a few MW analogs using color cuts.

✔ **Stage 2:** Use data from Stage I to design an efficient targeting strategy.

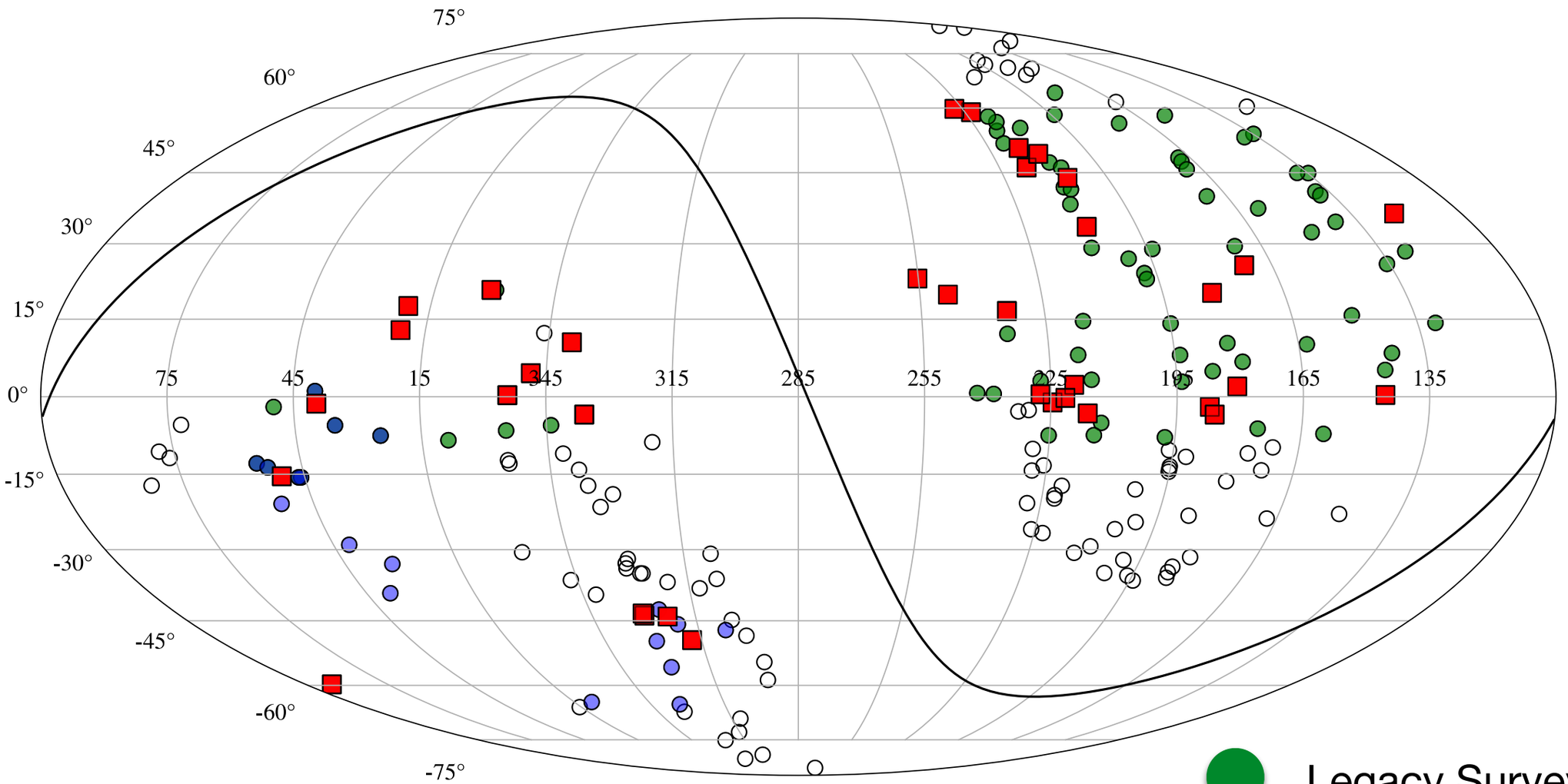
➡ **Stage 3:** Efficiently measure satellite LF for 100 MW analog to $M_r = -12.3$.

| **Geha et al. (2017)** | **Y.Y. Mao et al. (2021)** | **Final Survey (2022)** |
|---|---|---|
| 8 hosts | 36 hosts | 102 hosts |
| 27 satellites | 127 satellites | 363 satellites |
| 14 newly discovered | 69 newly discovered | ~150 newly discovered |
| (12,000 redshifts) | (25,000 redshifts) | (~50K redshifts) |

# THE SAGA SURVEY: DATA RELEASE II

**Y-Y. Mao et al. (2021)**

Identified 127 satellites around 36 host systems.




