Galactic stellar halos in the DESI Legacy Imaging Survey

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Outline

Introduction

- Galaxy and stellar halo

Data

- DESI-LS
- SGA-2020
- Dragonfly Survey

Method

- Masking & Photometry
- MCMC fitting

Result

- Galaxy density profile
- Define stellar halo

Discussion

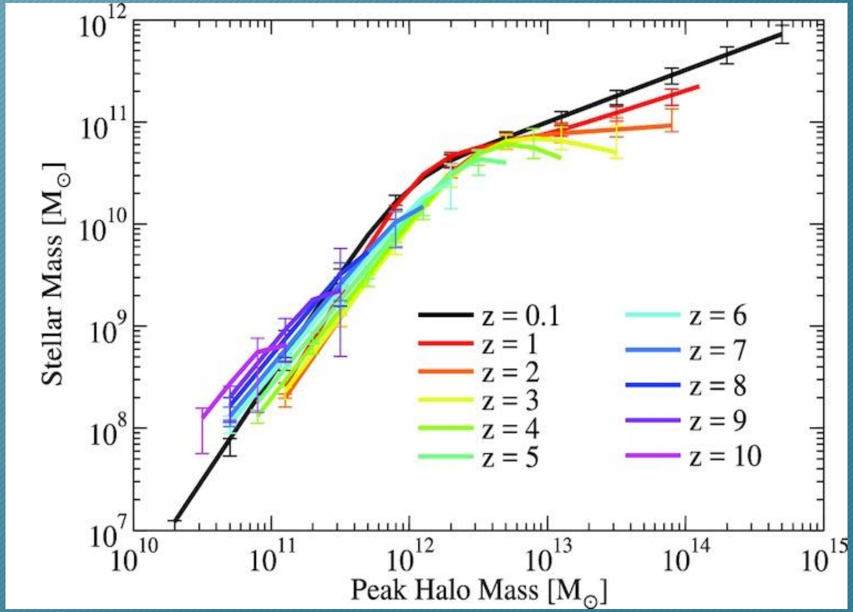
- Compare with other observation
- Compare with simulation
- How robust ?

Introduction

- Stellar halo
- Motivation
- Main goal

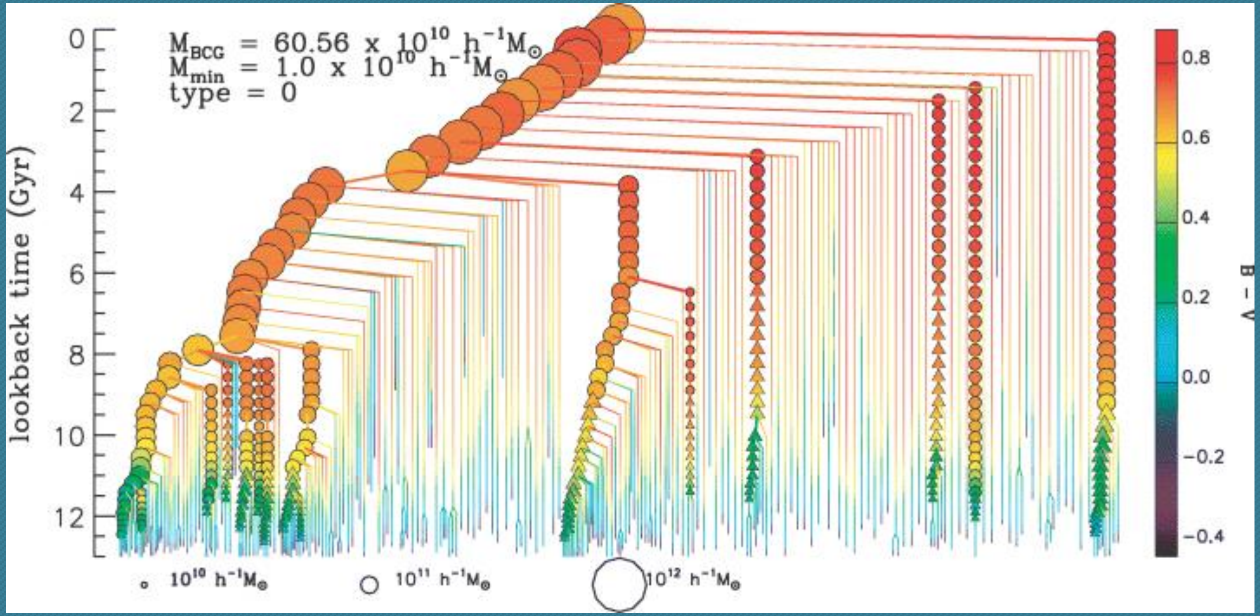
ΛCDM universe

- Hierarchical galaxy formation
- Merger tree
- Bottom-up formation model



Stellar Mass—Halo Mass Relation

Behroozi et al, 2019



BCG merger tree

Lucia et al, 2007

Stellar halo

Accreting event

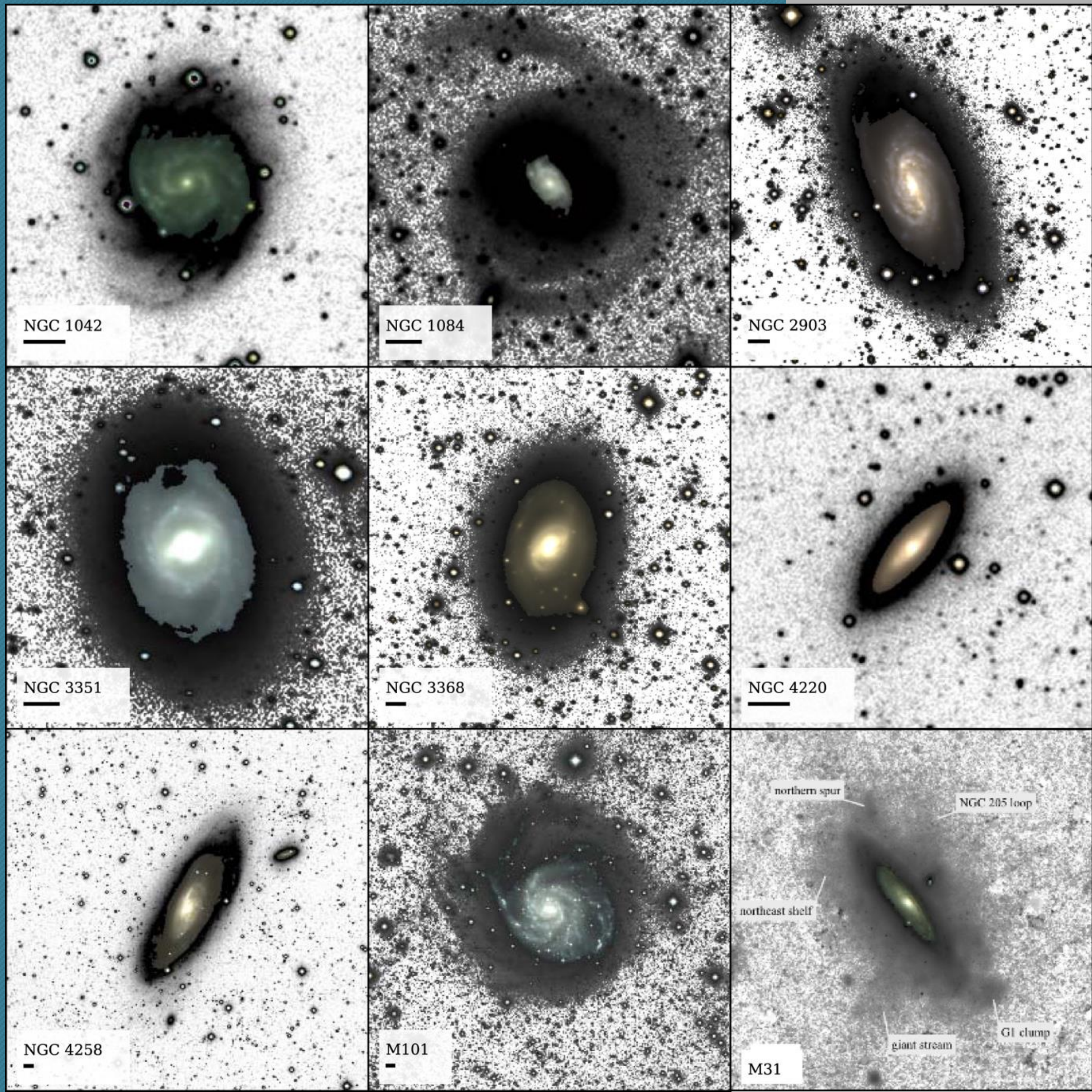
- Morphology
  - Diffuse, roughly spherical
- LSB structures
  - stellar shells
  - tidal streams
  - tidal tails

➢ **Reflecting a series of mergers and low-mass accretion events of galaxies**

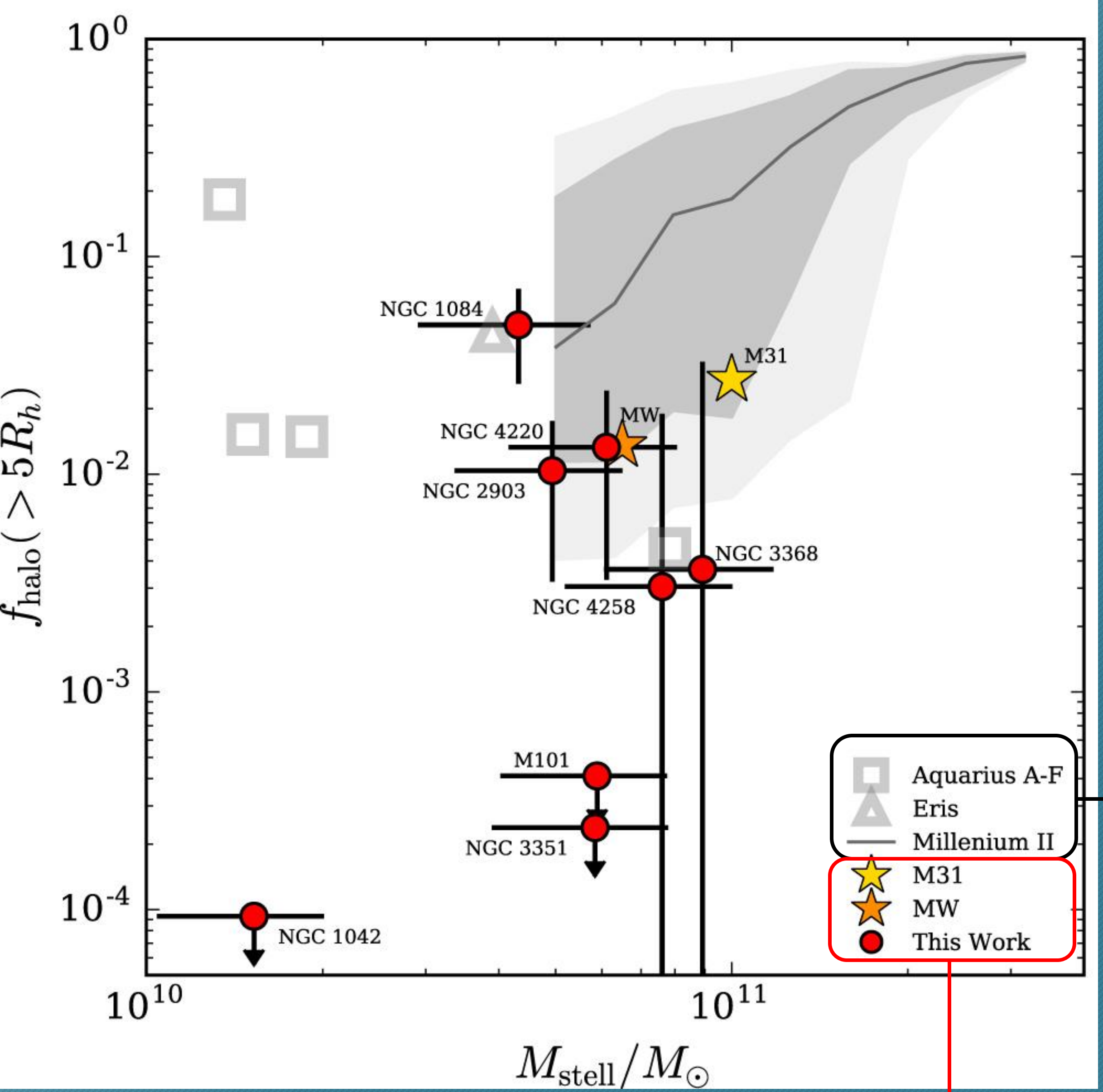
➢ **Exploring the properties of dark matter**

DRAGONFLY NEARBY GALAXIES SURVEY

Merritt et al. 2016



Motivation



Simulation

Observation

Stellar halo mass fractions
(Merritt et al. 2016)

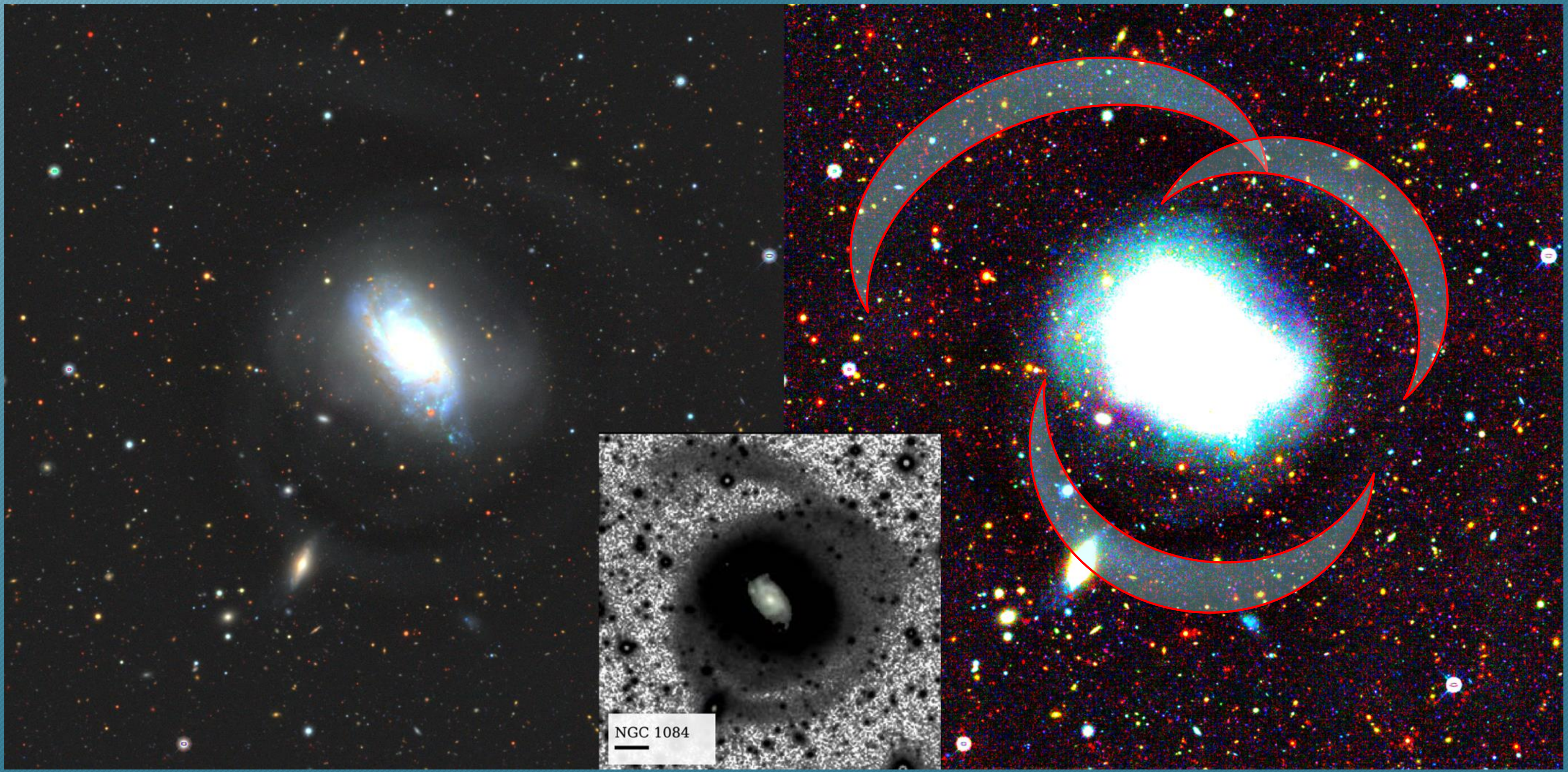
Statistical analysis of stellar halo characteristics is still lacking in observations.

Need to extend the observation data

Key question: Do the observation data agree with the simulation ?

NGC1084

By eye, we can see the tidal streams surrounding the host galaxy.



Main goal

- We are exploring a different approach:

  our goal is to develop uniform, automated measurements of bulk stellar halo properties that are easier to apply to large datasets and to compare with models.

- The DESI-LS (SGA-2020) has provided us with a substantial number of galaxy image samples(~400000).

Stellar halo is faint!

Deeper imaging

Large sky coverage

Data

- DESI-LS & SGA-2020
- Dragonfly Survey

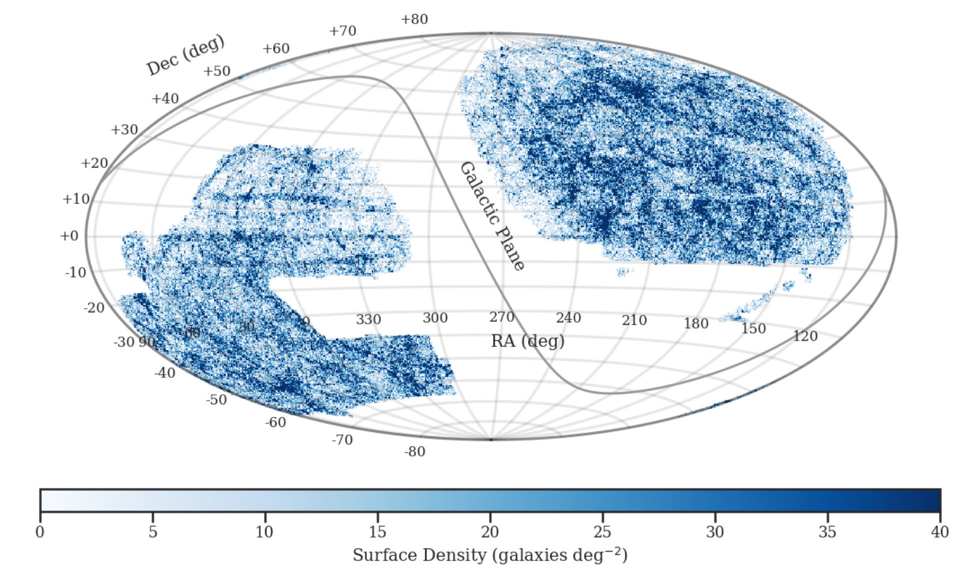
DESI-LS
Siena Galaxy Atlas 2020 (SGA2020)

DESI-LS *(Dark Energy Spectroscopic Instrument-Legacy Imaging Surveys)*

- Targets for DESI observation are selected using LS and Gaia
- North - MzLS (z)+ BASS (g,r) $\rightarrow$ Dec $\geq 32^\circ$
- South - DECaLS (g,r,z) $\rightarrow$ Dec $\leq 32^\circ$

SGA2020

- Galaxies with angular diameter D(25) > 0.2arcmin
- Multiwavelength atlas of 383,620 (g,r,z) nearby galaxies
- Large enough to be spatially resolved from our vantage point
- ~20000 deg^2



SGA-2020

Dragonfly survey

(Merritt et al. 2016)

Dragonfly Telephoto Array

48 telephoto lenses, equivalent to 1m aperture

Design for detect LSB features

- PSF is very well-controlled with low power distributed in far wings
- two-stage sky background model

27.2 $\mathrm{mag}/arcsec^{-2}$(r-band) in 10″°×10″ boxes with 3σ

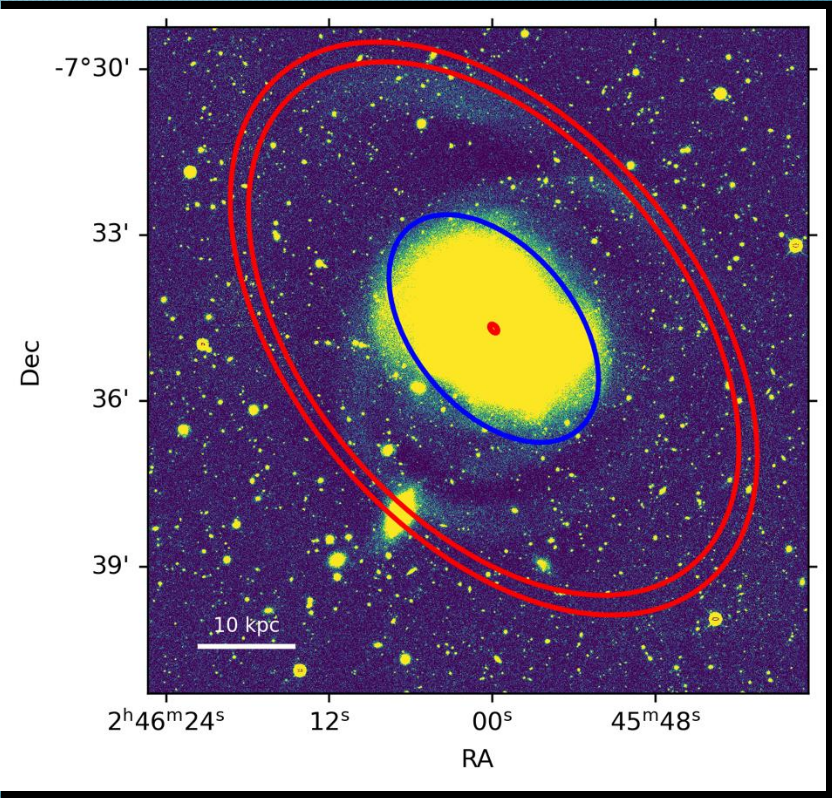
➡ Provides some powerful and robust analyzes of stellar halos