Legacy Survey coverage

DES coverage

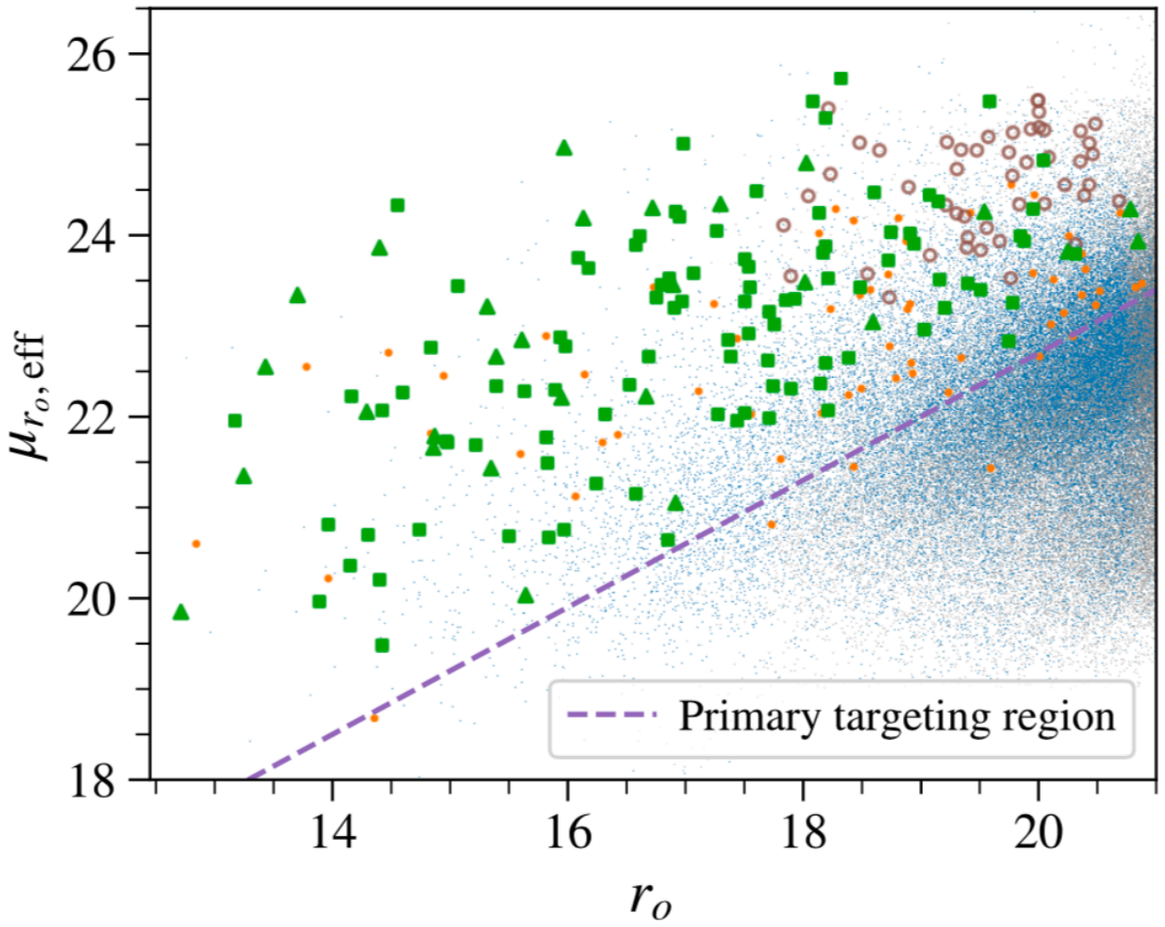
**36** complete hosts

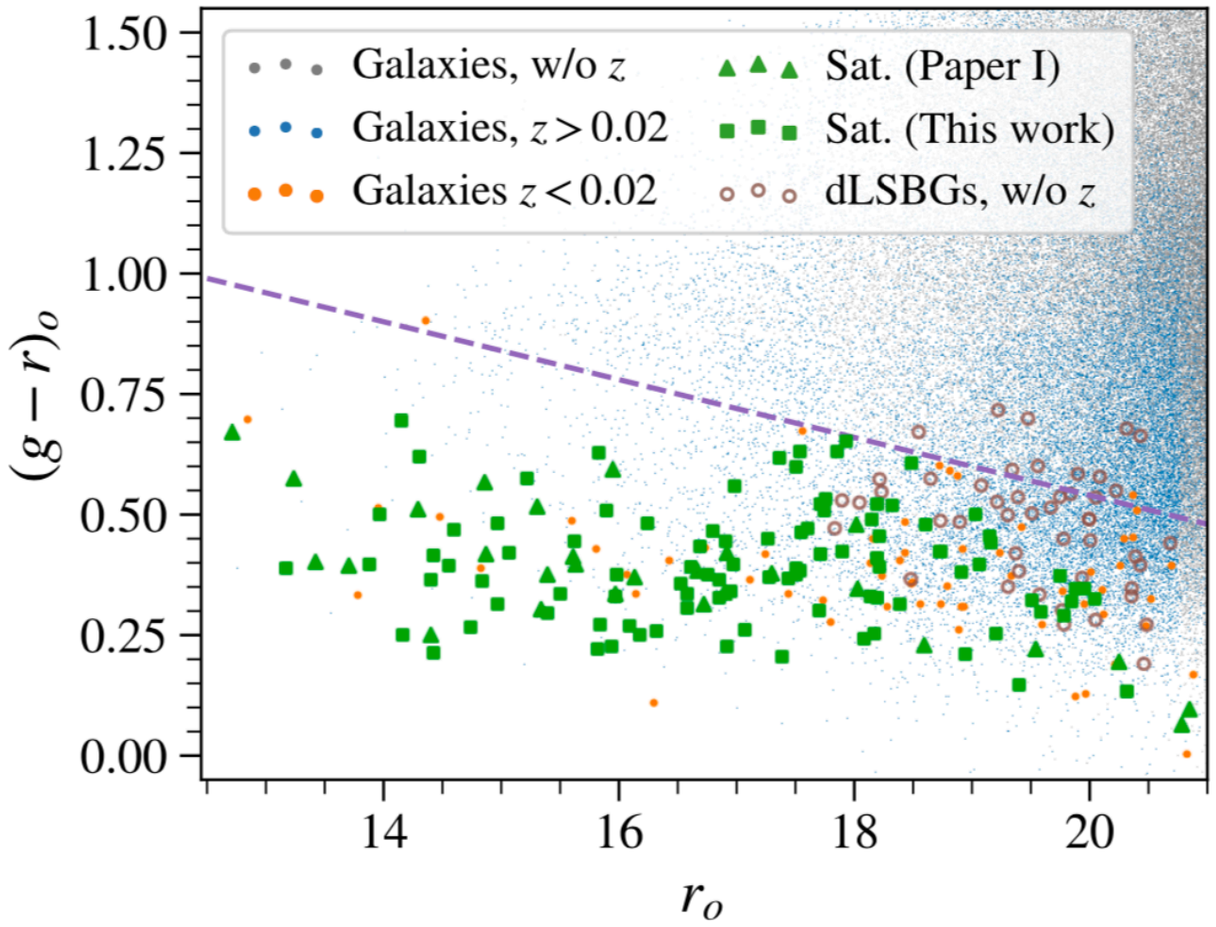
25 Mpc < Dist < 40 Mpc

203 hosts pass SAGA host criteria

134 hosts with deep public imaging (r ~ 24)

# THE SAGA SURVEY: FINDING SATELLITES




We search for satellites in two modes:

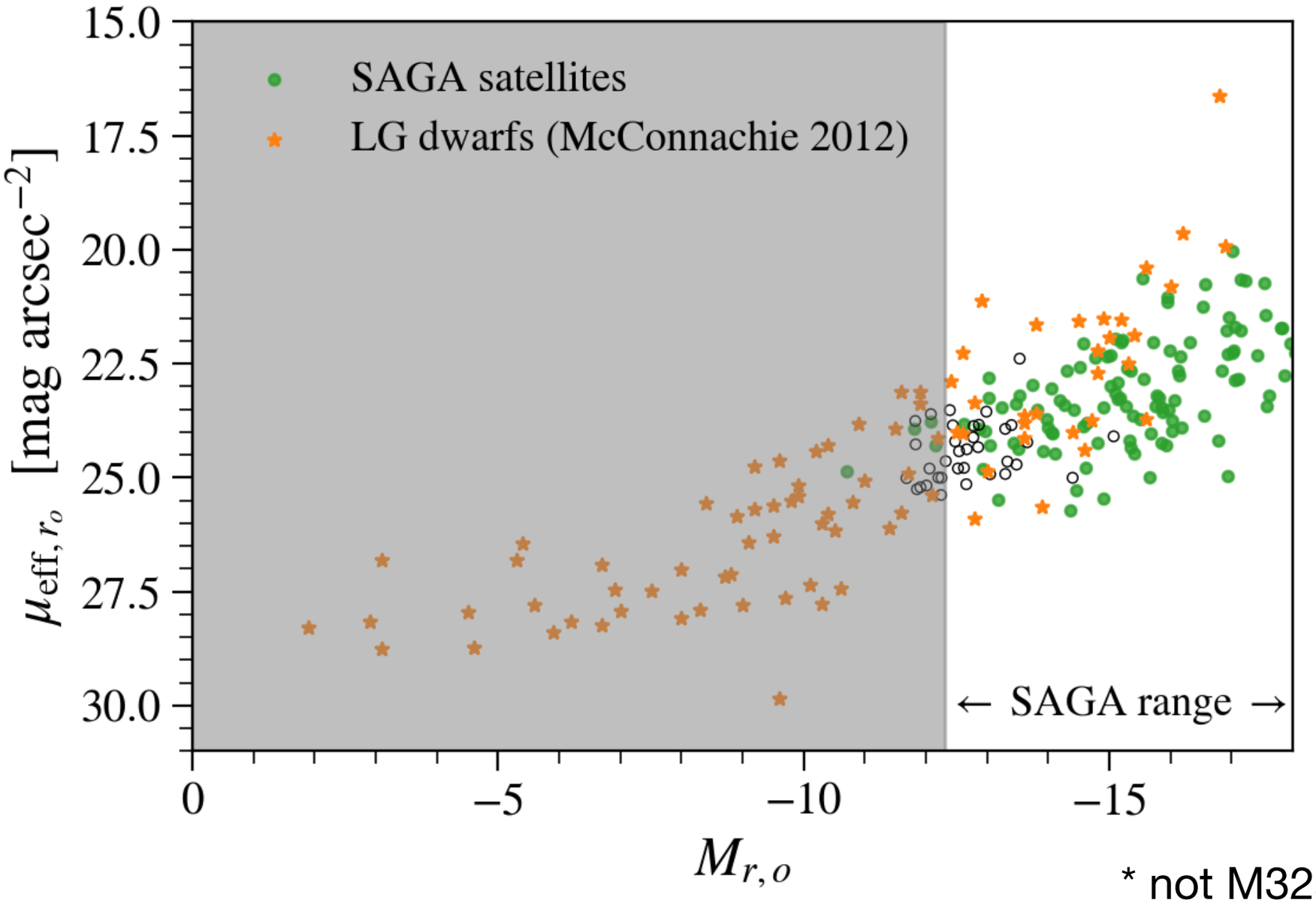
1. Complete spectroscopy in r-SB-gr region where most of our satellites reside.