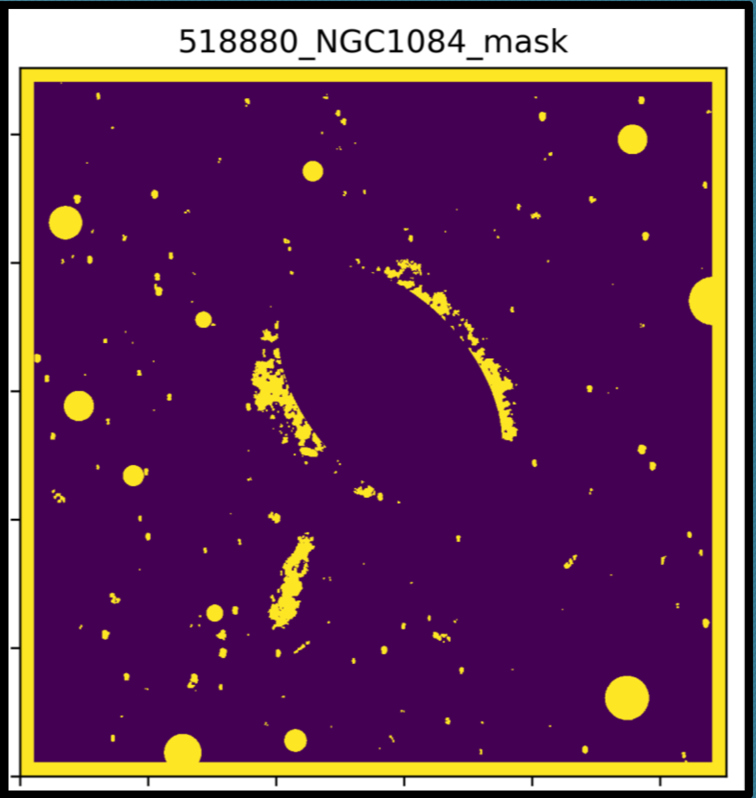
Masking and Photometry

- Surface brightness density profile
- Mass-to-light ratio

Photometry method

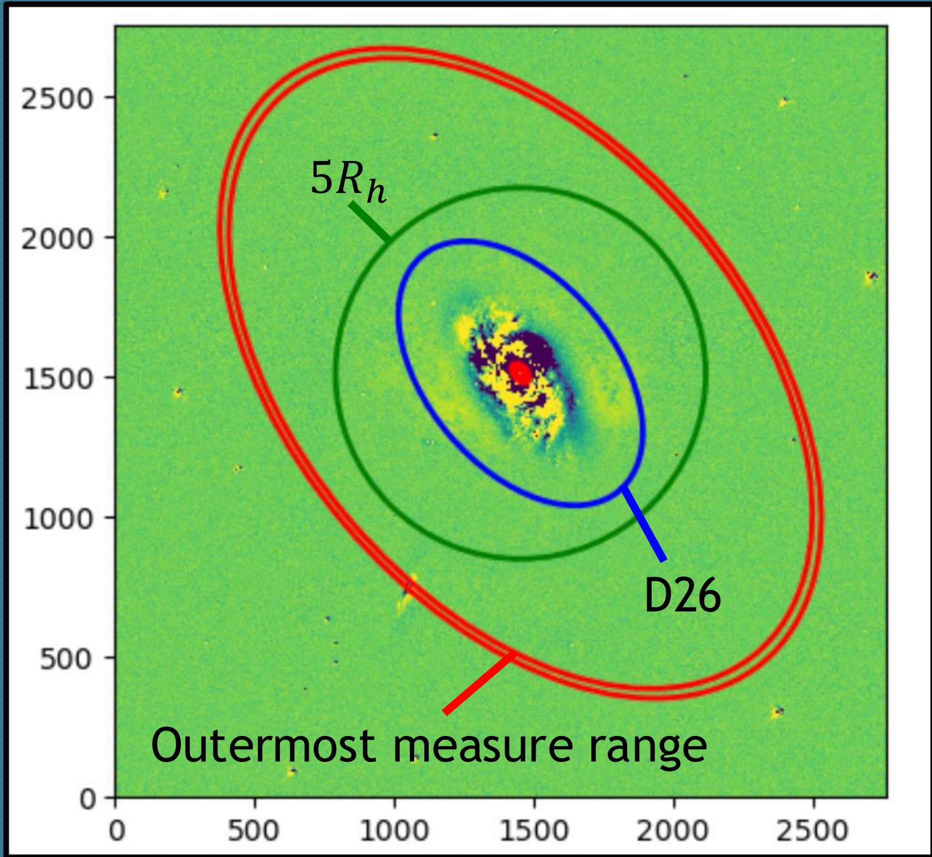
Masking is important





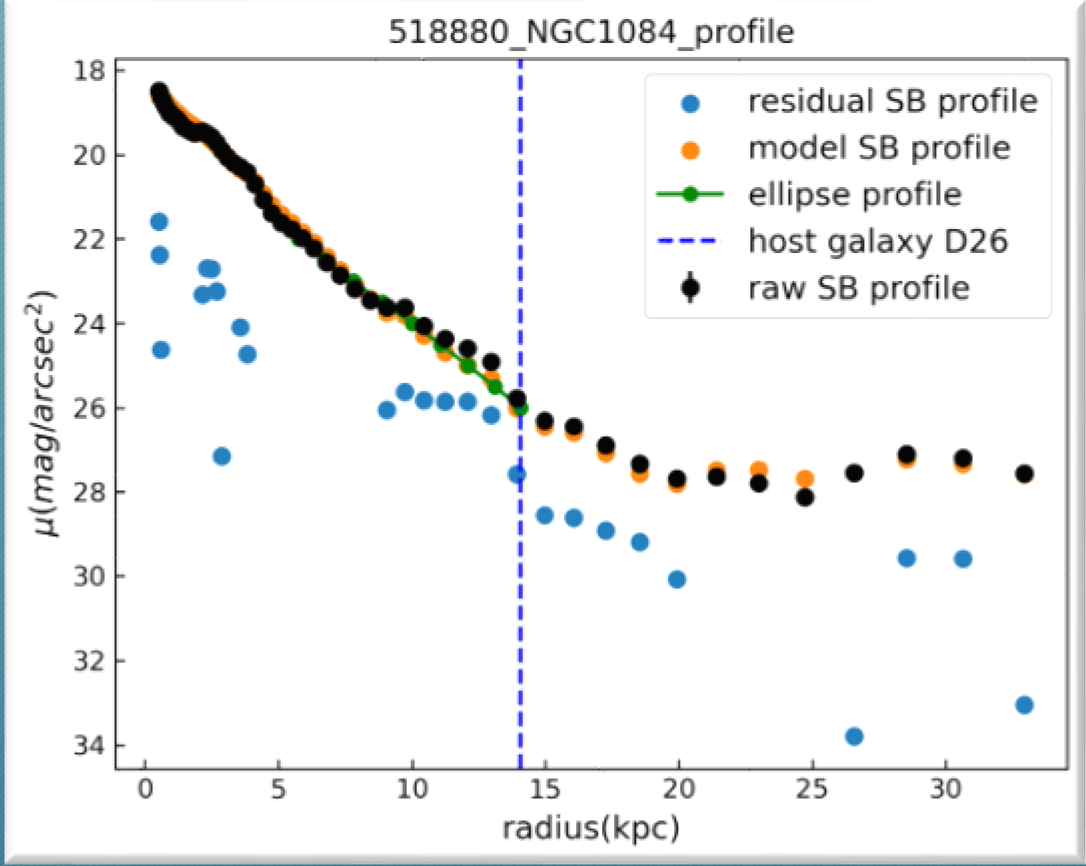
g-band raw image

Masking image

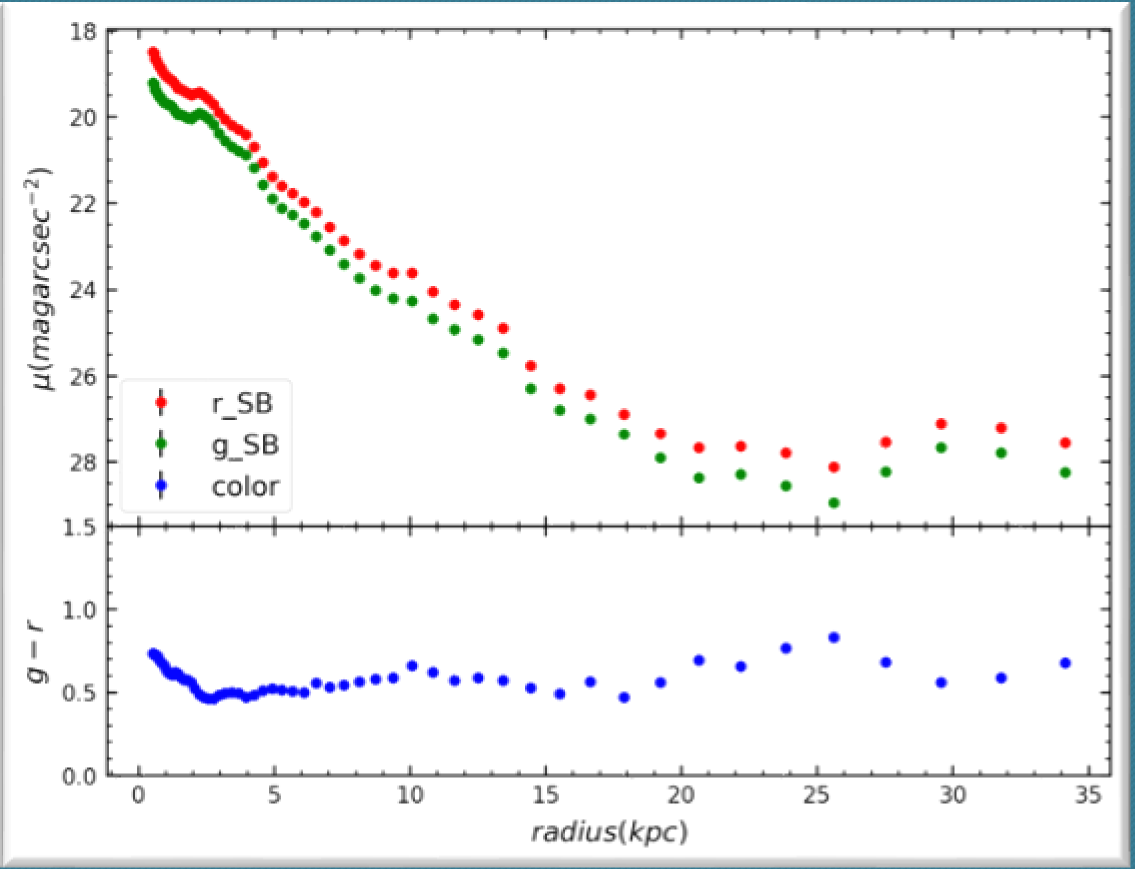


Using color and SB, we can convert magnitude to mass.

Surface Brightness Profile



Color Profile



Surface Brightness: $\mu = m + 2.5 \times \log_{10} \frac{A_{pix}}{arcsec^2}$

Mass-to-light ratio

Dragonfly Survey convert the residual sky background brightness into a stellar mass surface density.

$$\log_{10}(\rho) = -0.4(\mu_g - 29.23) + 1.49(g - r) + 4.58$$ (SDSS DR7 & Chabrier IMF)

Background Under-estimate

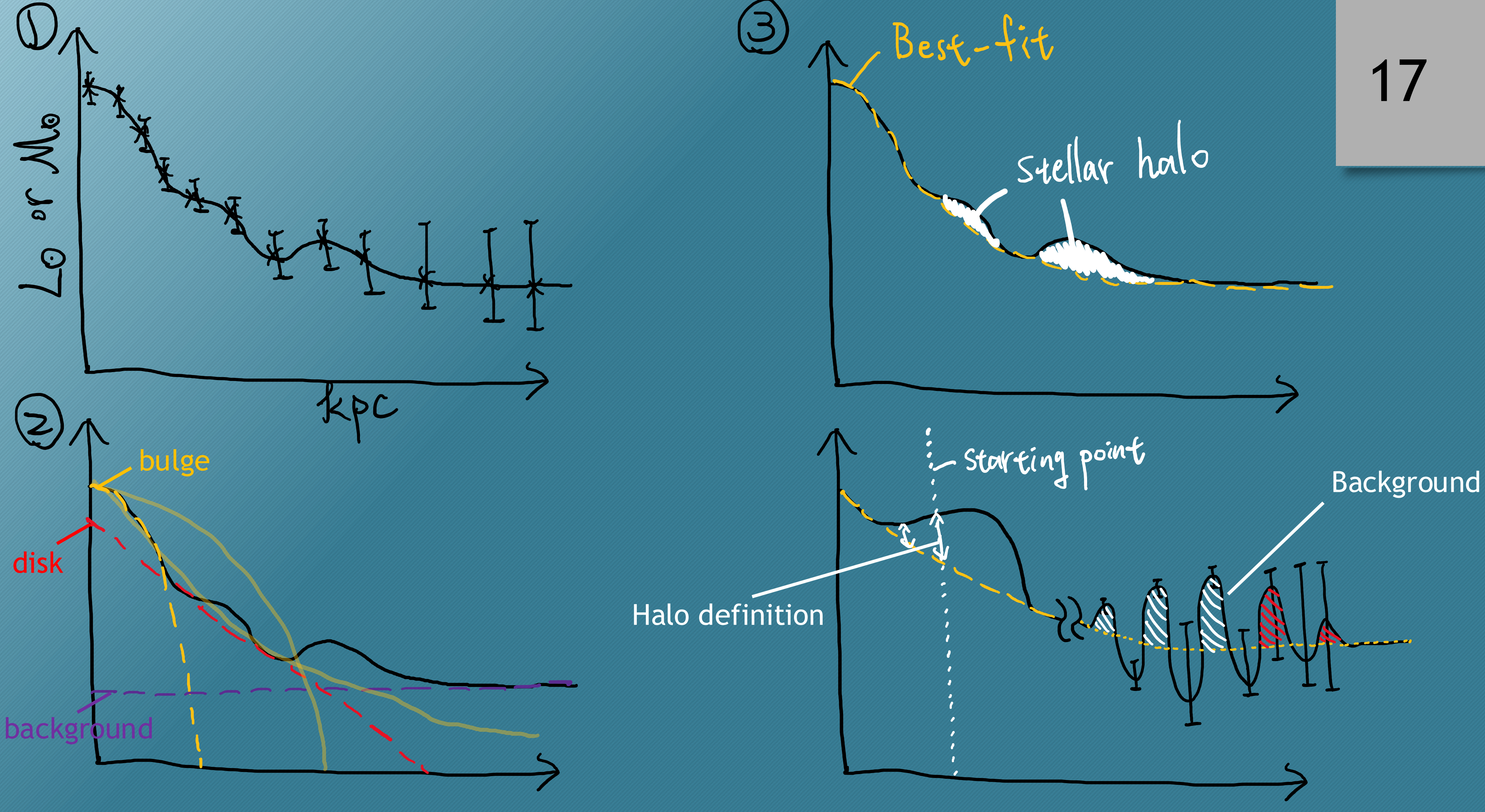
In LS, we need another method to define the background.

$$-2.5 \times \log_{10}\Sigma\left(\frac{L_\odot}{kpc^2}\right) = \mu - M_{abs,\odot} - 21.572 + 6$$ (surface luminosity conversion)

Mass-to-light ratio only meaningful for a real stellar population, not for the background!

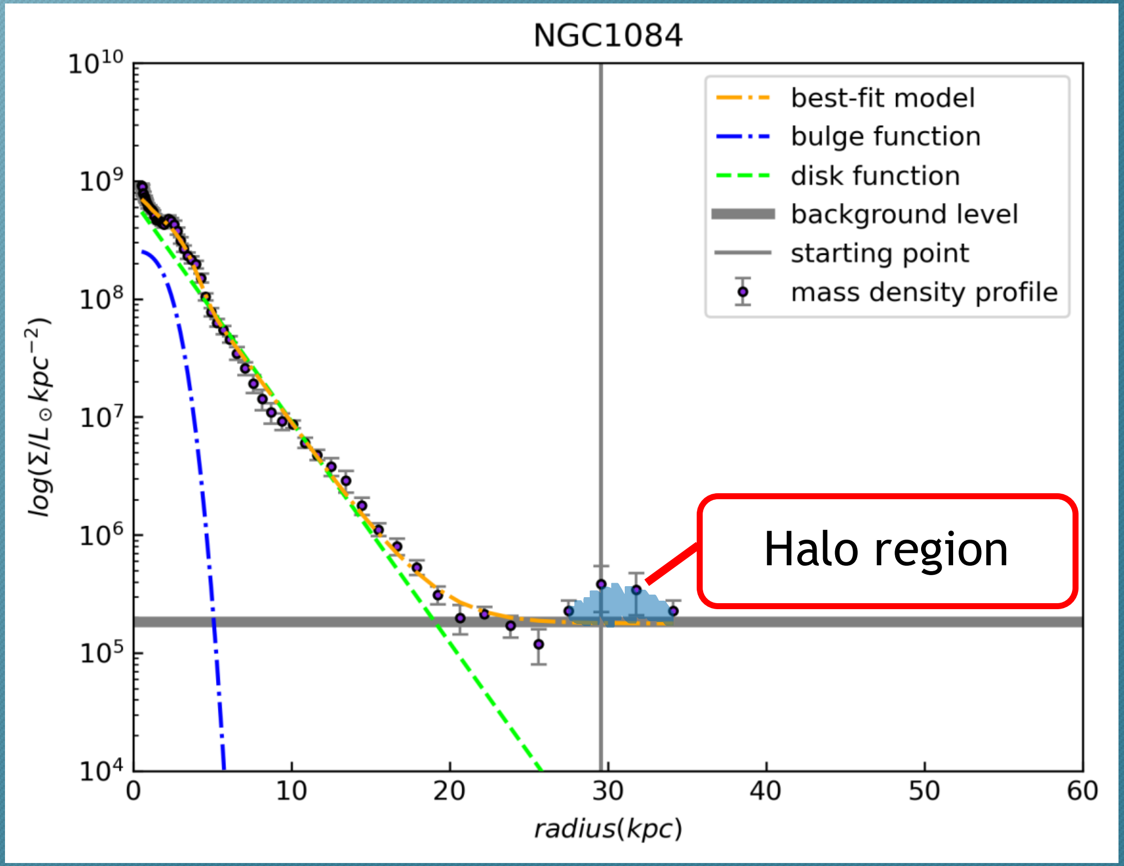
Fitting process- MCMC

- Markov chain Monte Carlo (MCMC)
- Stellar mass surface density profile



1
L⊙ or M⊙
kpc
2
bulge
disk
background
3
Best-fit
Stellar halo
starting point
Background
Halo definition

Stellar mass surface density profile



Surface density profile

Stellar mass density profiles and Best-fit models of NGC1084

Black dots → SGA data

Best-fits → (MCMC) Bulge + disk model

Subtract → Stellar halo mass!