2. Discovery mode using various selection methods outside of primary cuts.


NGC6181
NGC7716
NGC6278
NGC1309
NGC5297
PGC068743
UGC04906
NGC7166
NGC7541
NGC5602
NGC5750
NGC4158
NGC5448
NGC5962
NGC7029
NGC7079
NGC5792
NGC4454
NGC2962
NGC6909
UGC00903
PGC013646
NGC5690
NGC3976
NGC5604
NGC2543
ESO121-026
NGC1015
ESO288-025
NGC7328
NGC3689
NGC5347
NGC2967
NGC4348
NGC5869
NGC5633
Quenched
Below $M_{r,o}$ limit

# THE SAGA SURVEY: FINDING SATELLITES

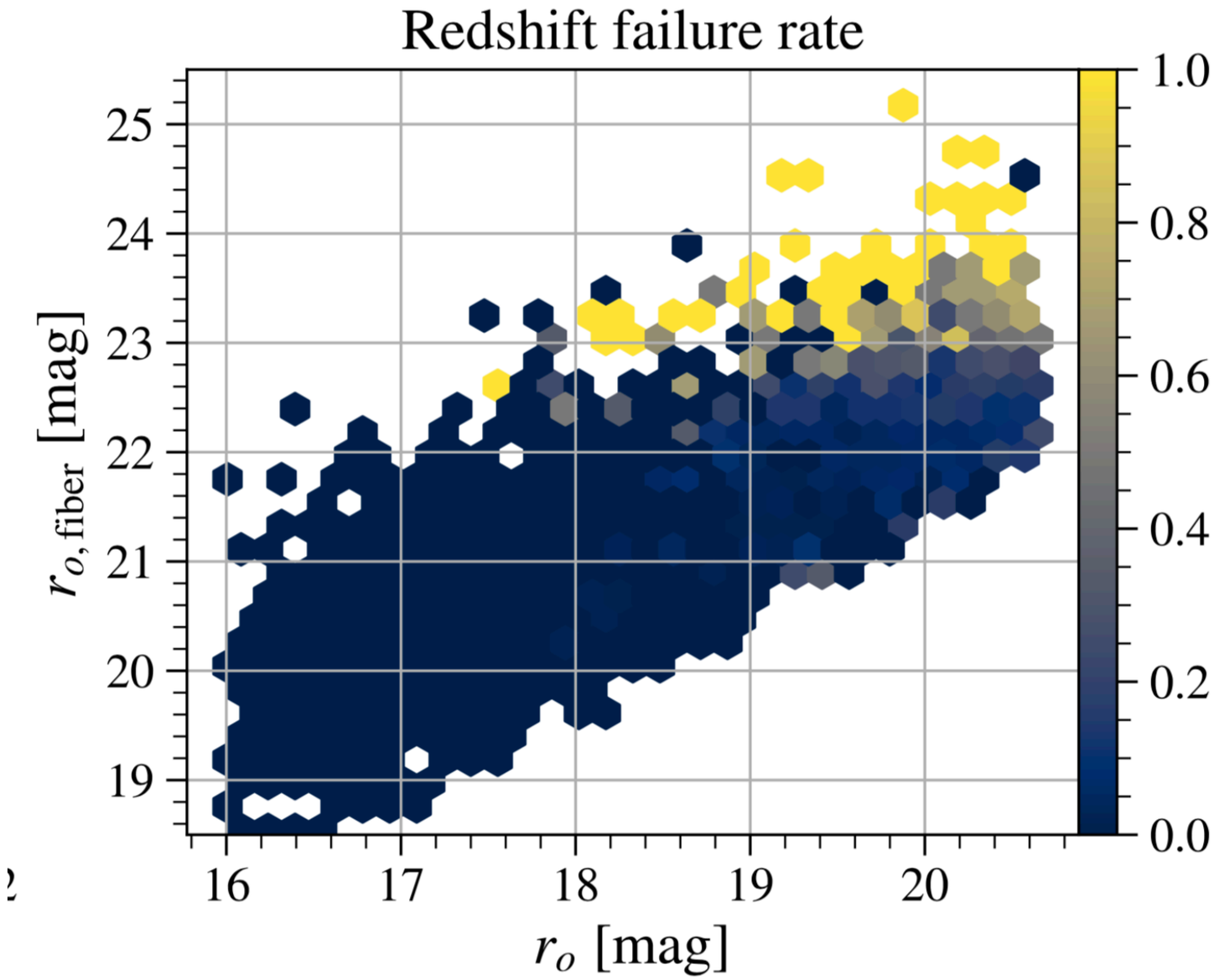
All* Milky Way and M31 satellites pass primary SAGA cuts.




* not M32s

Lowest surface brightness SAGA galaxies are similar to MW/M31.

# THE SAGA SURVEY: FINDING SATELLITES




Primary survey incompleteness is due to bias in measuring successful redshift.

We have quantified this incompleteness and correct for it.

# Satellite Galaxies as Useful Tools

1. **Cosmology**

***The Question:*** What is the nature of dark matter?

***The Tool:*** The ratio of low mass to high mass galaxies.

***The Observation:*** Count satellites around Milky Way-analogs, compare to both MW and to simulations.

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***The Question:*** What processes quench star formation in low mass galaxies?