Steps

GOAL

1. Develop a method that differs from the Dragonfly Survey

2. Suitable for large data statistical analysis

Markov Chain Monte Carlo (MCMC) to fit galaxy profile
(Bulge + Disk + Background)
(6 parameters)

Adjust proper prior and likelihood function

Define background error (systematic error)

Sample posterior density functions (PDFs)

1. Median of posterior as best-fit model
2. Define stellar halo as stellar mass exceeding disk + bulge model

Starting point (R_s):
Profile > 1.5 best-fit

1. Remove points with too low S/N
2. Best-fit located within profile error

Integrate total stellar halo mass (lower limit)

Sersic function:

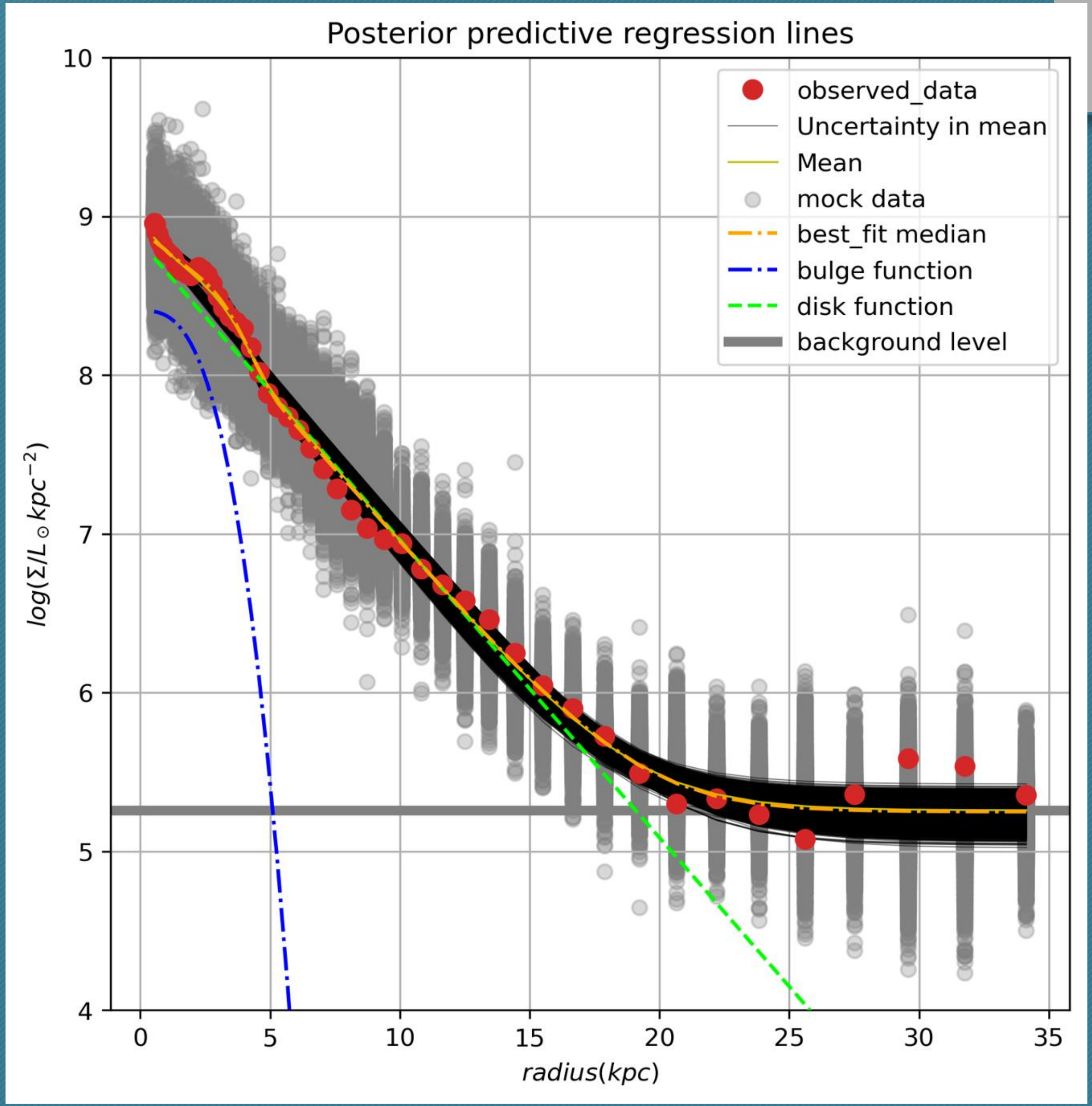
$$I(R) = A \times e\{-b_n \times [(\frac{R}{R_{eff}})^{\frac{1}{n}} - 1]\}$$

$(b_n \approx 1.9992n - 0.3271, 0.5 < n < 10)$

R_{disk}(kpc)	$\Sigma_{0,disk}(L_{\odot}kpc^{-2})$
R_{disk}(kpc)	$\Sigma_{0,disk}(M_{\odot}kpc^{-2})$

R_{bulge}(kpc)	$\Sigma_{0,bulge}(L_{\odot}kpc^{-2})$	n
R_{bulge}(kpc)	$\Sigma_{0,bulge}(M_{\odot}kpc^{-2})$	n

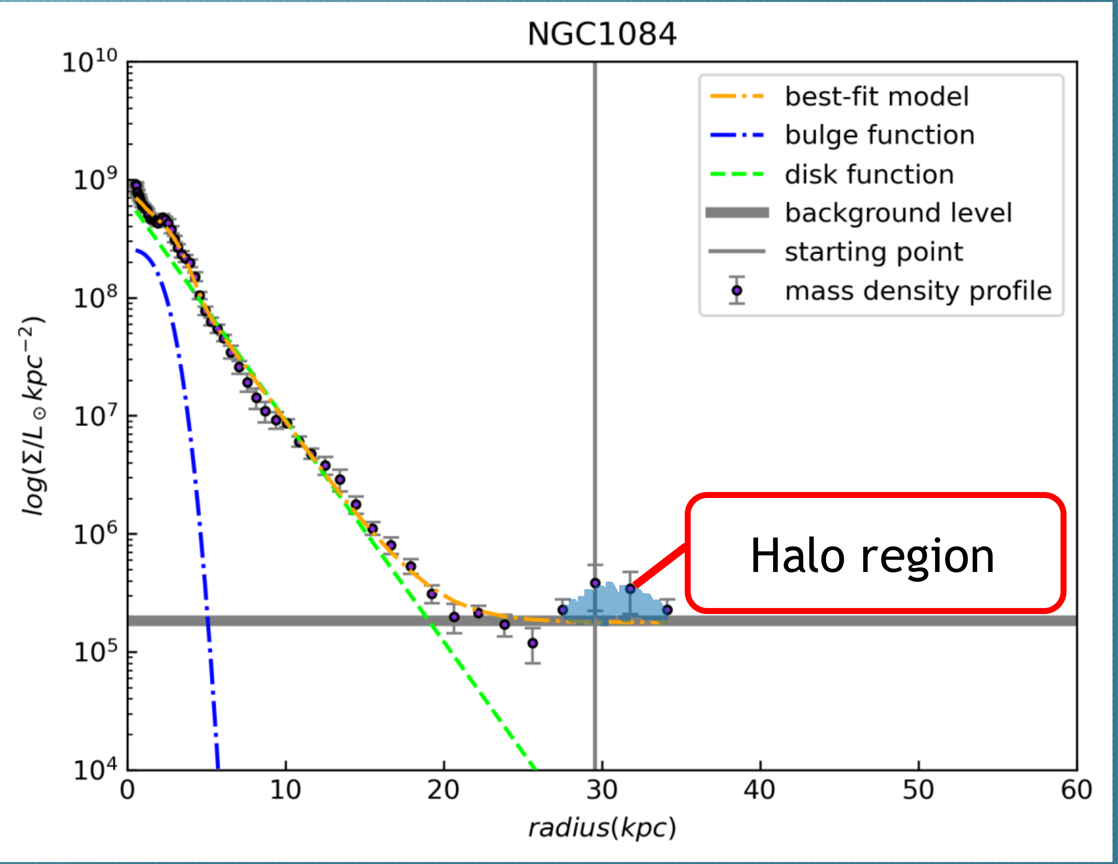
Posterior distribution



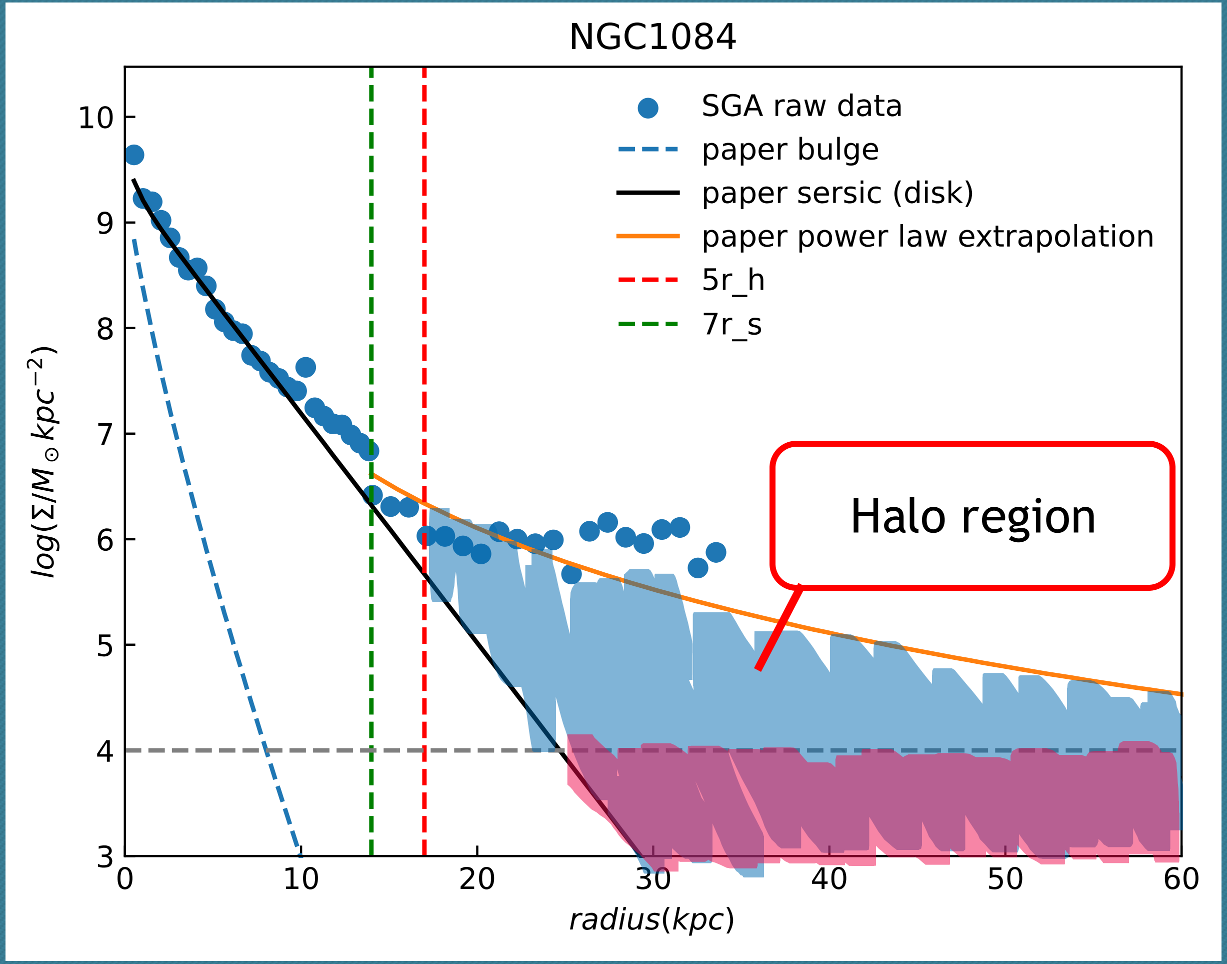
Result- stellar halo

Halo fraction estimate

Stellar halos contribute significantly only to the outermost regions of the galaxy.



(our method)



(Dragonfly method)

Our work | | Dragonfly

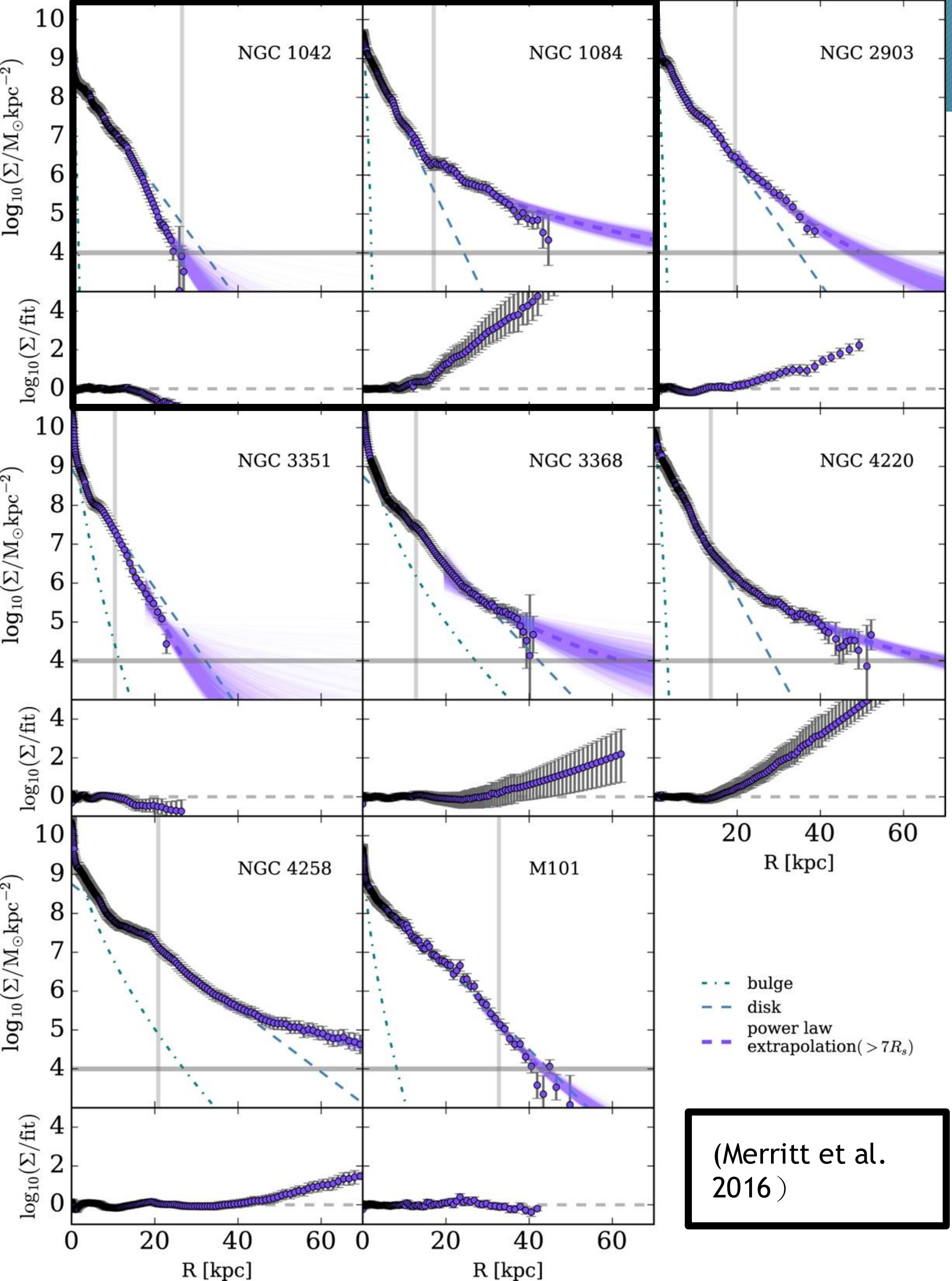
$R_s(kpc)$	Galaxy	$5R_{\mathrm{h}}(kpc)$
15.49	NGC 1042	26.6
29.56	NGC 1084	17.0
42.08	NGC 2903	19.5
12.21	NGC 3351	10.4
16.89	NGC 3368	12.8
9.27	NGC 4220	13.7
16.37	NGC 4258	20.8

Dragonfly method is already good enough, all our effort is to make it work on a larger samples.

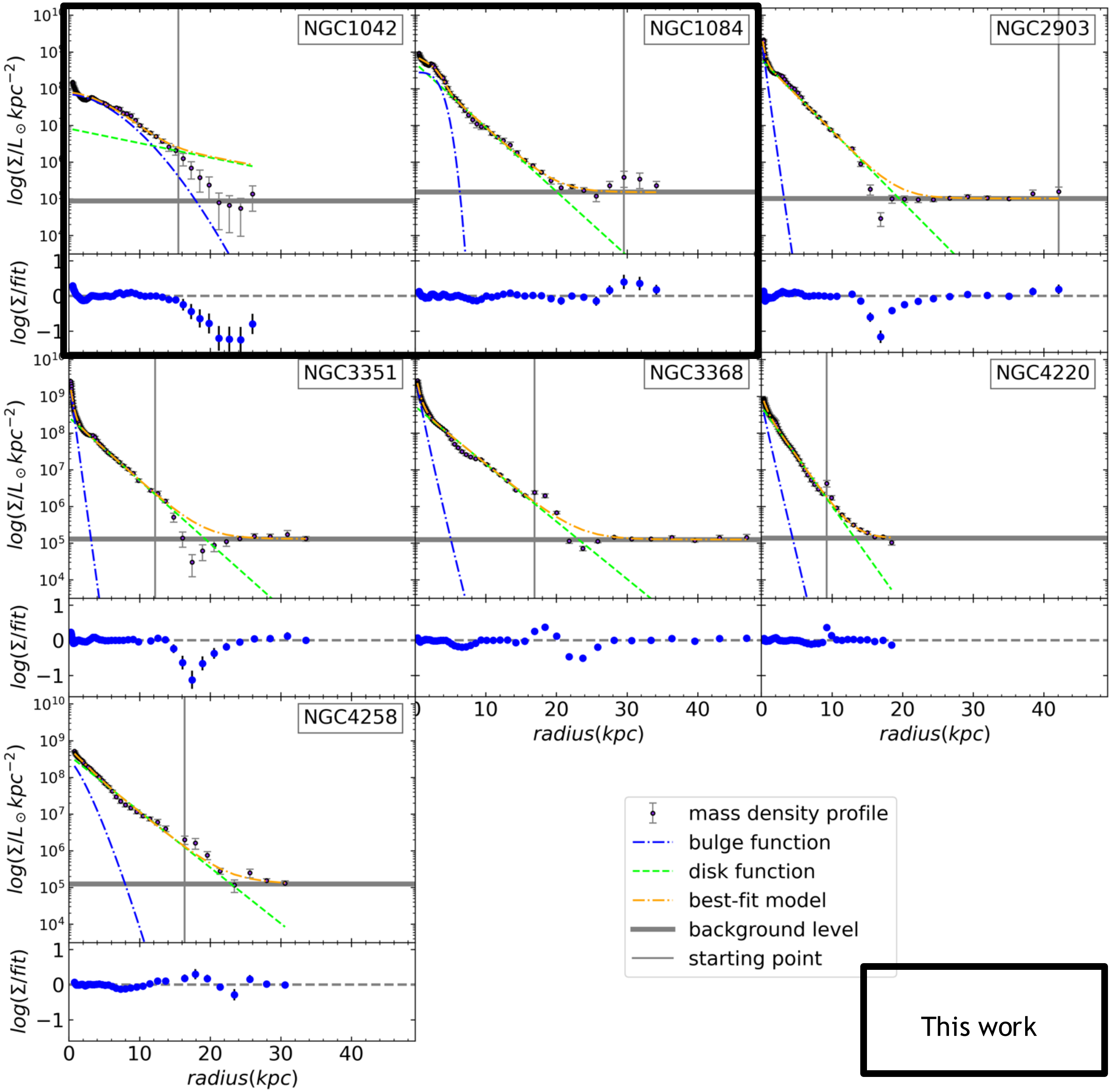
Avoid:

- Artificial steps
- subjective methods

Compare with Dragonfly Survey



(Merritt et al. 2016)

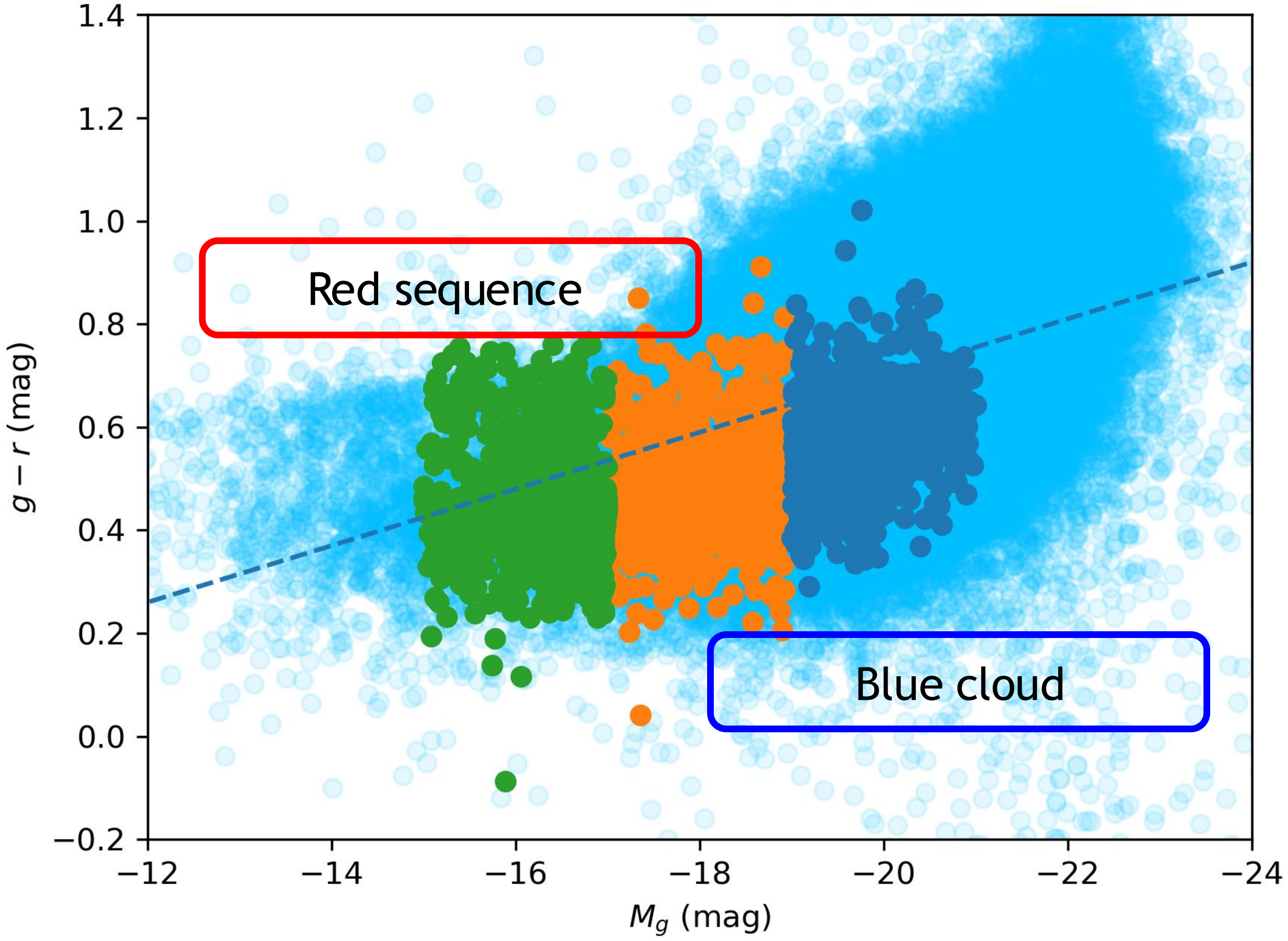


This work

Discussion

- SGA selection (Color magnitude diagram)
- Distribution of galaxy and stellar halo mass
- Compare with Dragonfly
- Compare with simulation

Select the MW-like galaxies in SGA



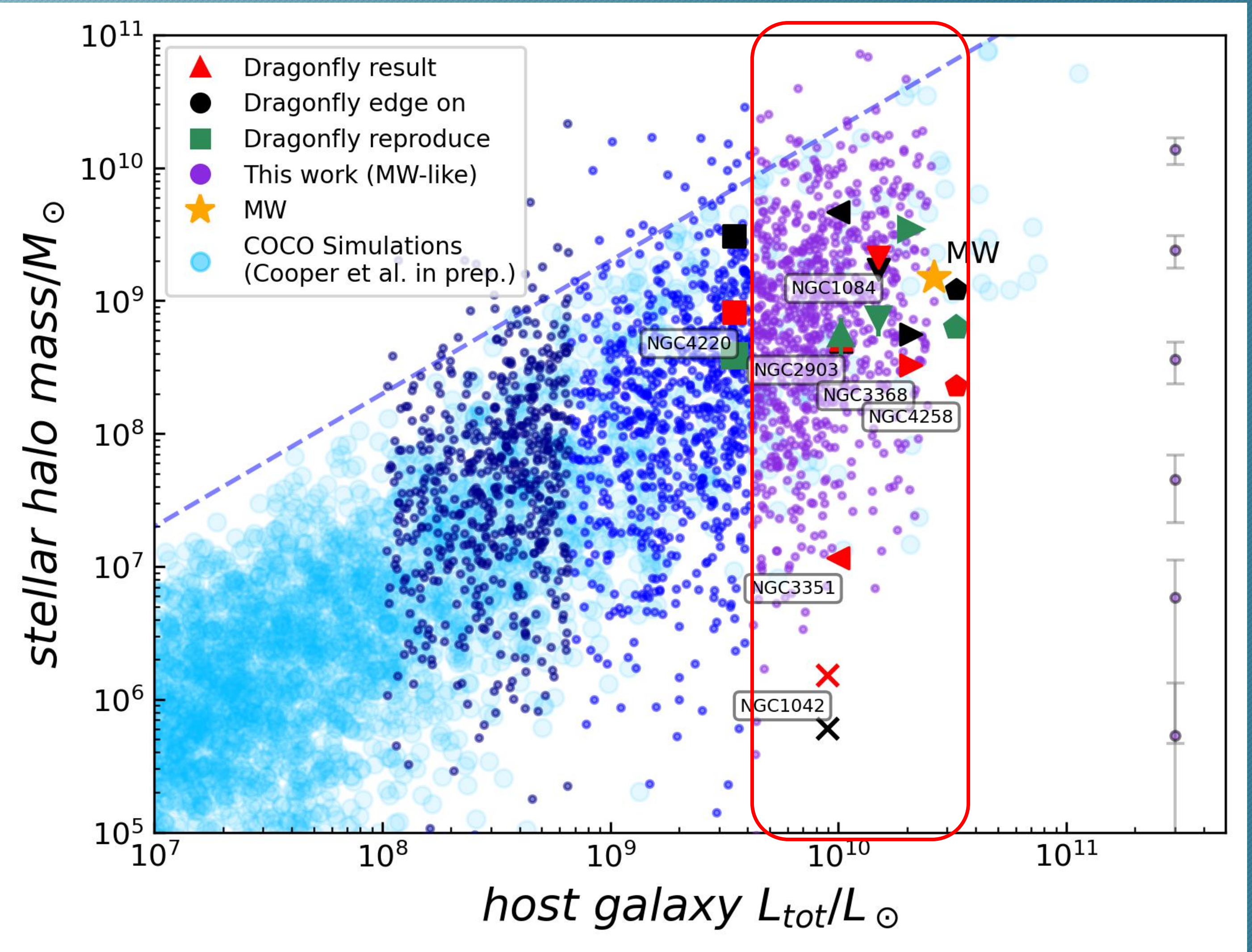
- BA > 0.5
- Sersic index < 1.5
- Z < 0.03 (~120mpc)

MW-like: -19 > M_{abs} > -21
Mid-mass: -17 > M_{abs} > -19
Low-mass: -15 > M_{abs} > -17

Separation: $(g-r) = -0.055\, M_g - \ 0.4$
from *Liao et al, 2022*

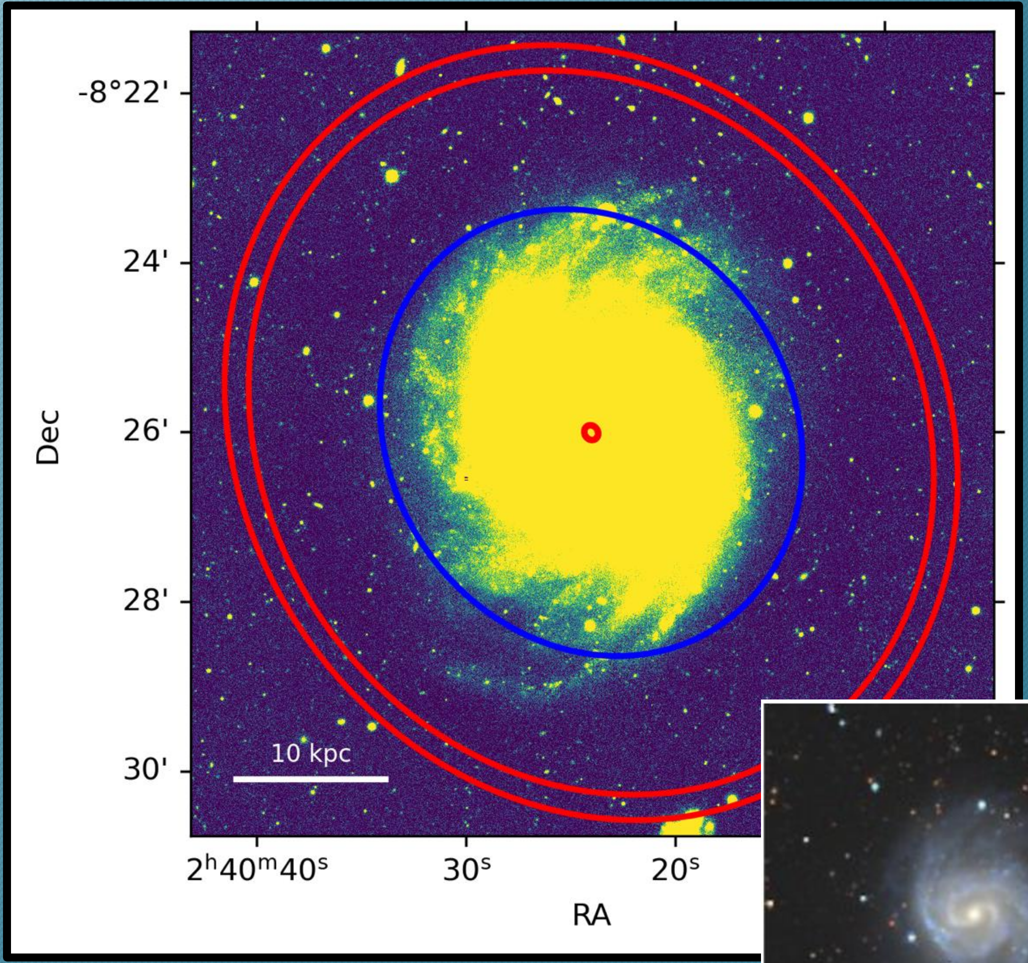
Distribution of galaxy and stellar halo mass

Luminosity vs. Stellar halo mass

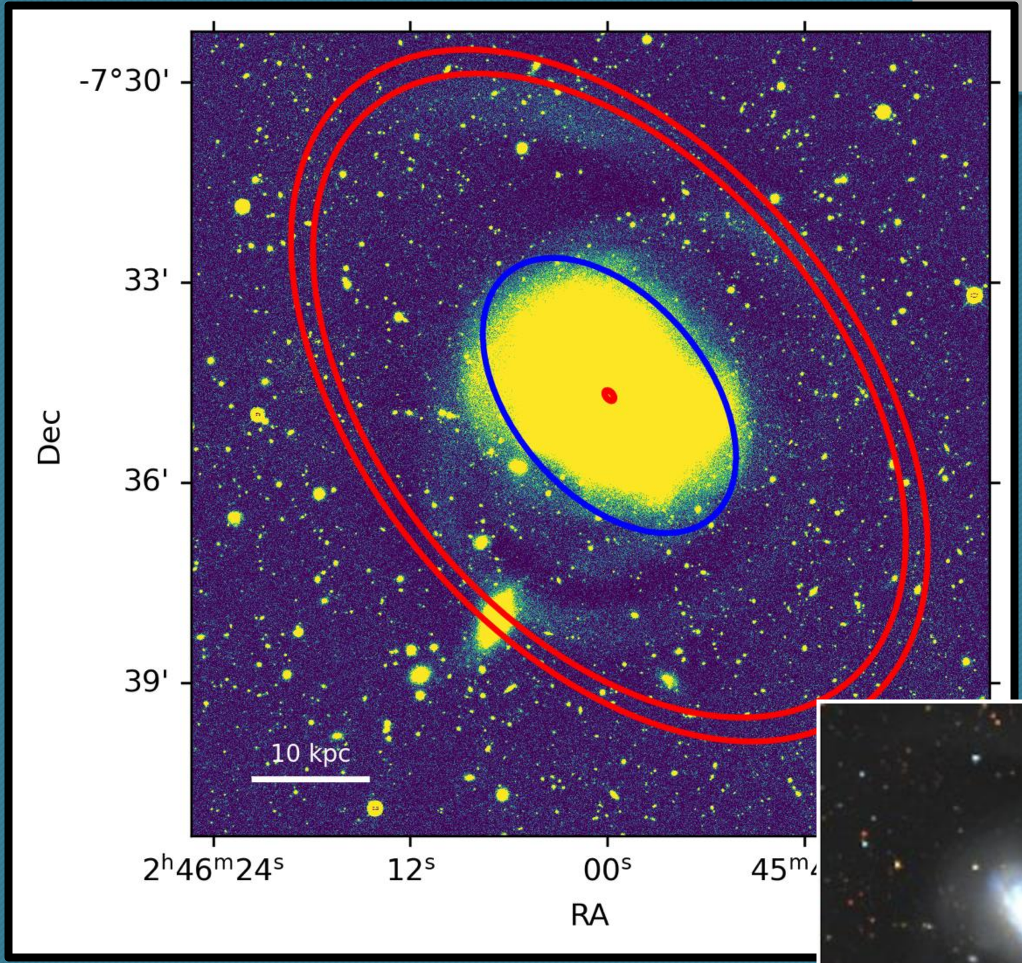


Scatter hints the accreting history and how stars form in dwarf galaxies

Our technique agrees with Dragonfly; large scatter is consistent with simulations.



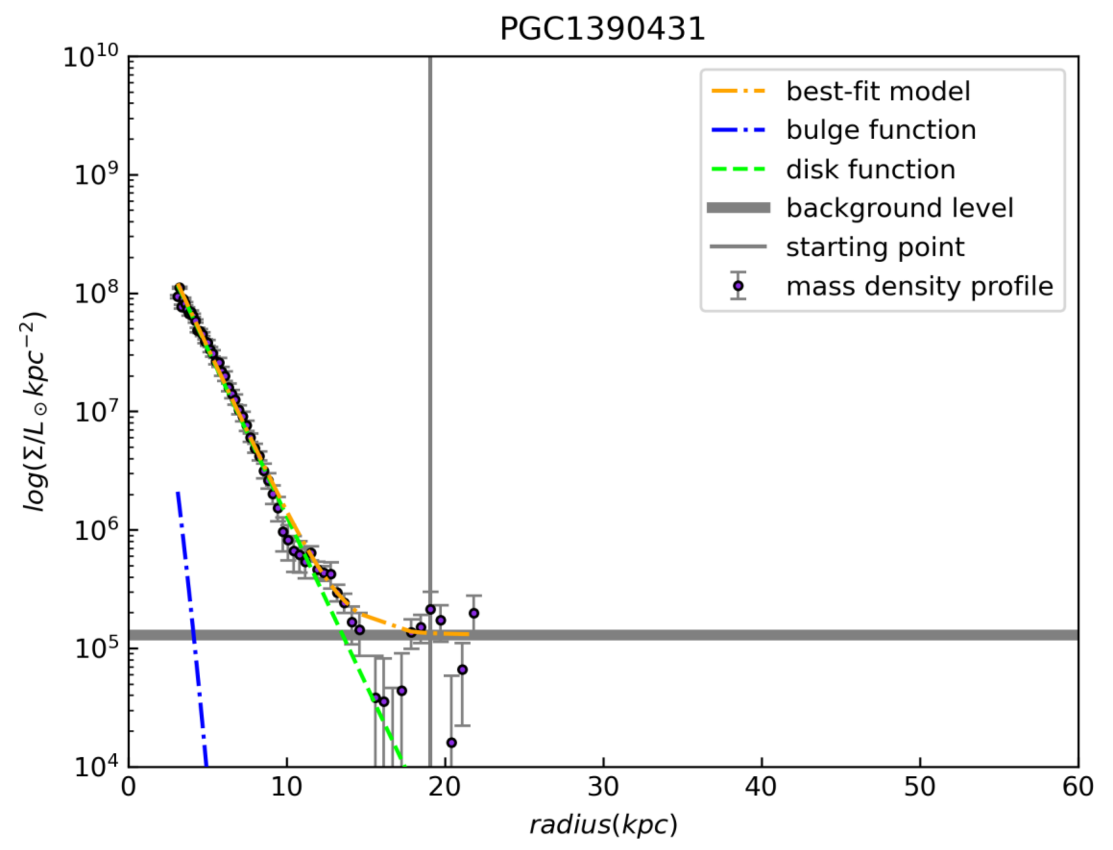
NGC 1042

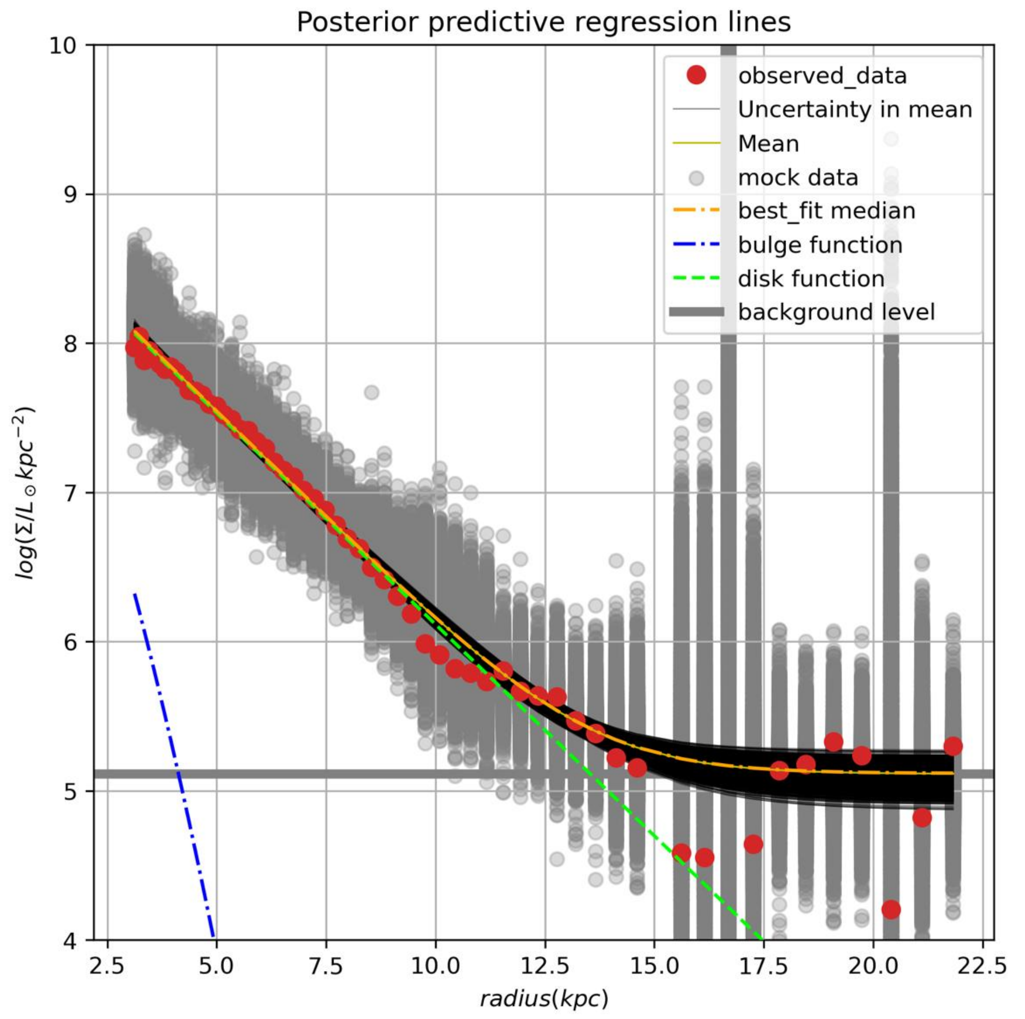


NGC 1084

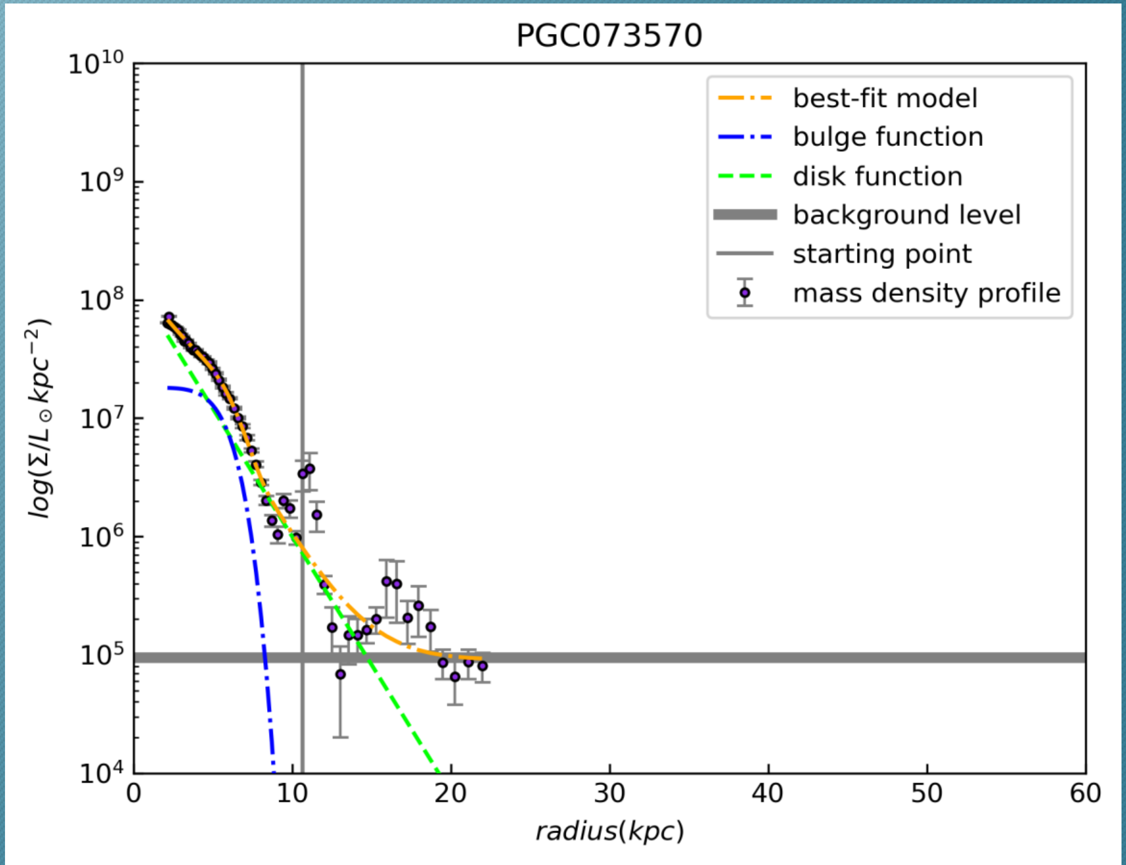
	MW-like(1000)	Mid-mass(1000)	Low-mass(1000)
Successful fits	928	906	889
Halo detected	775	677	593
Fraction with halo	0.83	0.74	0.66