***The Tool:*** The ratio of star forming to quenched galaxies.

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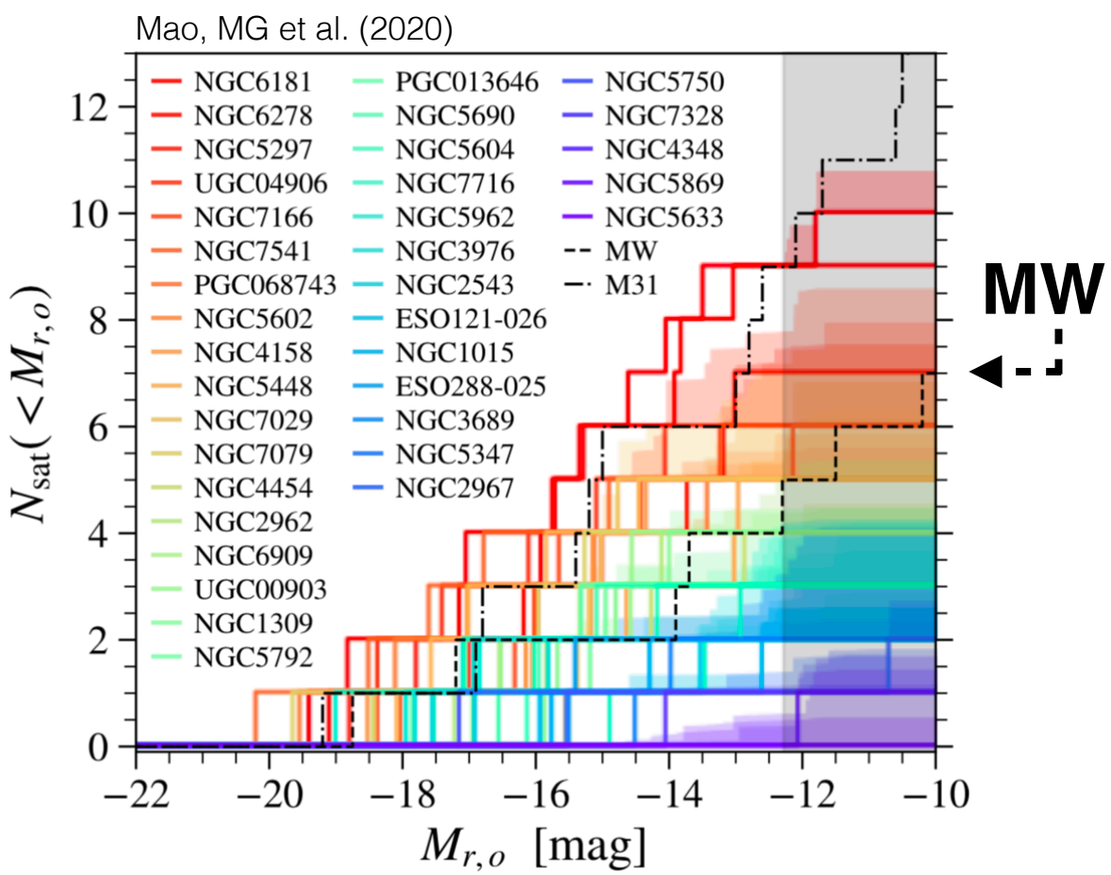
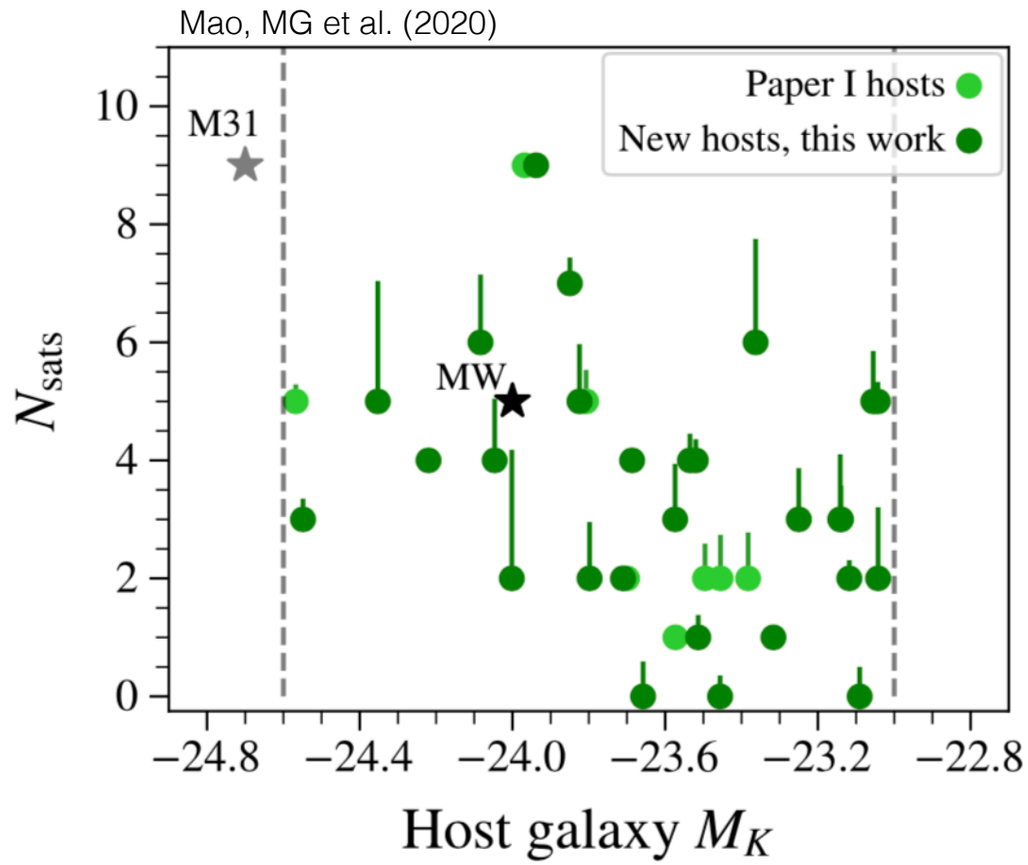
# How many satellites are around a Milky Way-like halo?

Paper II: 36 host



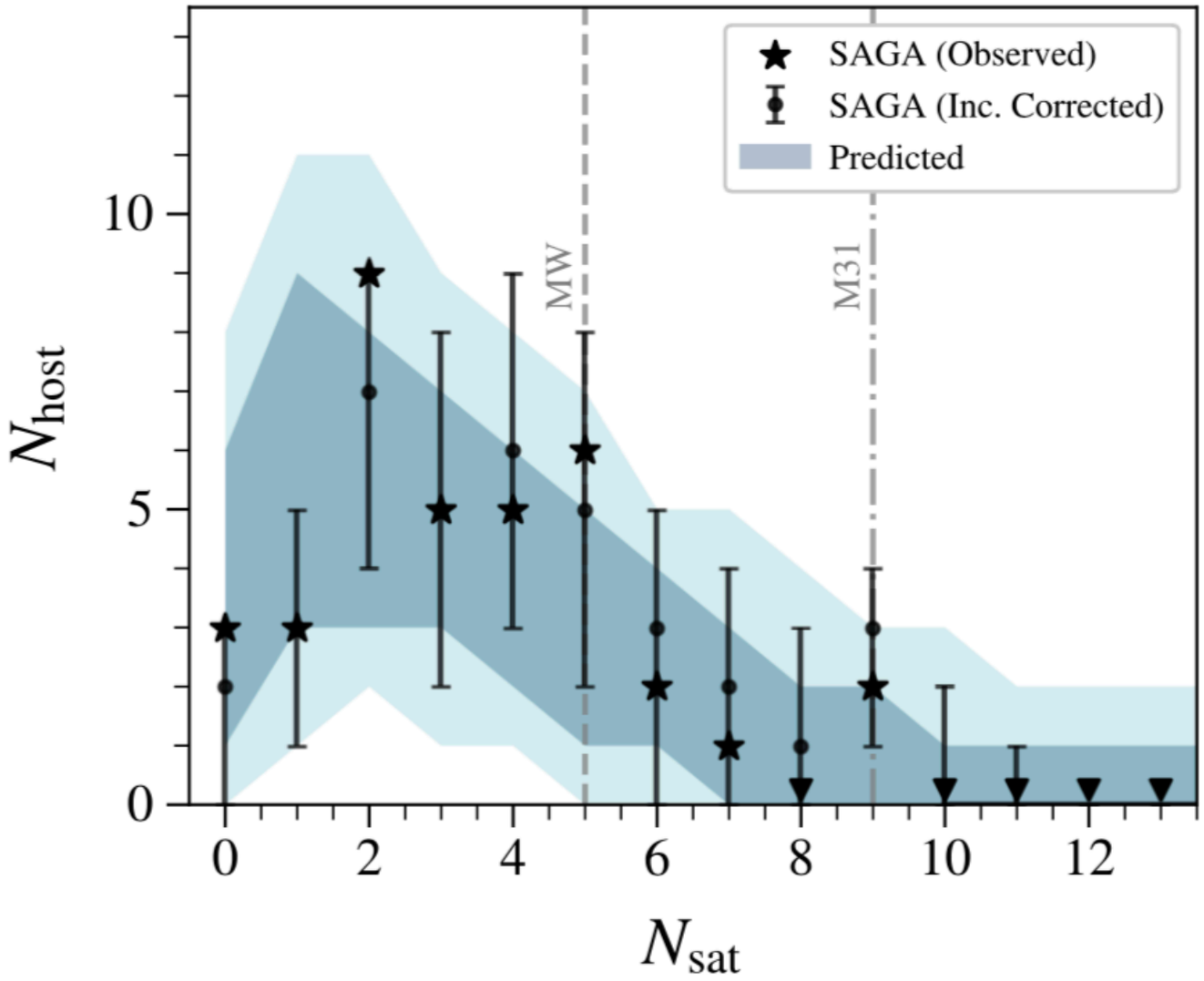

There are between 0 and 9 satellites per SAGA host.