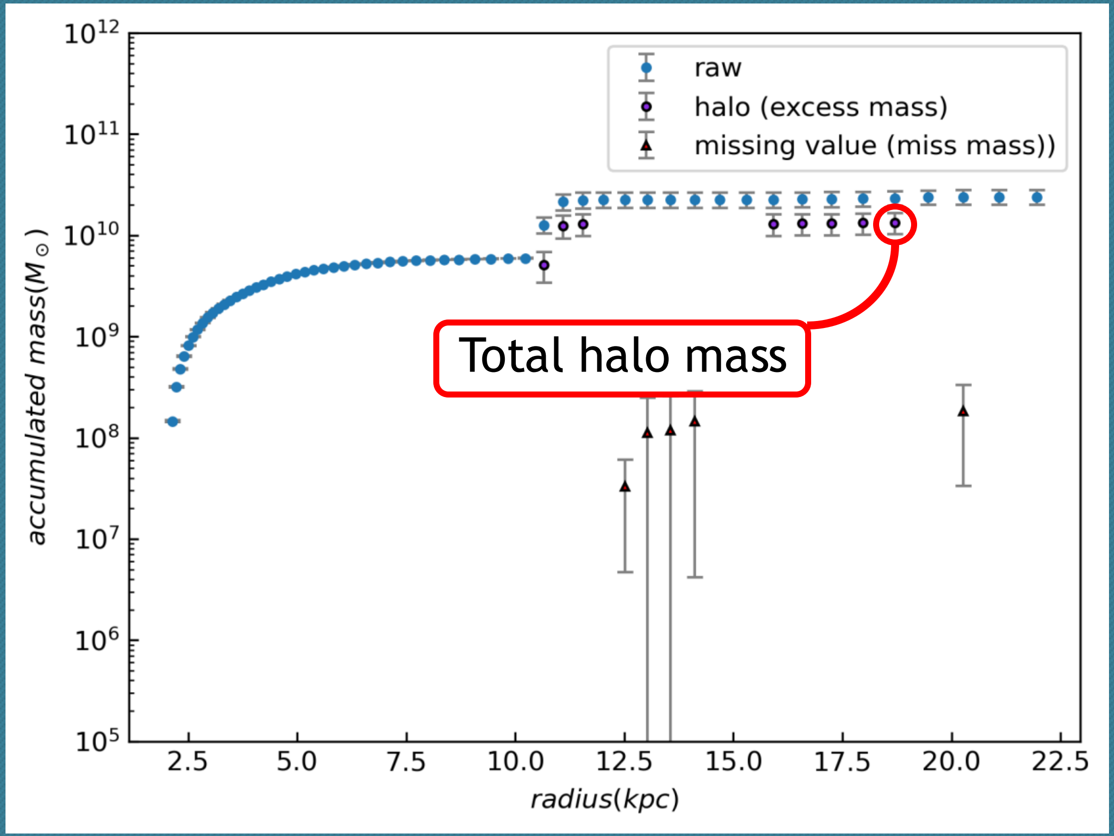
- Non-stellar halo detection: 153



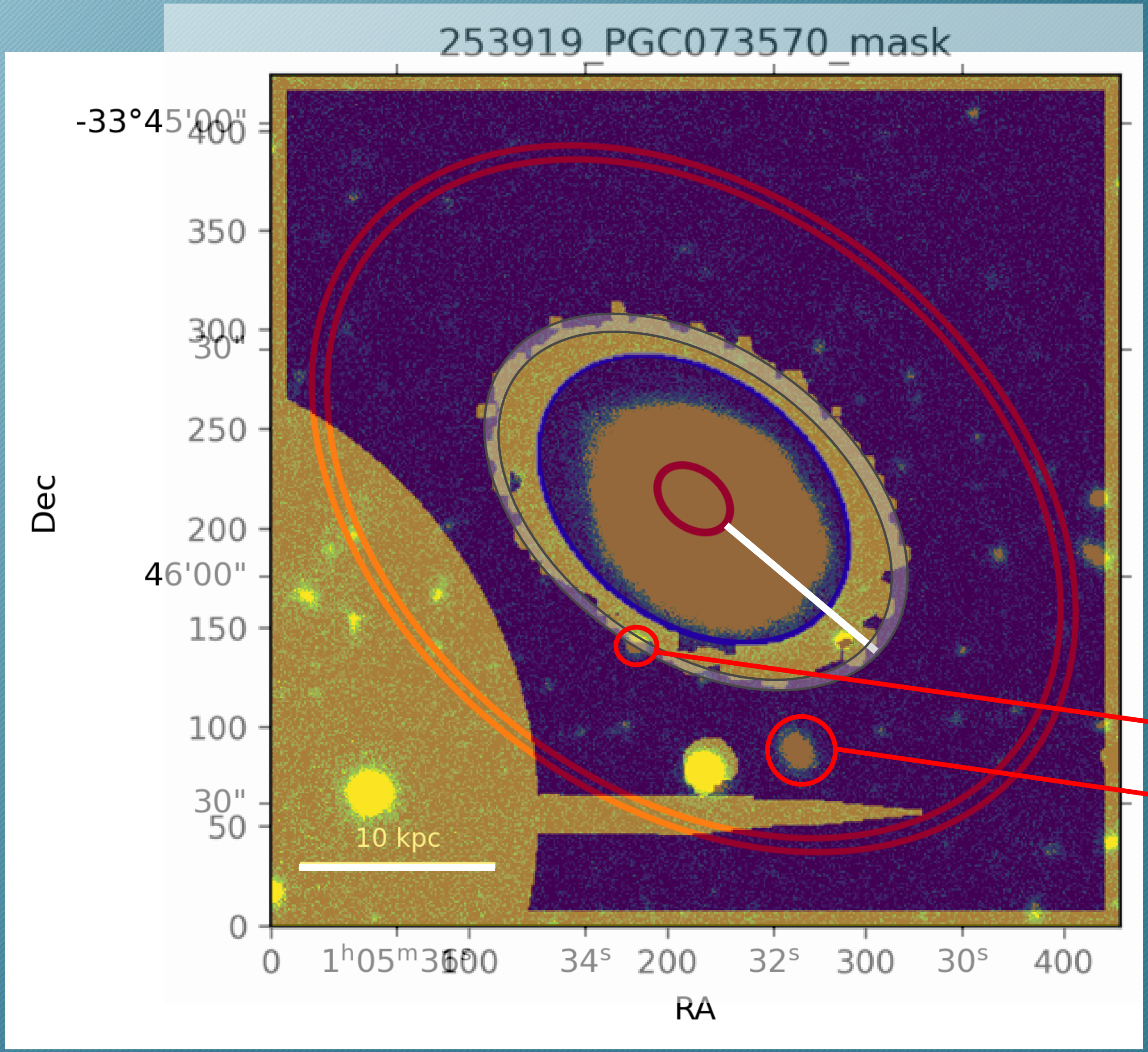


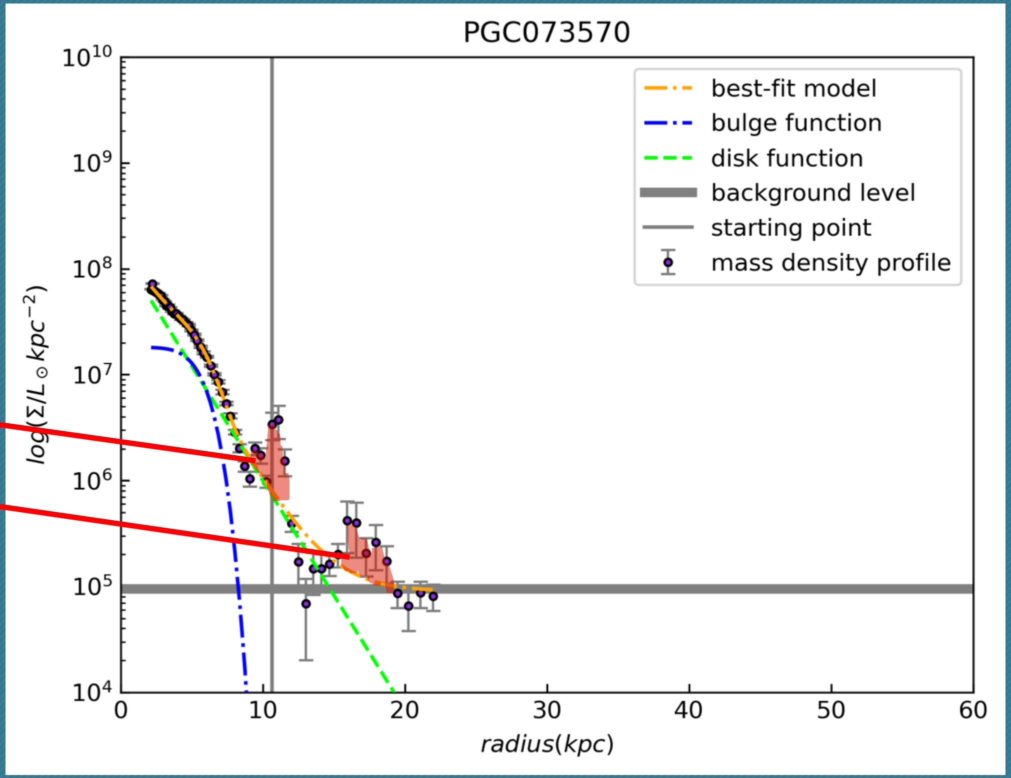
- excessive stellar halo mass (*stellar halo mass* > 2 L_{tot}): 15



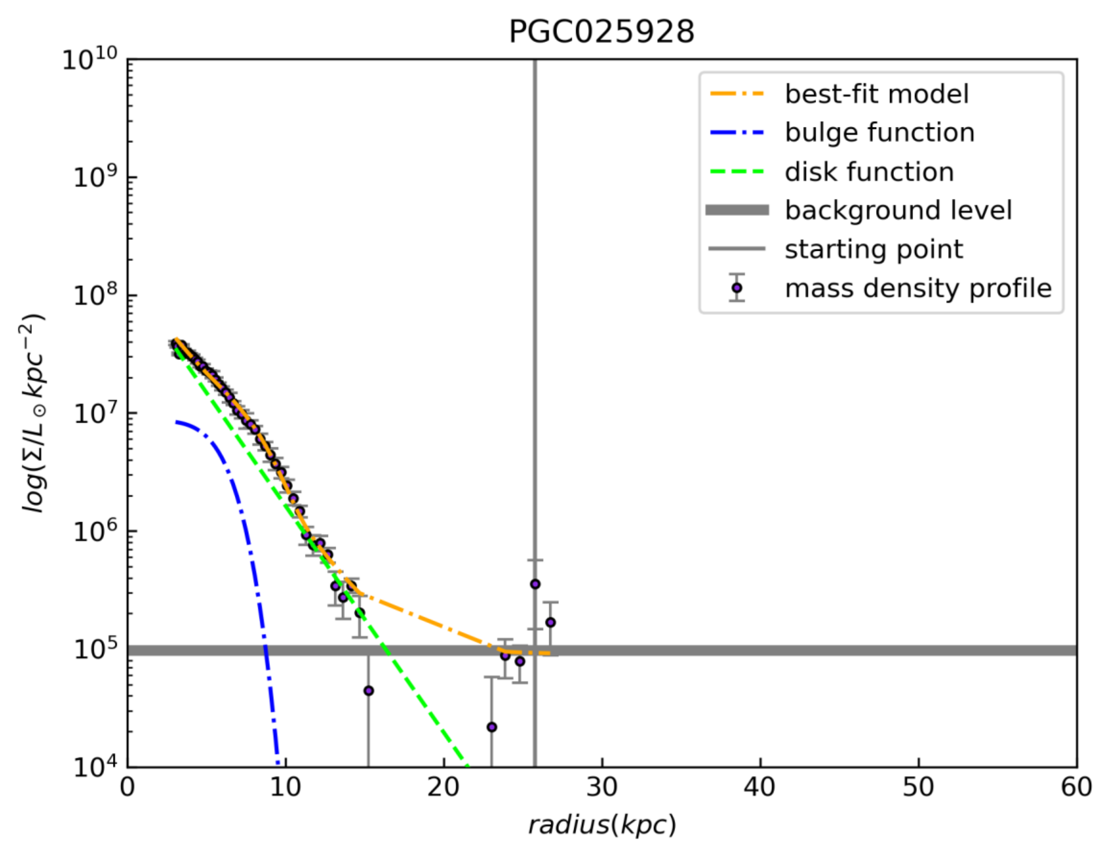


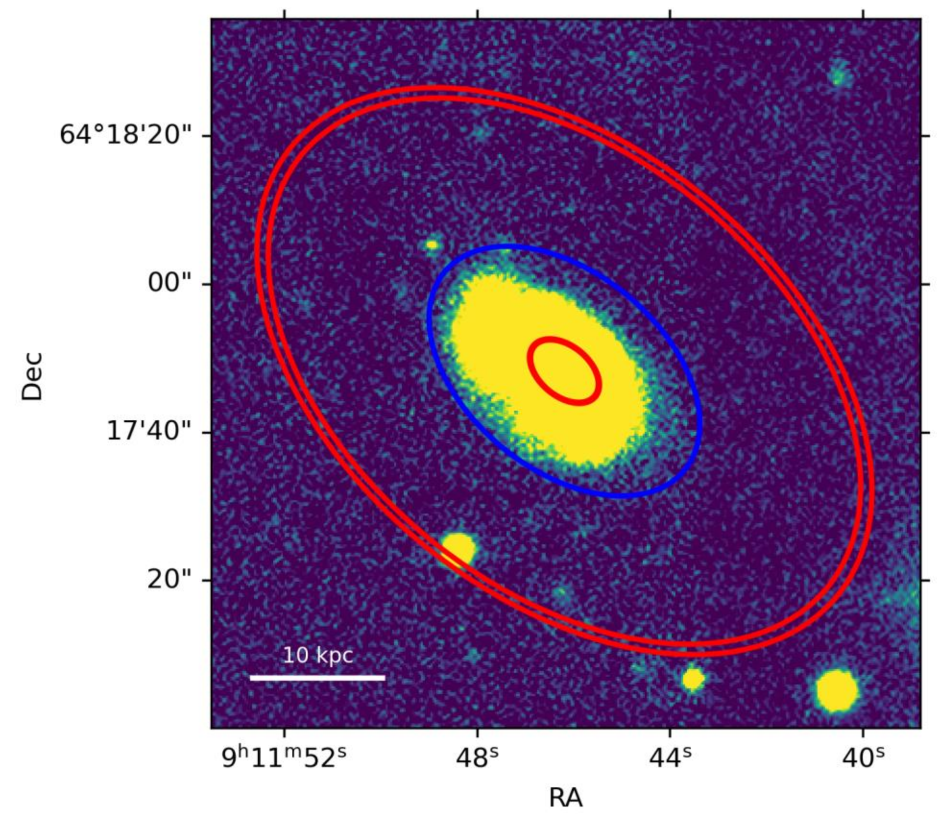
Accumulated stellar halo mass


253919_PGC073570_mask
Dec
RA
10 kpc
-33°45'00"
30"
46'00"
30"
1h05m36s
34s
32s
30s
0
50
100
150
200
250
300
350
400


PGC073570
best-fit model
bulge function
disk function
background level
starting point
mass density profile
$log(\Sigma/L_\odot kpc^{-2})$
radius(kpc)
10^{10}
10^9
10^8
10^7
10^6
10^5
10^4
0
10
20
30
40
50
60