Number modestly correlates with host luminosity.
Stronger correlation with brightest satellite magnitude.

MW LF consistent with being drawn from SAGA LF.

# How many satellites are around a Milky Way-like halo?

Model based on N-body sims (Y.Y. Mao+ 2015) and an empirical satellite model (Nadler+ 2019,2020).

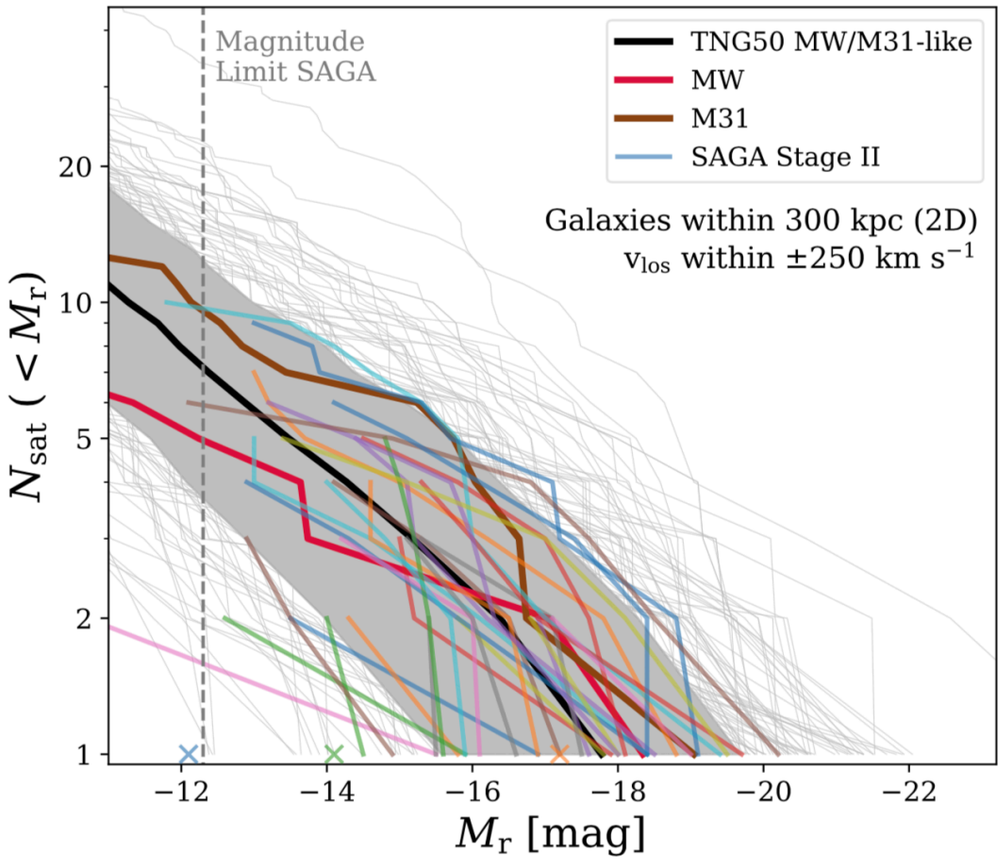



SAGA satellite systems are broadly in agreement with predictions from ΛCDM + SHAM model.

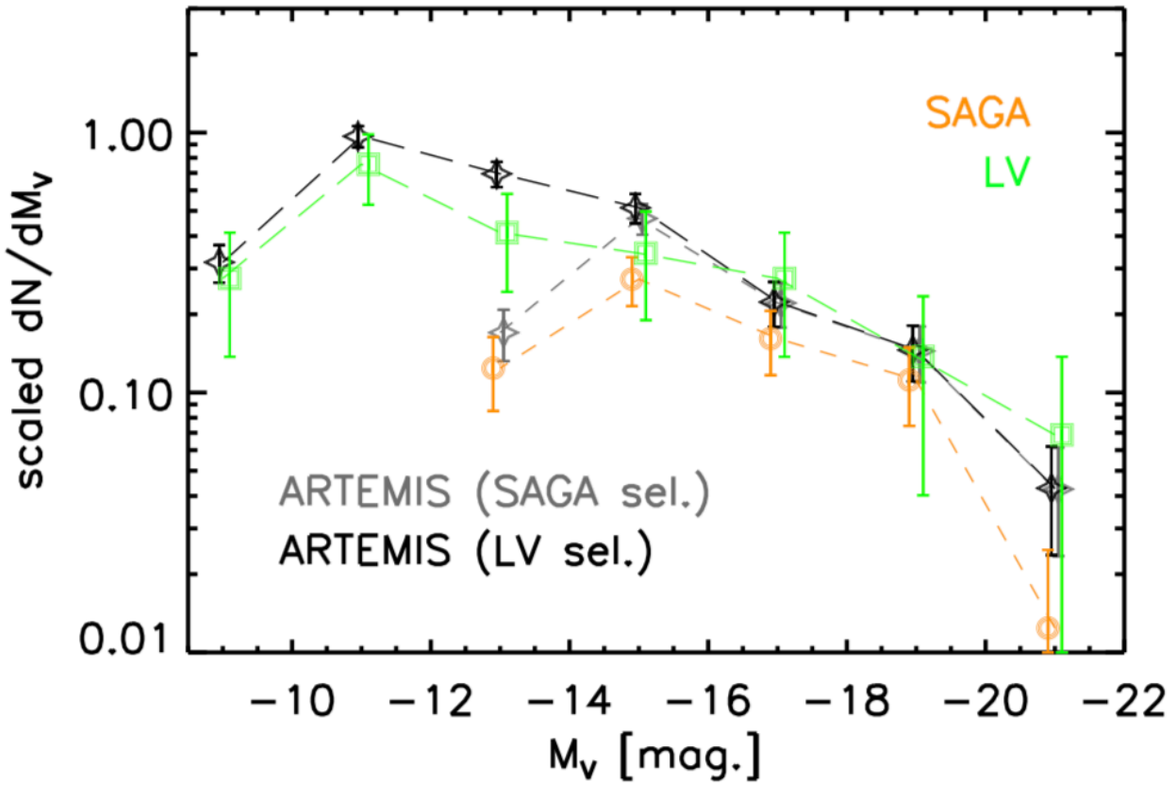
# How many satellites are around a Milky Way-like halo?

SAGA satellite systems are broadly in agreement with predictions from cosmological hydro-simulations.

**TNG50:** Engler et al (2021)



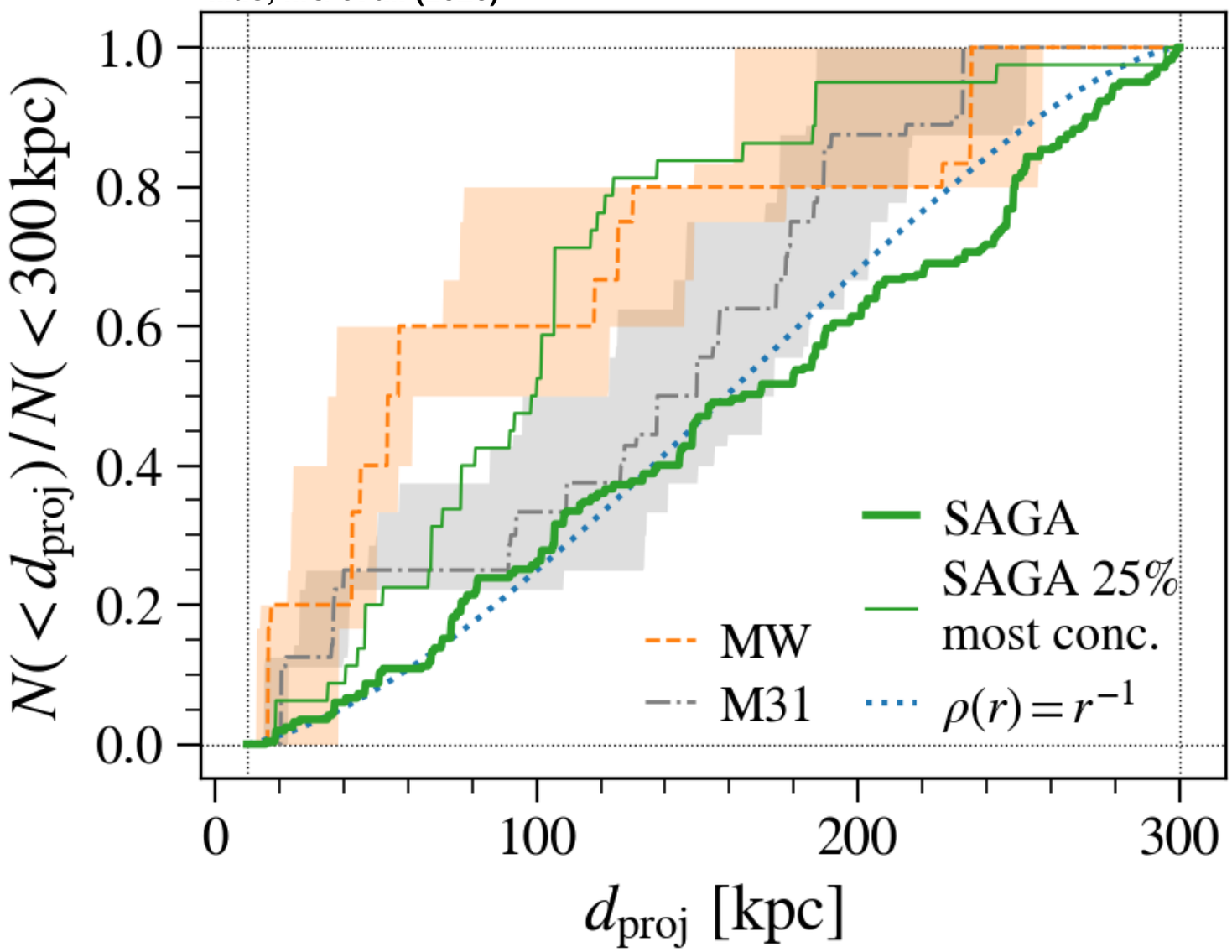

**ARTEMIS:** Font et al (2021)




The hydro-simulations capture the large halo-to-halo diversity in the shape and amplitudes of the SAGA luminosity functions.

# SAGA Results: Radial Distribution of Satellites

Mao, MG et al. (2020)



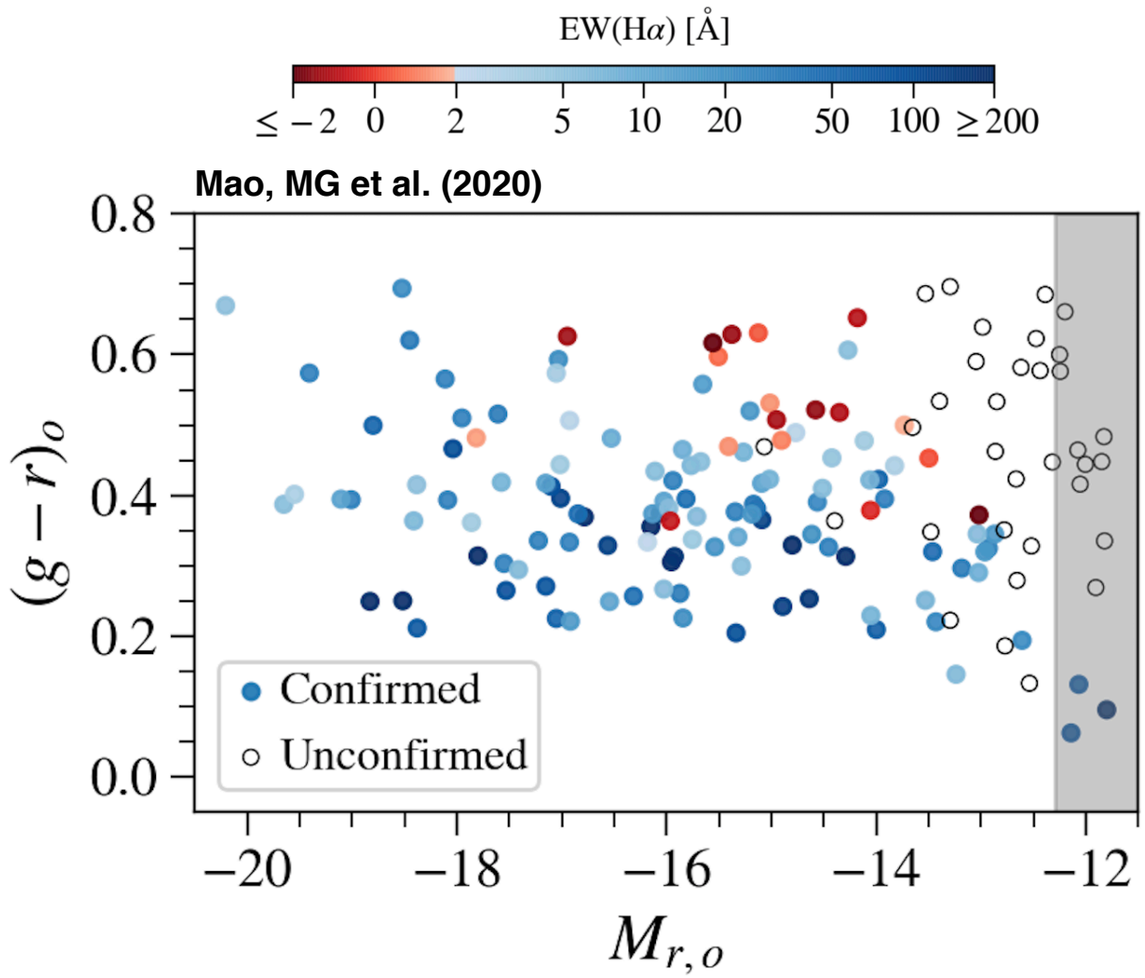

Radial distribution of SAGA satellites is less concentrated than MW, but difference can be accounted for by host-to-host scatter.