- too low stellar halo mass (*stellar halo < 3.5 orders of* L_{tot}): 5





Stellar halo mass distribution

Peak value: $\sim 10^9 M_\odot$ in SGA
$\sim 10^{8.7} M_\odot$ in simulation

MW mass: $5 \times 10^{10} M_\odot$

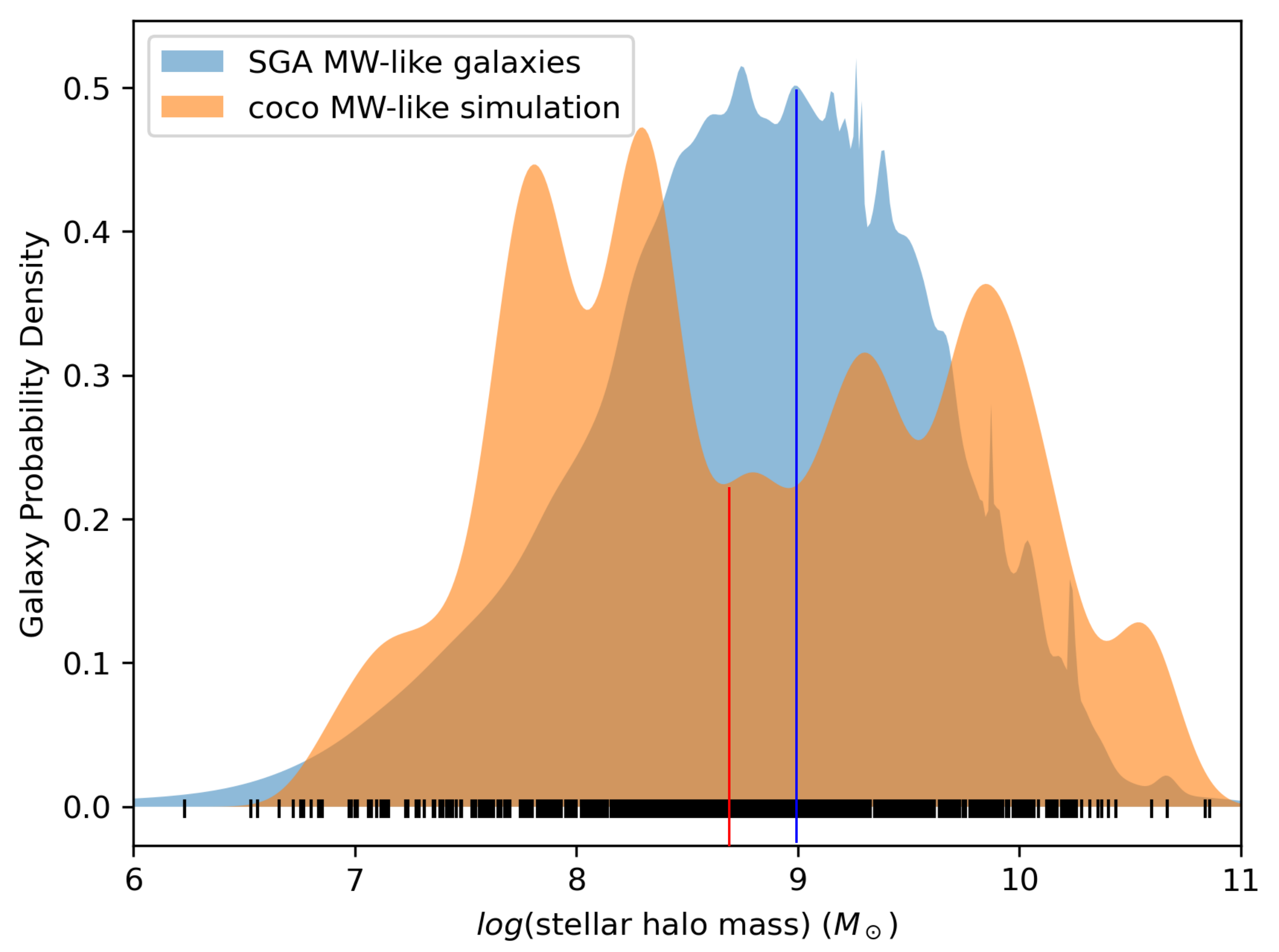
LS: $5.69 \times 10^8 M_\odot$

Dragonfly: $5.73 \times 10^8 M_\odot$

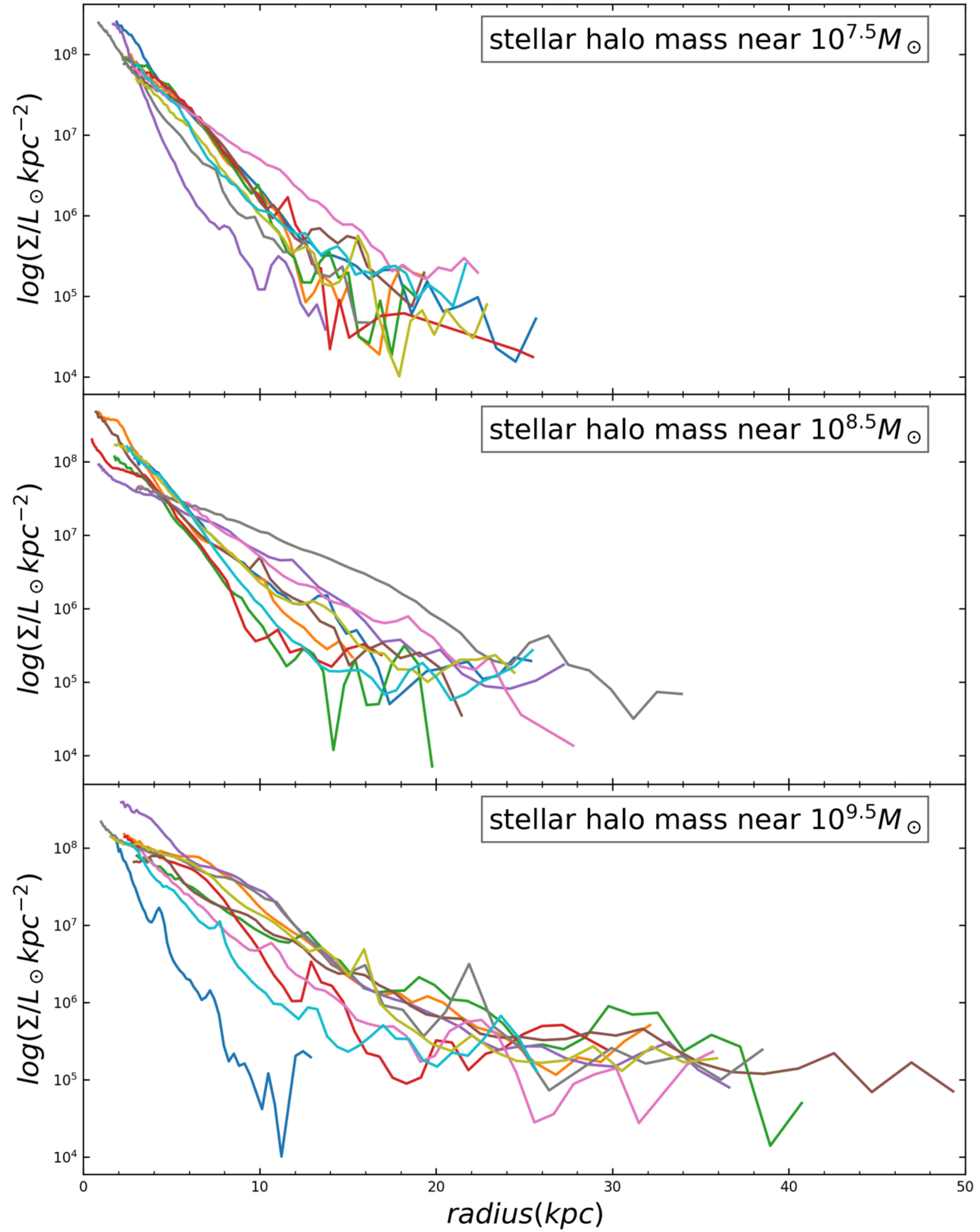
< 1%

Dragonfly Edge-on: $1.66 \times 10^9 M_\odot$

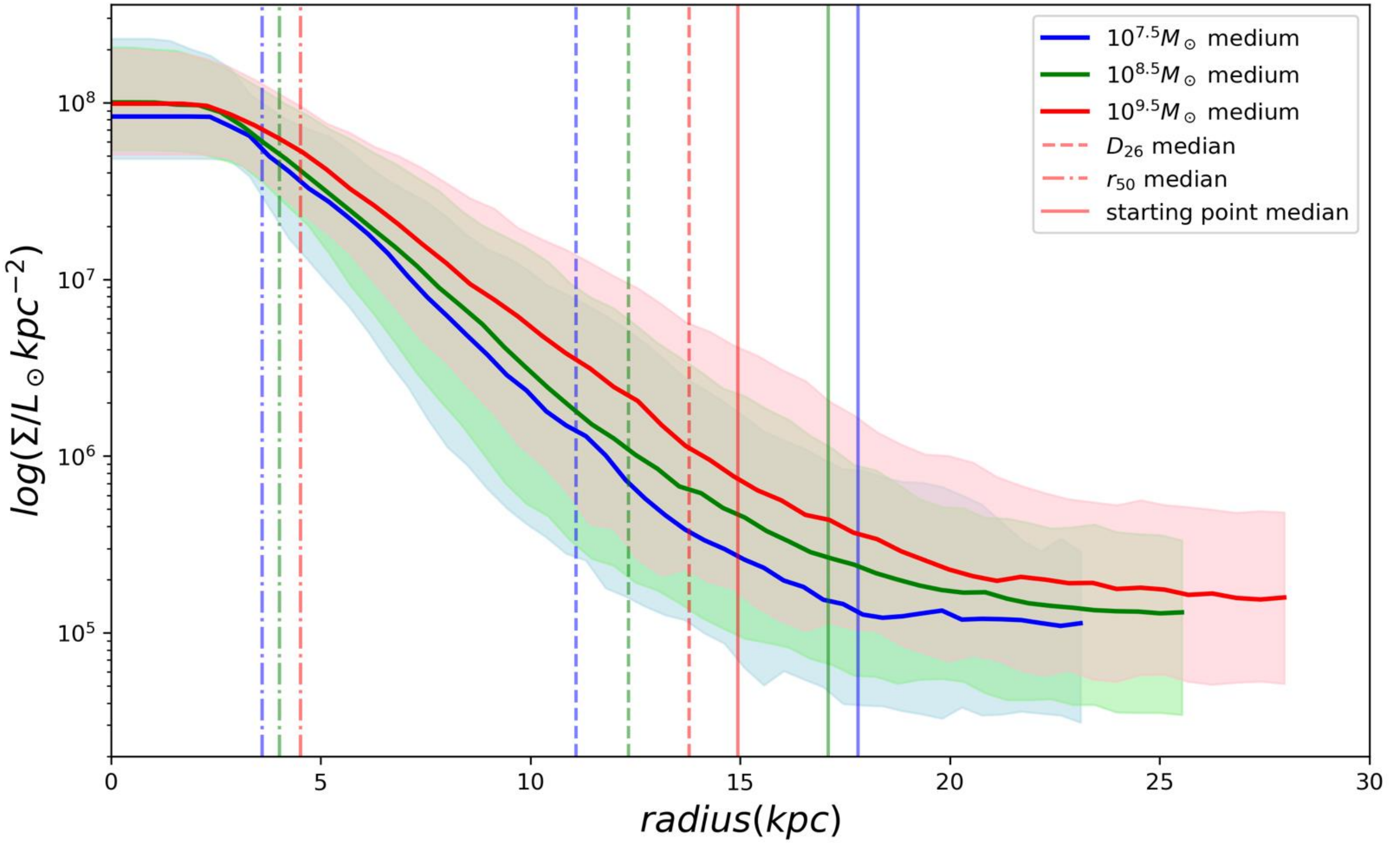
Kernel Density Estimate

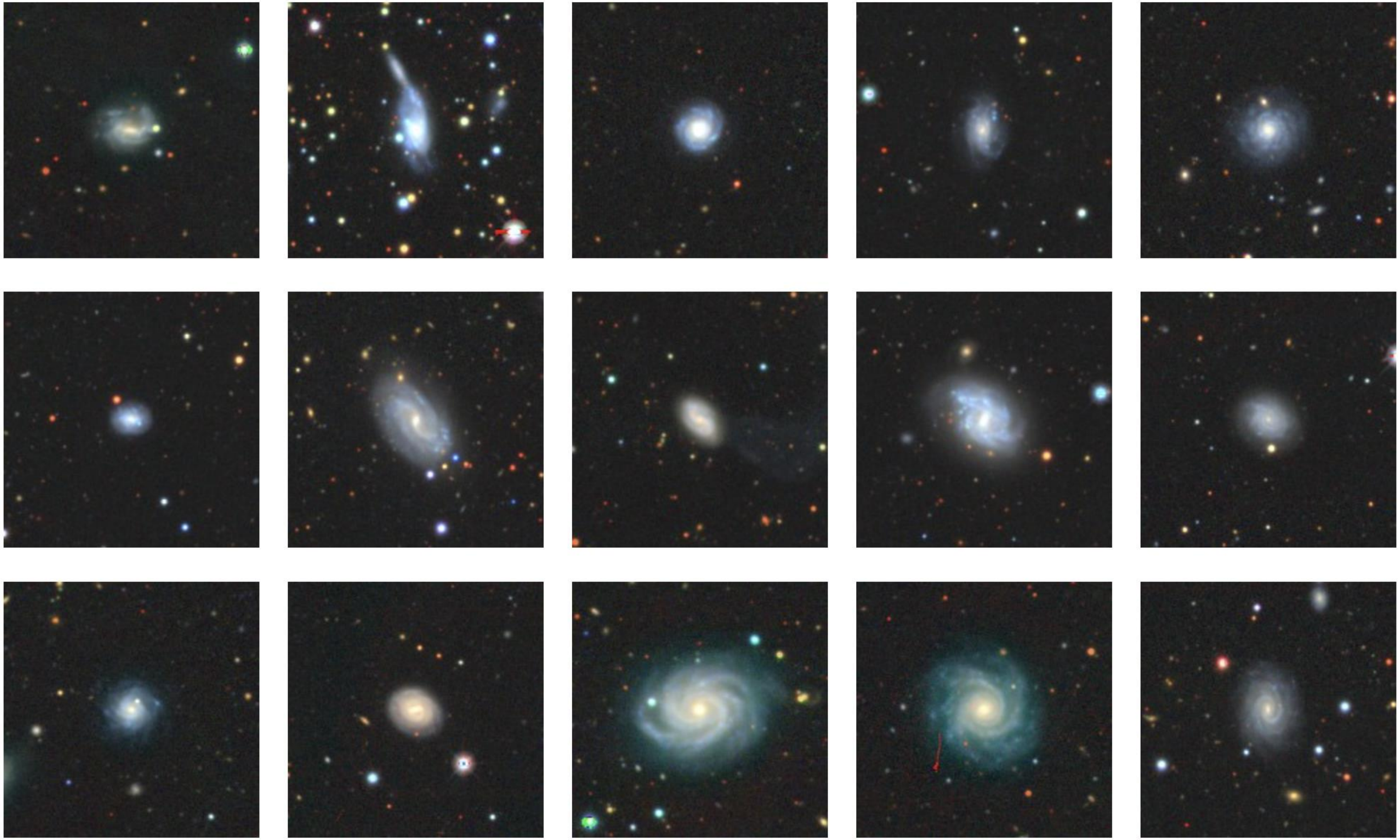


How robust ?



Median profile in three different mass bins





Future work

Creating masking and photometry

- pixel binning to improve the signal-to-noise ratio
- increase the detection limit of surface brightness

Use MCMC model to fit density profiles

- Autocorrelation
- clarify the reasons for model fitting failure

Analysis of stellar halo mass distribution

- statistical analysis for other mass bin
- Check the "missing value" problems

Conclusion

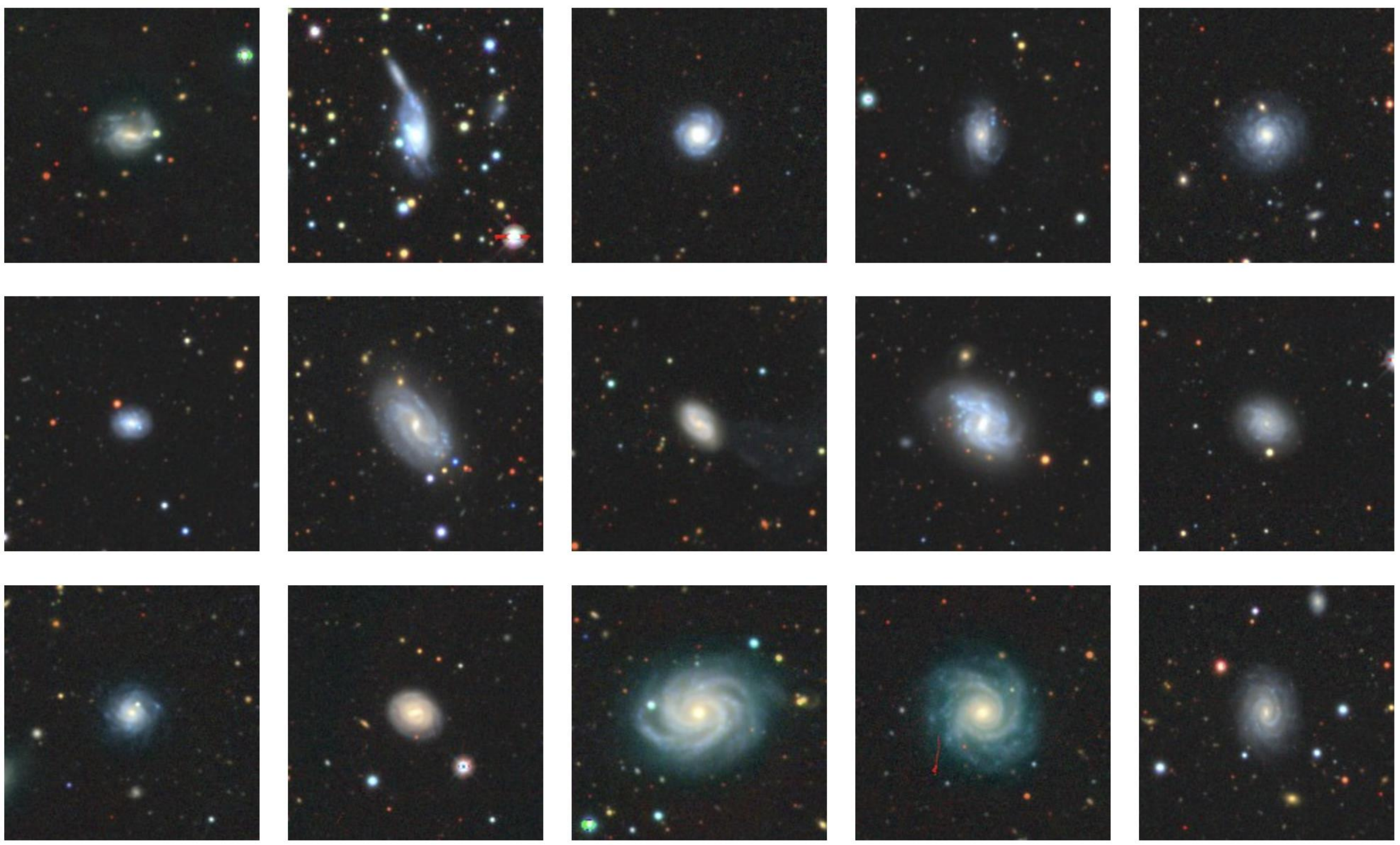
- We use our own pipeline to conduct photometry and measure the stellar halo mass for Milky Way-like galaxies.

- Agree with the state-of-the-art result from the Dragonfly survey.

  ⇒ The DESI-LS is capable of accurately measuring more stellar halos.

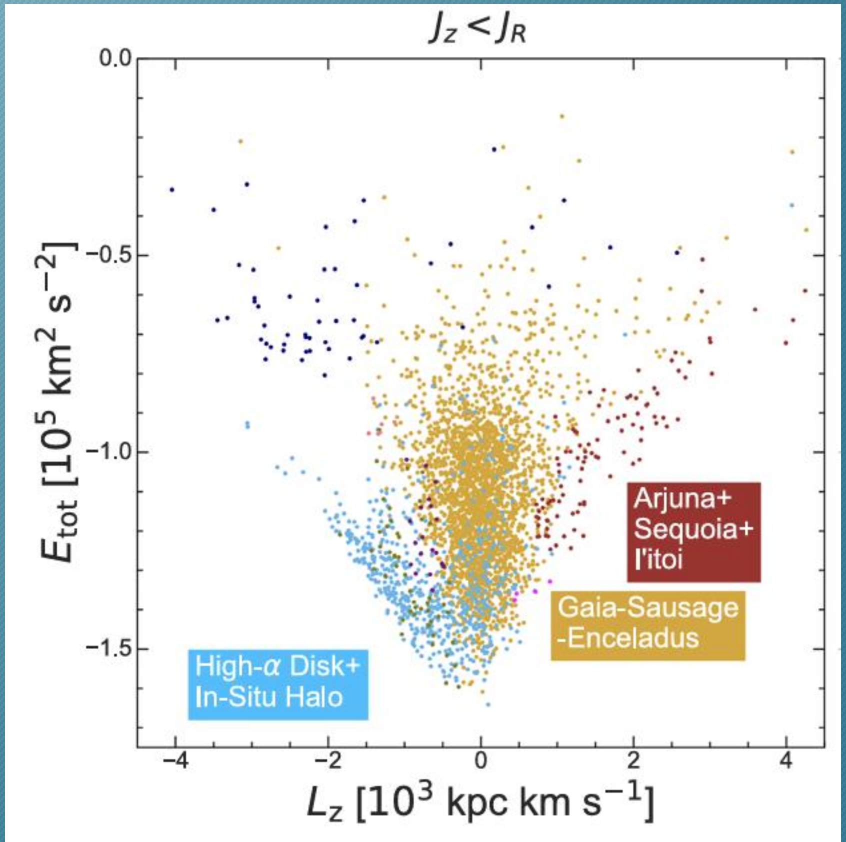
- By applying to all-sky survey, we have done some **statistical analysis and compare them with simulations, this** should help support the theory.

Thanks for listening



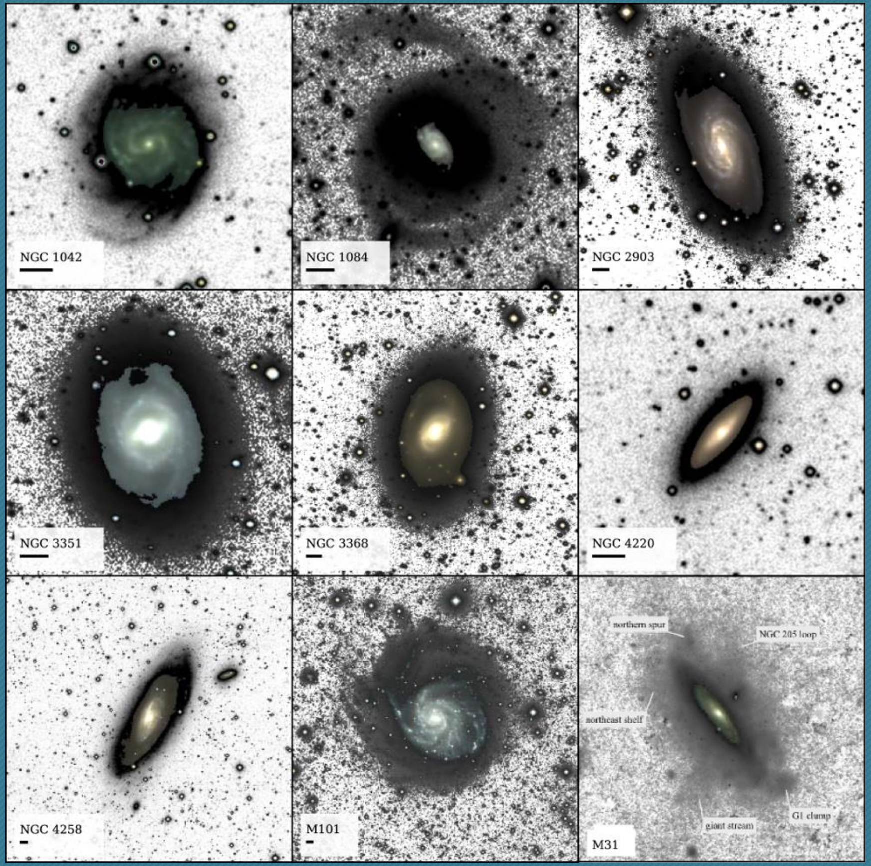
Two methods:

- ◆ Star counts (resolve stars)
- ◆ Integrated light surveys



➢ Robust but distance limit

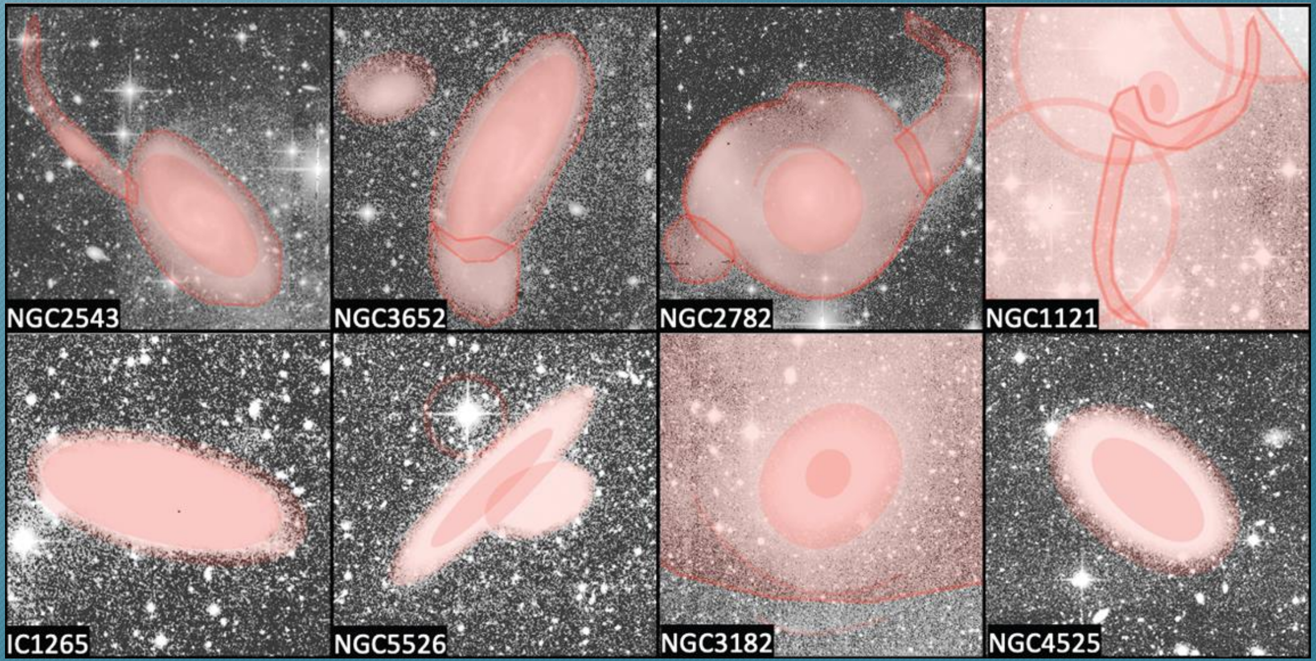
Naidu et al. 2020



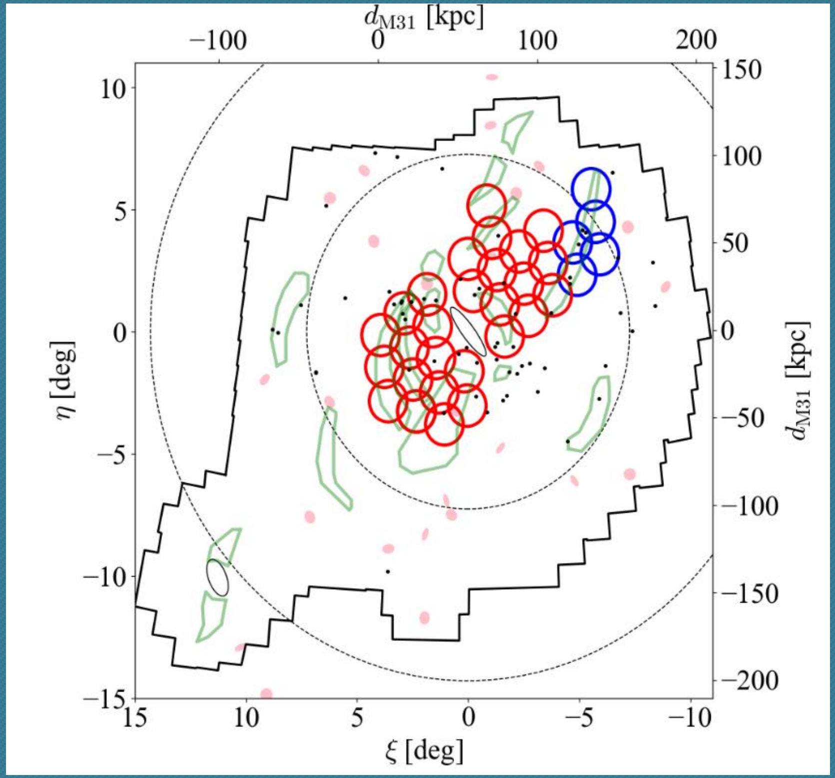
➢ Efficient but not precise enough

Merritt et al. 2016

Most previous work on images of extragalactic stellar halos has focused on identifying and classifying individual LSB features.



Canada-France-Hawaii Telescope (CFHT) (Sola et al, 2022)



HSC survey fields (Ogami et al, 2024)

Our

Galaxy Name	R_{disk}(kpc)	$\Sigma_{0,disk}(L_{\odot}kpc^{-2})$	R_{bulge}(kpc)	$\Sigma_{0,bulge}(L_{\odot}kpc^{-2})$	n	$R_s(kpc)$
NGC 1042	18.41	1.5×10^6	5.41	3.1×10^7	0.56	15.49
NGC 1084	4.14	9.3×10^7	2.40	2.1×10^8	0.27	29.56
NGC 2903	3.74	1.1×10^8	0.51	4.9×10^8	1.05	42.08
NGC 3351	4.22	5.0×10^7	0.51	6.1×10^8	1.01	12.21
NGC 3368	4.63	9.9×10^7	0.75	6.8×10^8	1.12	16.89
NGC 4220	2.68	9.8×10^7	0.84	1.3×10^8	1.04	9.27
NGC 4258	4.75	7.4×10^7	1.91	8.9×10^7	0.76	16.37

Dragonfly

Galaxy Name	R_{disk}(kpc)	$\Sigma_{0,disk}(M_{\odot}kpc^{-2})$	R_{bulge}(kpc)	$\Sigma_{0,bulge}(M_{\odot}kpc^{-2})$	n	$5R_{\mathrm{h}}(kpc)$
NGC 1042	3.0	3.9×10^8	1.1	1.3×10^9	0.9	26.6
NGC 1084	2.0	2.3×10^9	2.3	3.2×10^9	1.3	17.0
NGC 2903	2.9	1.8×10^9	1.5	1.0×10^{10}	0.8	19.5
NGC 3351	2.9	7.5×10^8	1.7	6.8×10^{10}	1.7	10.4
NGC 3368	4.3	4.5×10^8	2.7	8.1×10^{10}	1.9	12.8
NGC 4220	2.3	3.3×10^9	2.6	5.1×10^9	0.9	13.7
NGC 4258	5.3	6.0×10^8	3.9	2.5×10^{10}	1.7	20.8

LSB structures

Tidal Tails

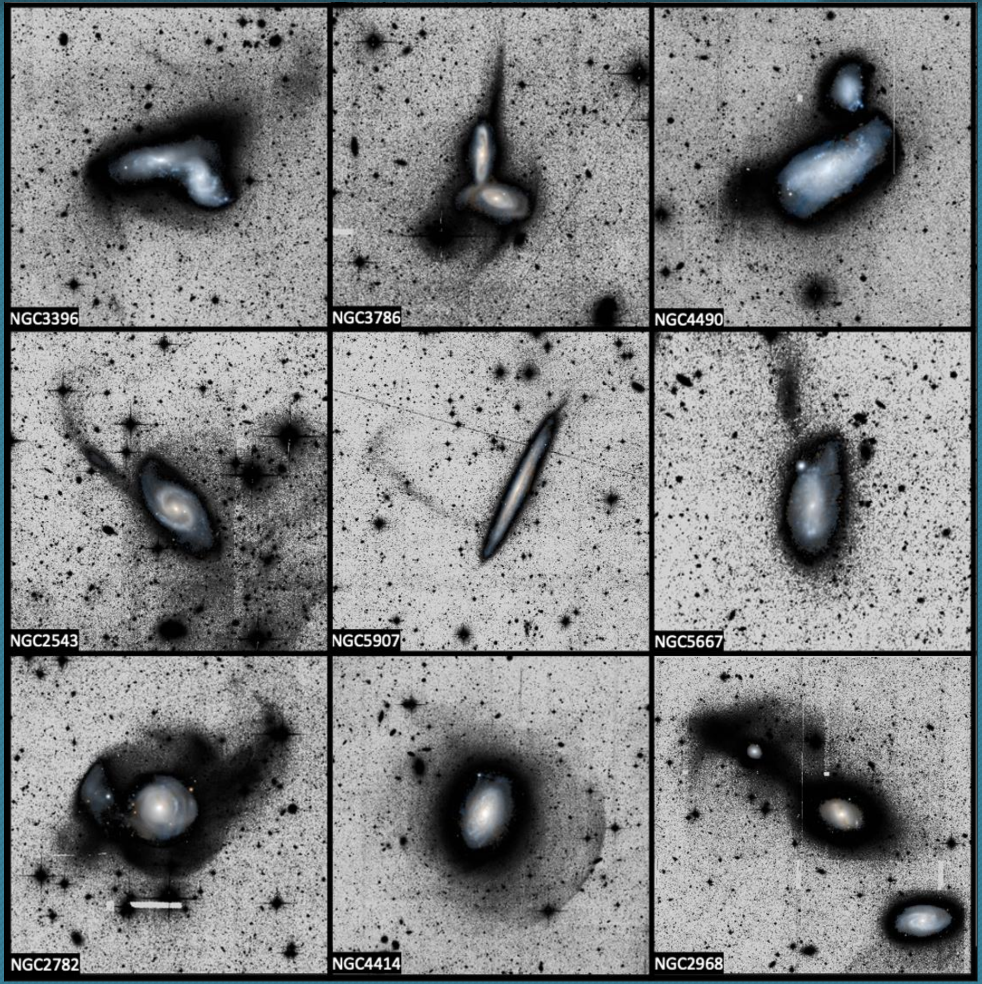
- Long, narrow structures extending from galaxies or star clusters
- Stars in systems distorted by tidal forces are pulled apart
- Irregular, blocky, and asymmetrical features, possibly from host galaxy or the companion

Tidal Streams

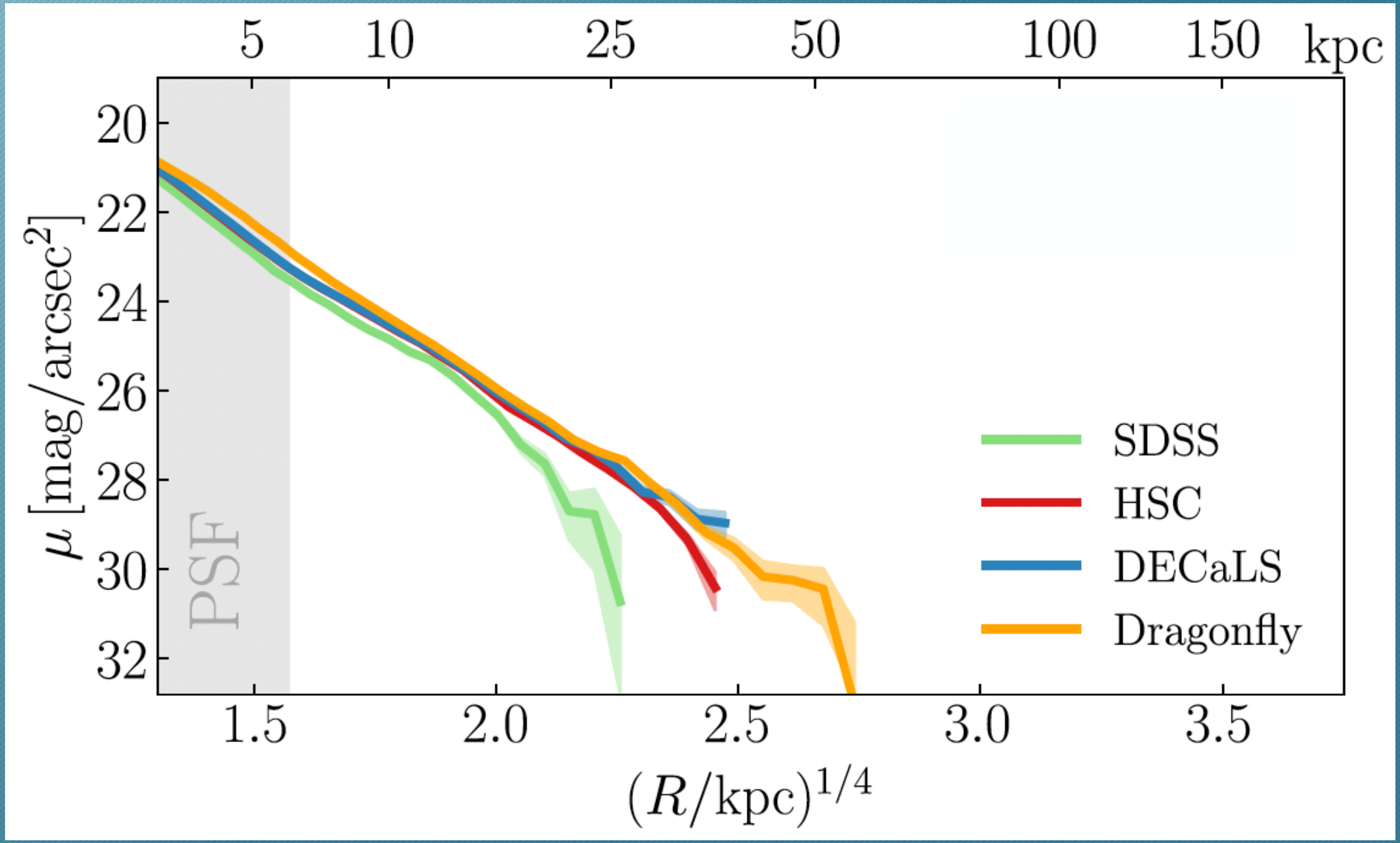
- Elongated, ribbon-like structures
- Consists of fragmented dwarf galaxies or stars of globular clusters
- Originate from interactions with other galaxies or satellite systems during mergers

Stellar Shells

- Concentric, roughly spherical structures surrounding a galaxy's center
- Formed from disrupted satellite galaxies or globular clusters
- Primarily come from the host galaxy itself



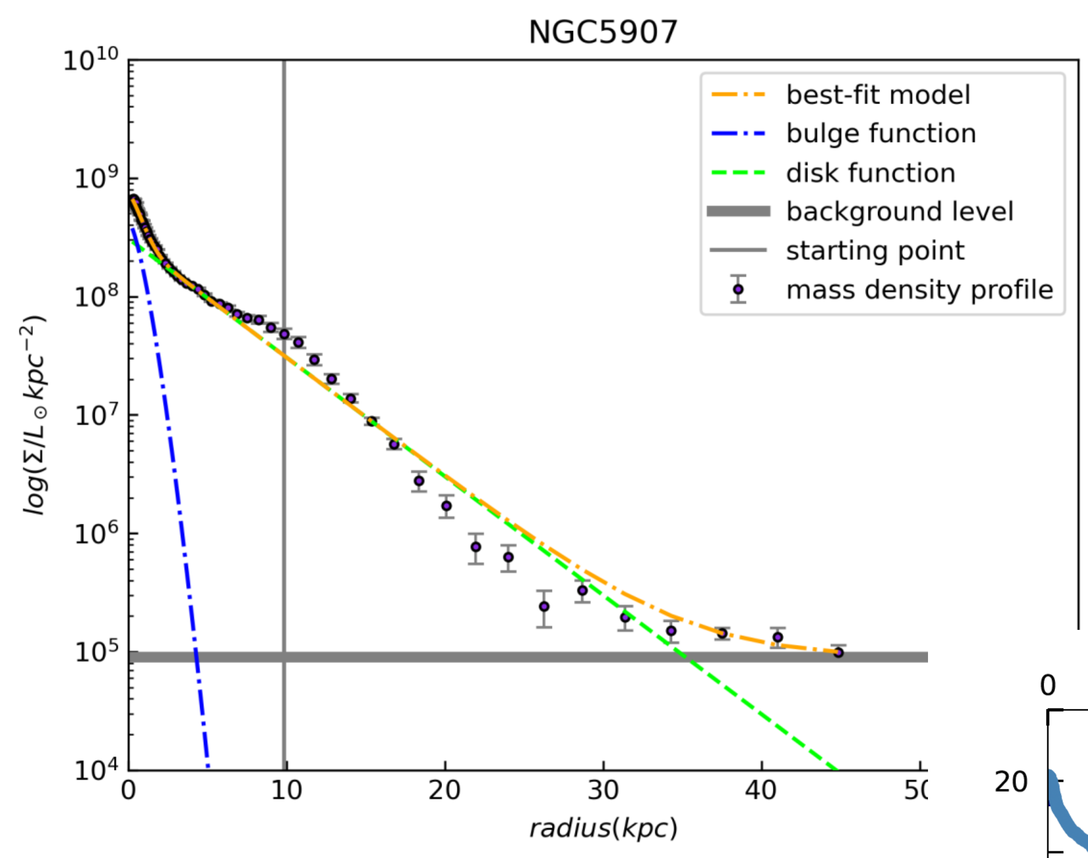
r -band surface brightness profiles of the low- z sample

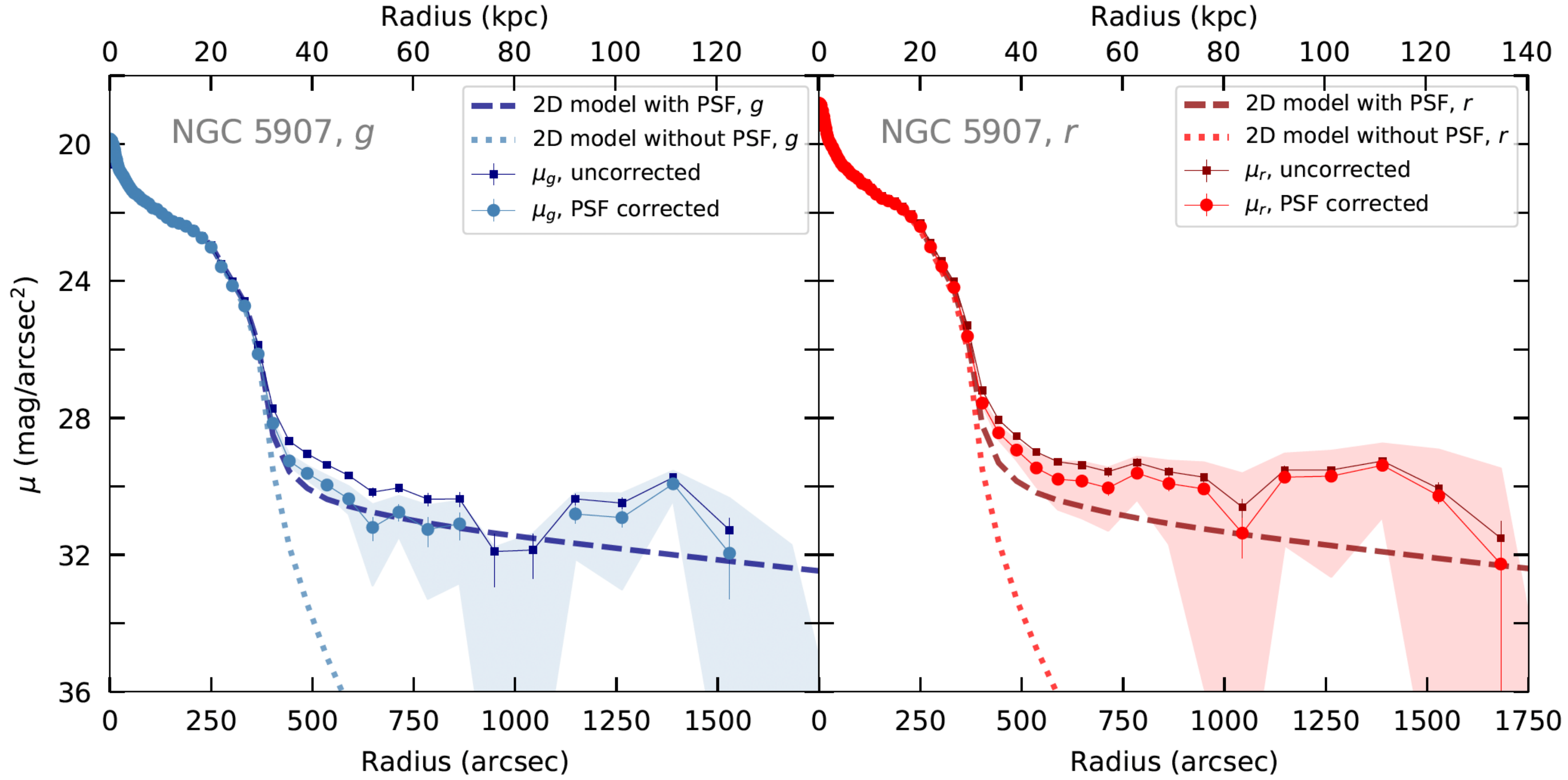


5σ point source detection limit:
HSC: 26.2 mag
DECaLS: 23.4 mag

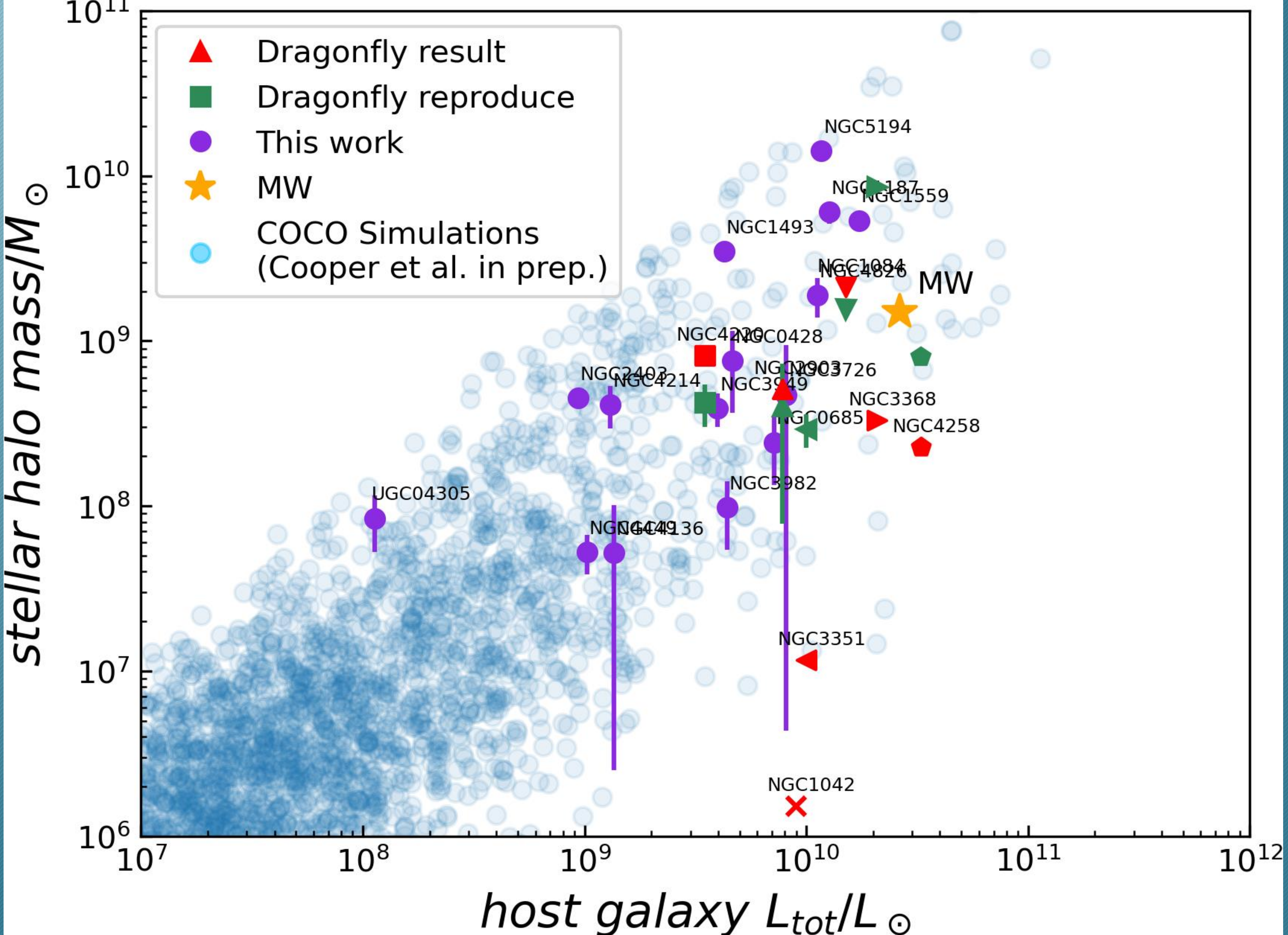
Li et al. 2022

Edge-on issue

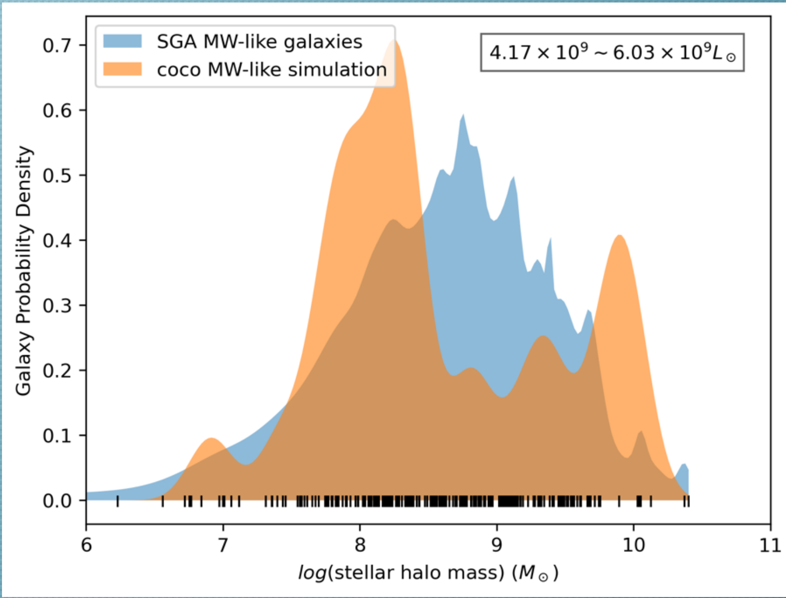


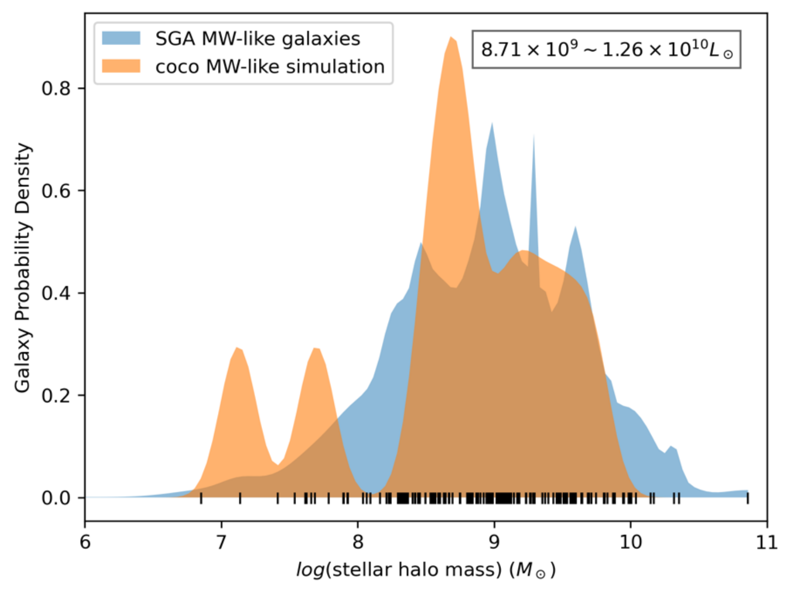


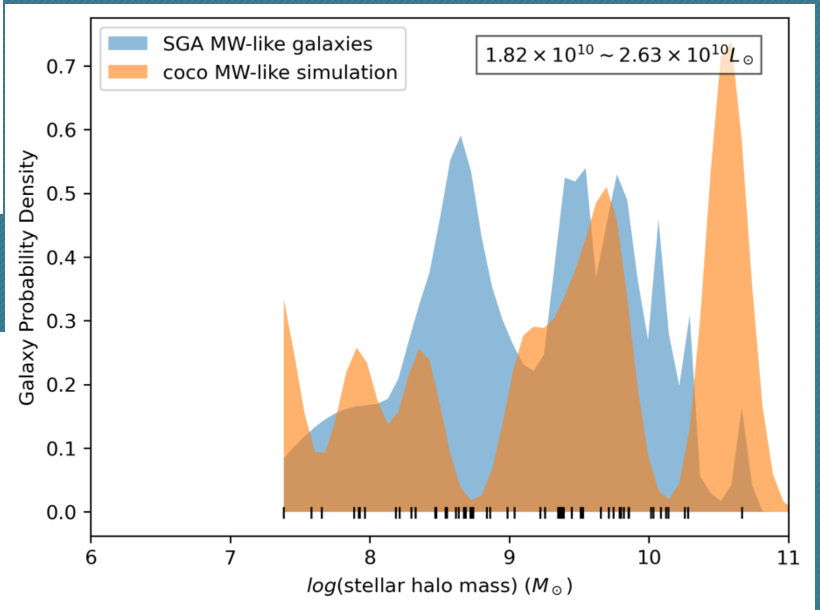
Combine function:
BrokenExponentialDisk3D + Sersic