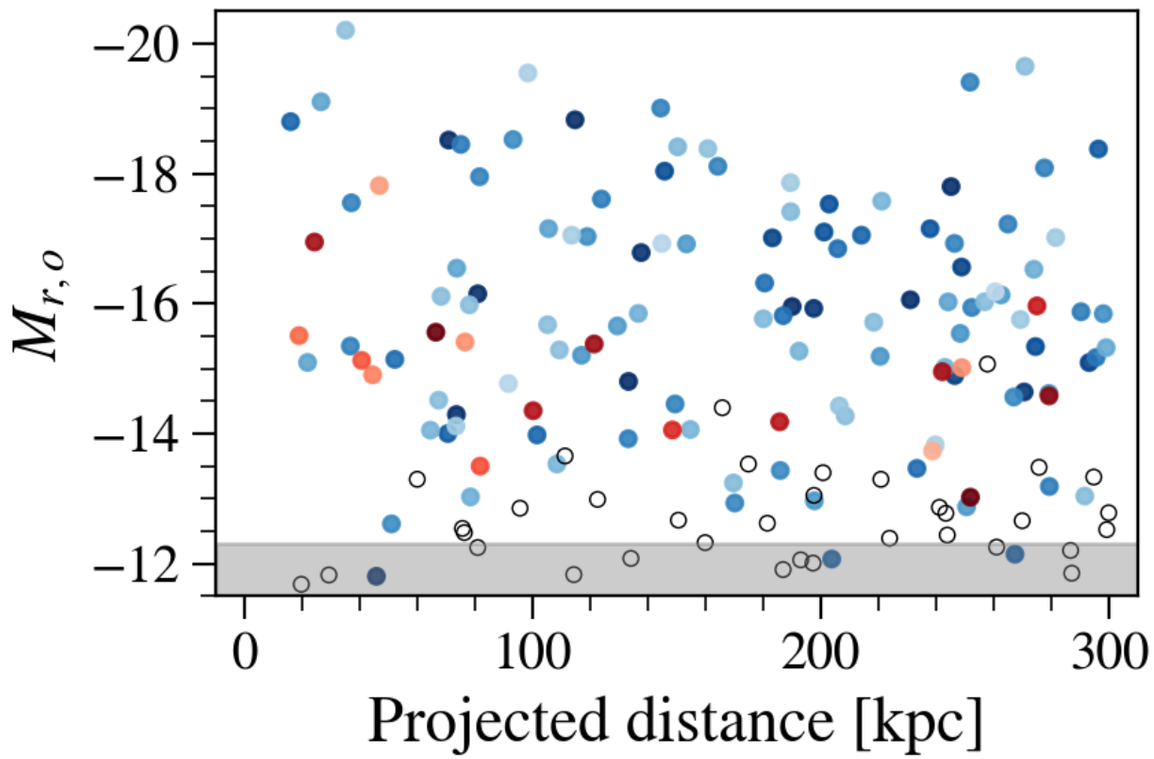
# THE SAGA SURVEY: QUENCHED FRACTION OF SATELLITES

SAGA defines a quenched satellites as having little to no H-alpha emission

$(H_\alpha\ EW < 2\ \text{Å})$

# THE SAGA SURVEY: QUENCHED FRACTION OF SATELLITES




Paper I: 1 of 26 satellites quenched

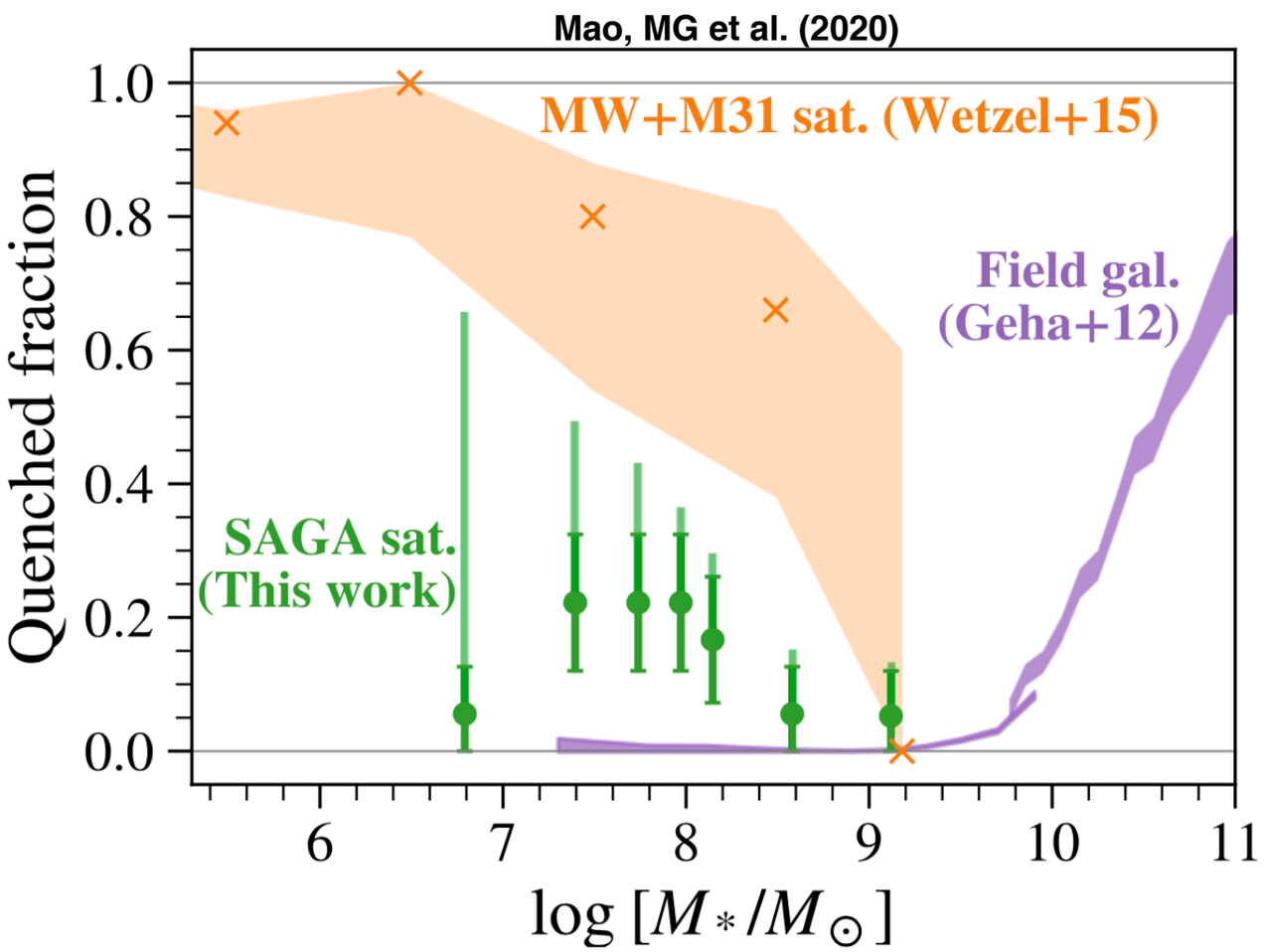
Paper II: 18 of 127 satellites quenched

Majority are fainter than $M_r$ ~ -16 or $10^8$ $M_{sun}$

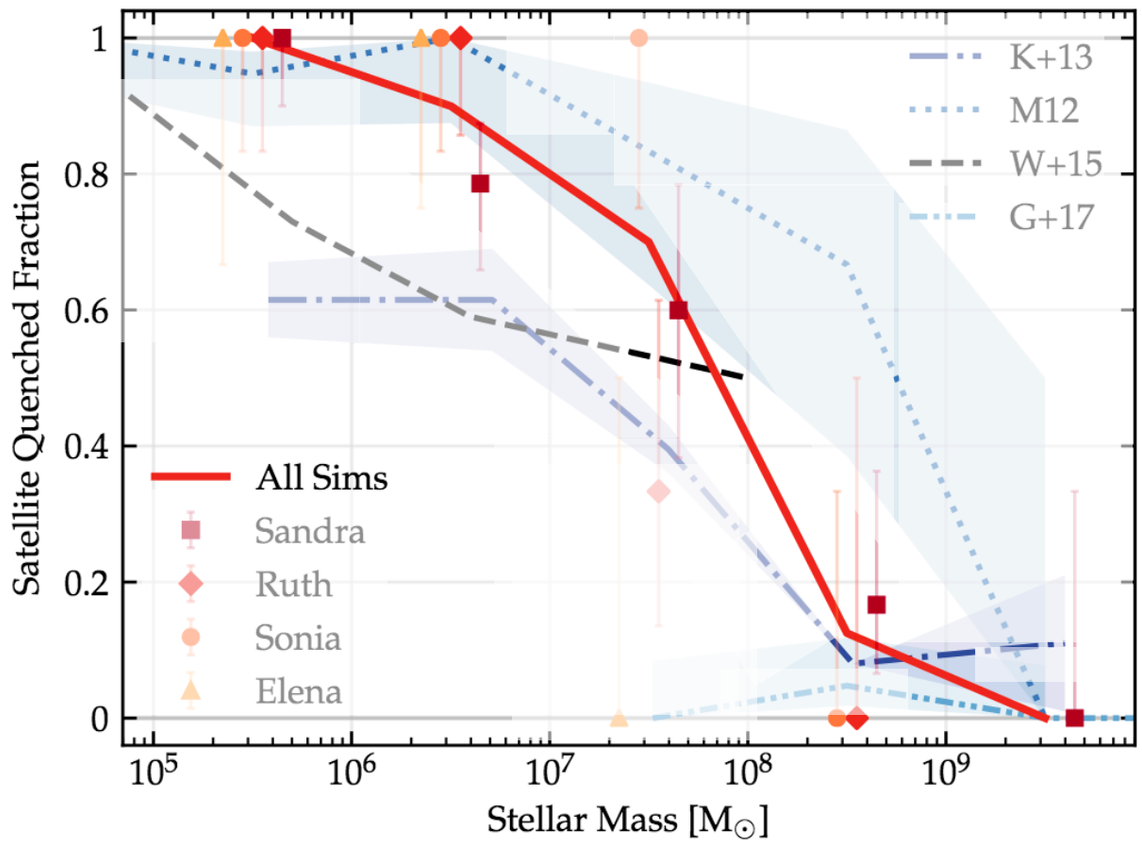
Quenched satellites are found preferentially at lower stellar mass and nearer host.

# THE SAGA SURVEY: QUENCHED FRACTION OF SATELLITES

Observed quenched fractions




Simulations: Akins+ 2021

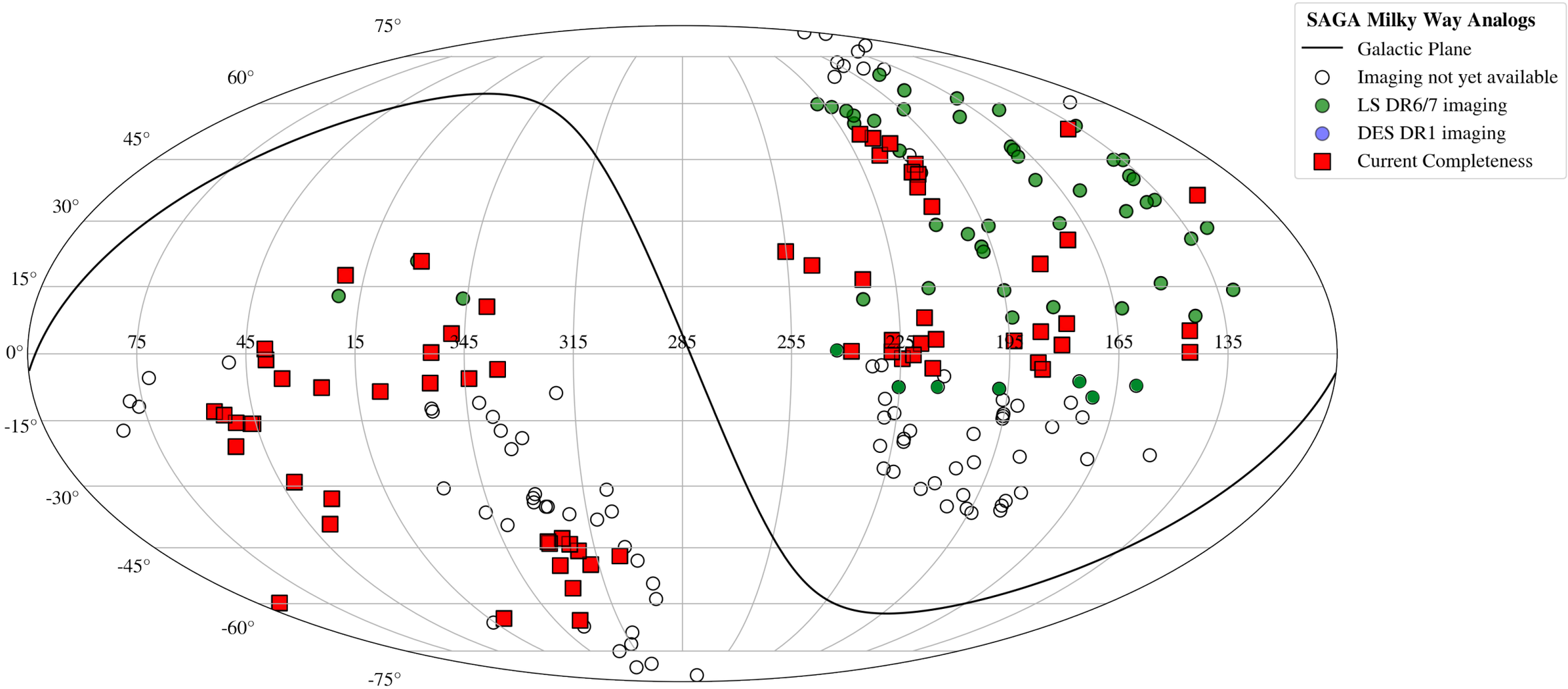



Justice League sims

Overall quenched fraction for SAGA systems is lower (more SF) than the Local Group.

# The SAGA Survey:  Towards 100 Milky Ways

## SAGA survey data taking was completed last month!




**Summer 2020:  36 completed hosts**

**Fall 2022:  102 completed hosts**

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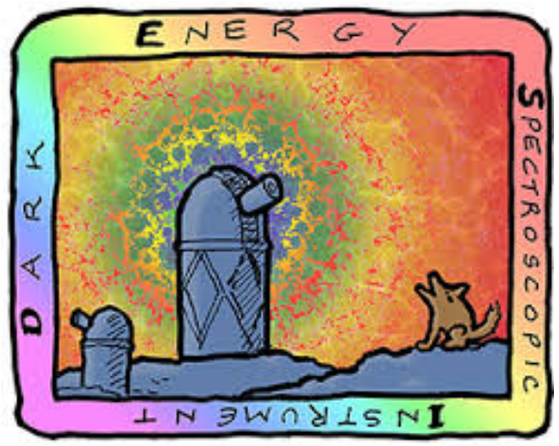
| (12,000 redshifts) | (25,000 redshifts) | (~50K redshifts) |

# BEYOND THE SAGA:  DESI SECONDARY FIBER PROGRAM

Can we expand this work beyond just Milky Way-like environments?


**PI Risa Wechsler**:  Secondary fiber program to target low-redshift galaxies with SAGA criteria and machine learning.

**John Wu** (STScI):  Developed a CNN trained on SAGA data to identify low redshift candidates based on the pixel image data.

**Elise Darragh-Ford** (Stanford):  Implementing SAGA cuts + CNN to select targets over full sky.

# Our Galaxy in Context:
# Satellite Galaxies Around the Milky Way Analogs

1. **Cosmology**

***The Question:*** What is the nature of dark matter?

***The satellites of Milky Way analogs are consistent with predictions from LCDM simulations.***

***The Milky Way is consistent with being drawn from the SAGA distribution.***

2. **Galaxy Formation**

***The Question:*** What processes quench star formation in low mass galaxies?

***Satellite quenched fractions are lower in SAGA systems than MW.***

***Simulated quenched fractions are too high (too quenched) at all satellite galaxy masses.***