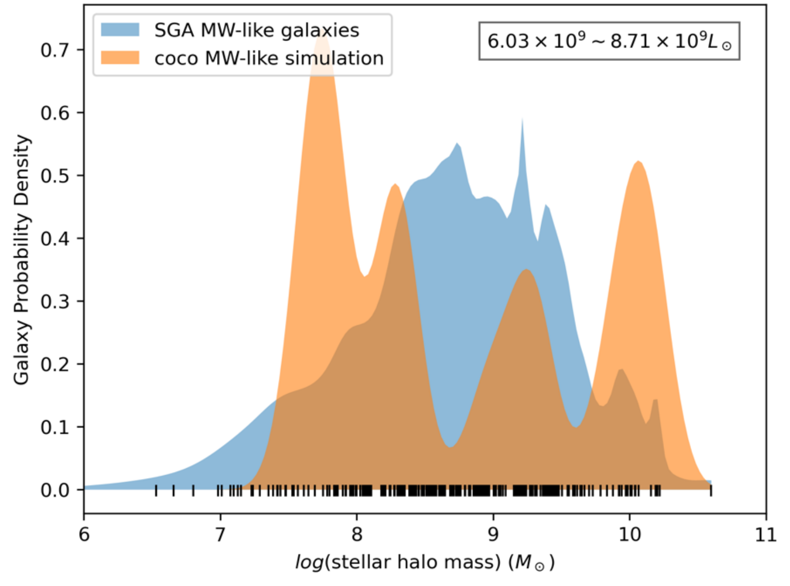


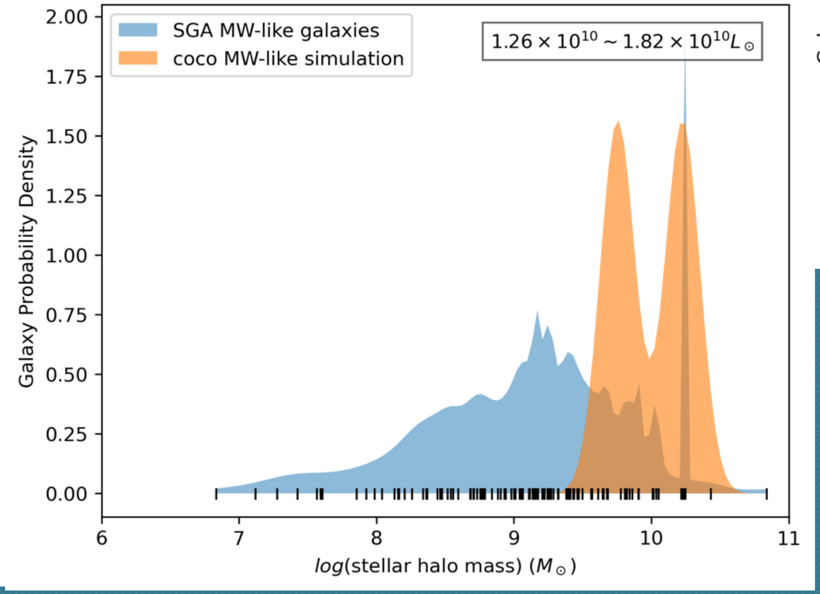
Dragonfly result
Dragonfly reproduce
This work
MW
COCO Simulations
(Cooper et al. in prep.)
NGC5194
NGC1187
NGC1559
NGC1493
NGC1084
NGC4826
MW
NGC4220
NGC0428
NGC2403
NGC4214
NGC2903
NGC3726
NGC3949
NGC3368
NGC0685
NGC4258
NGC3982
UGC04305
NGC4449
NGC4136
NGC3351
NGC1042
stellar halo mass/$M_\odot$
host galaxy $L_{tot}/L_\odot$

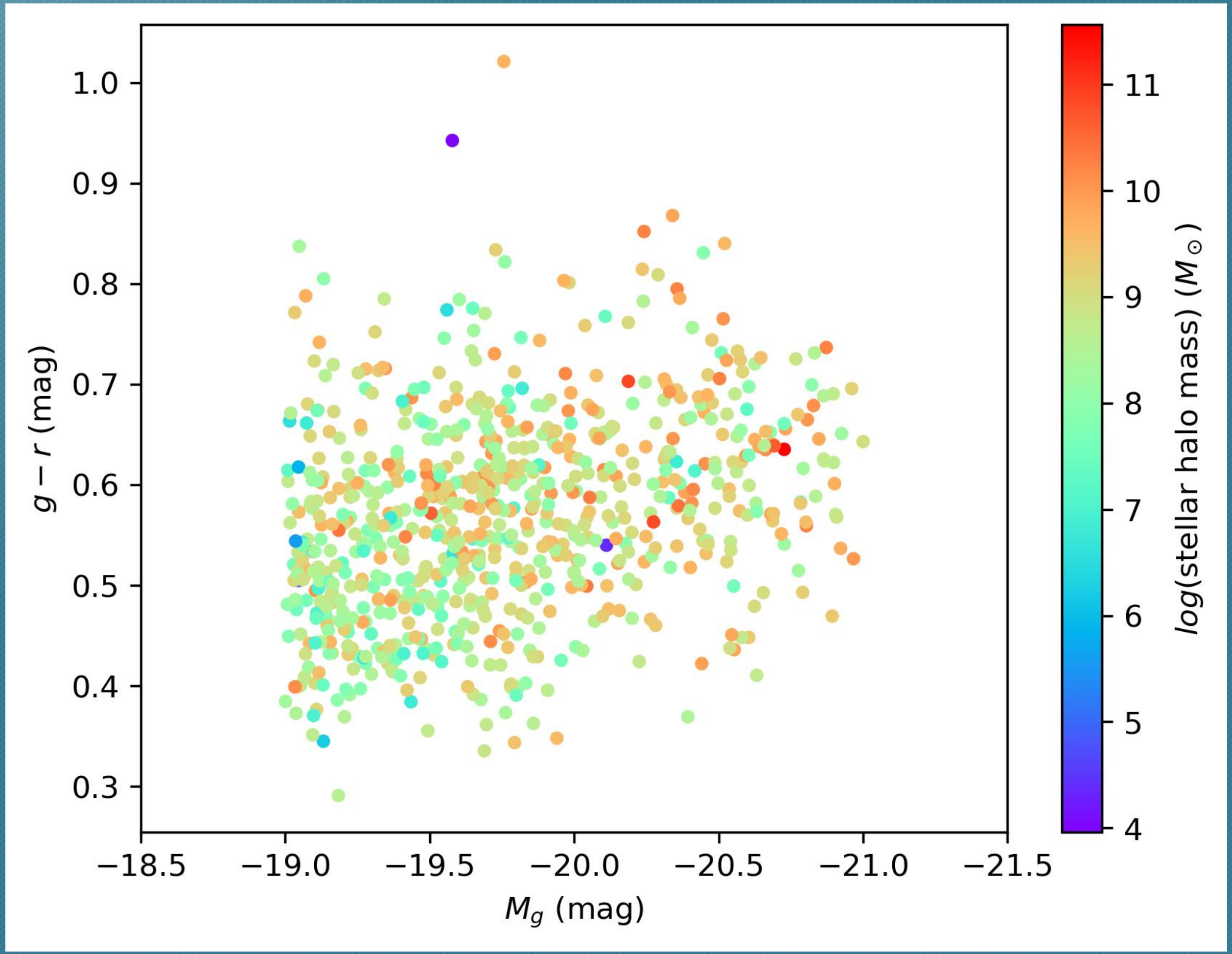

SGA MW-like galaxies
coco MW-like simulation
$4.17 \times 10^9 \sim 6.03 \times 10^9 L_\odot$
Galaxy Probability Density
log(stellar halo mass) ($M_\odot$)


SGA MW-like galaxies
coco MW-like simulation
$8.71 \times 10^9 \sim 1.26 \times 10^{10} L_\odot$
Galaxy Probability Density
log(stellar halo mass) ($M_\odot$)

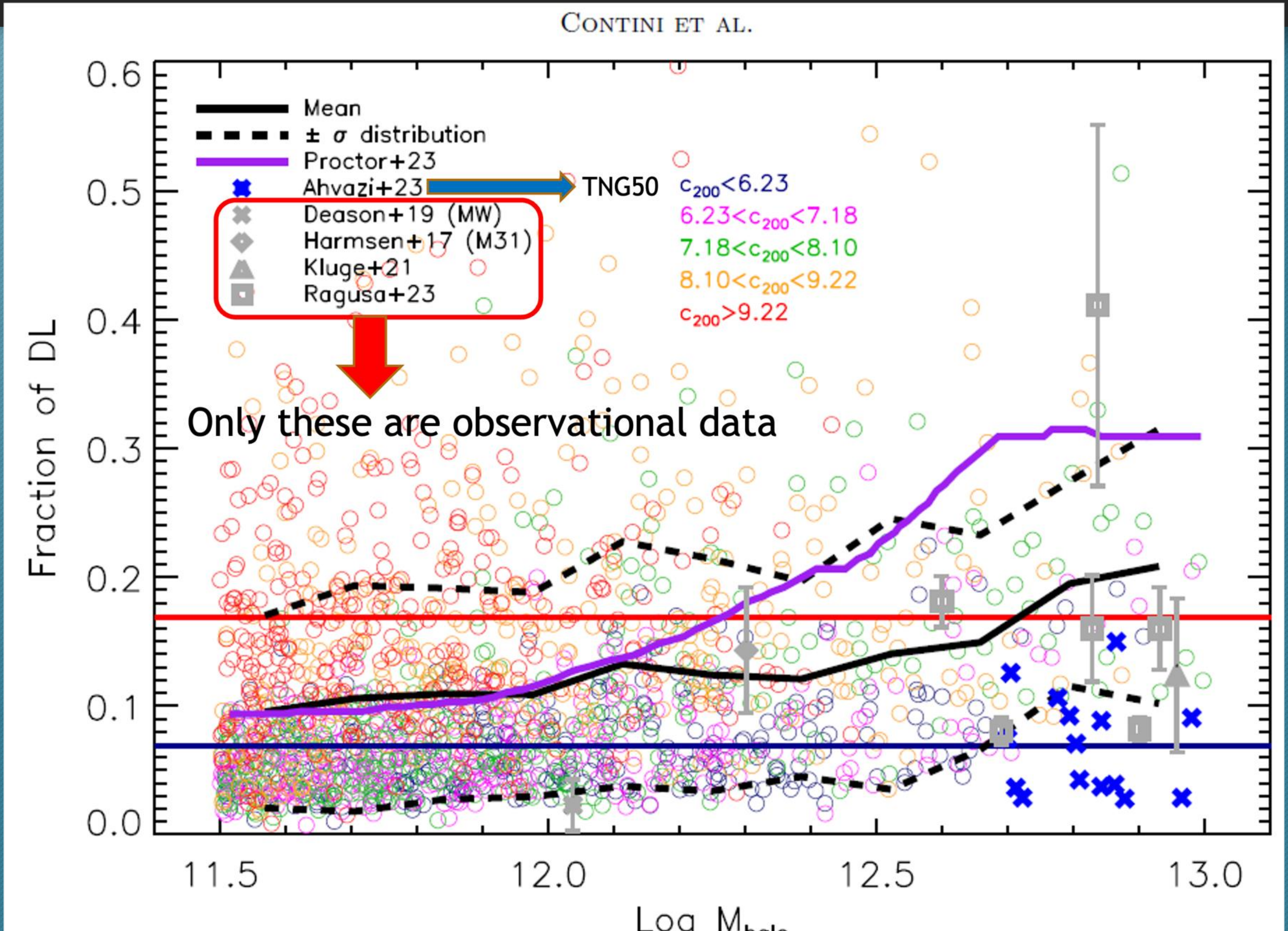

SGA MW-like galaxies
coco MW-like simulation
$1.82 \times 10^{10} \sim 2.63 \times 10^{10} L_\odot$
Galaxy Probability Density
log(stellar halo mass) ($M_\odot$)


SGA MW-like galaxies
coco MW-like simulation
$6.03 \times 10^9 \sim 8.71 \times 10^9 L_\odot$
Galaxy Probability Density
log(stellar halo mass) ($M_\odot$)

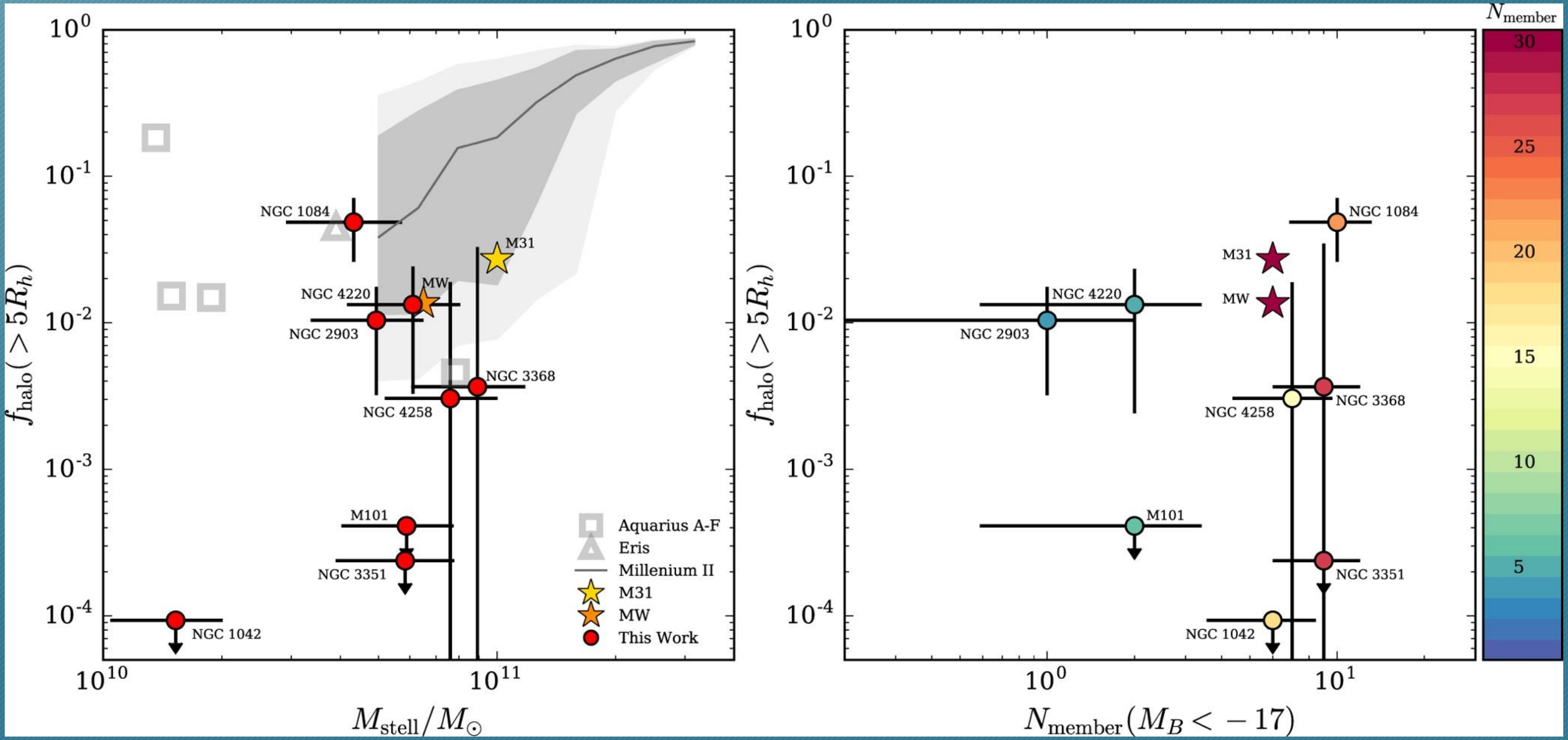

SGA MW-like galaxies
coco MW-like simulation
$1.26 \times 10^{10} \sim 1.82 \times 10^{10} L_\odot$
Galaxy Probability Density
log(stellar halo mass) ($M_\odot$)



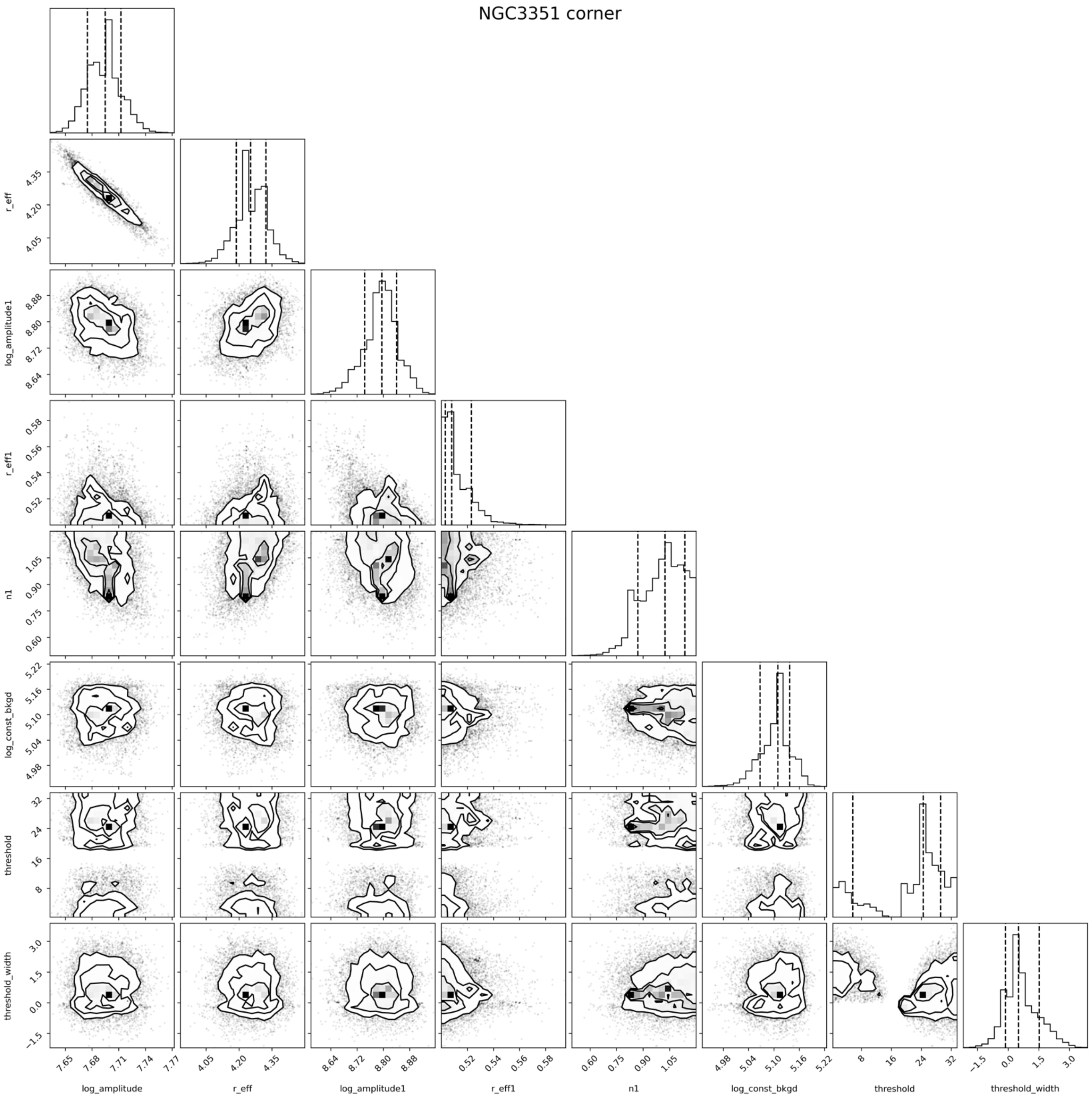
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
$g - r$ (mag)
−18.5
−19.0
−19.5
−20.0
−20.5
−21.0
−21.5
M_g (mag)
11
10
9
8
7
6
5
4
log(stellar halo mass) ($M_\odot$)



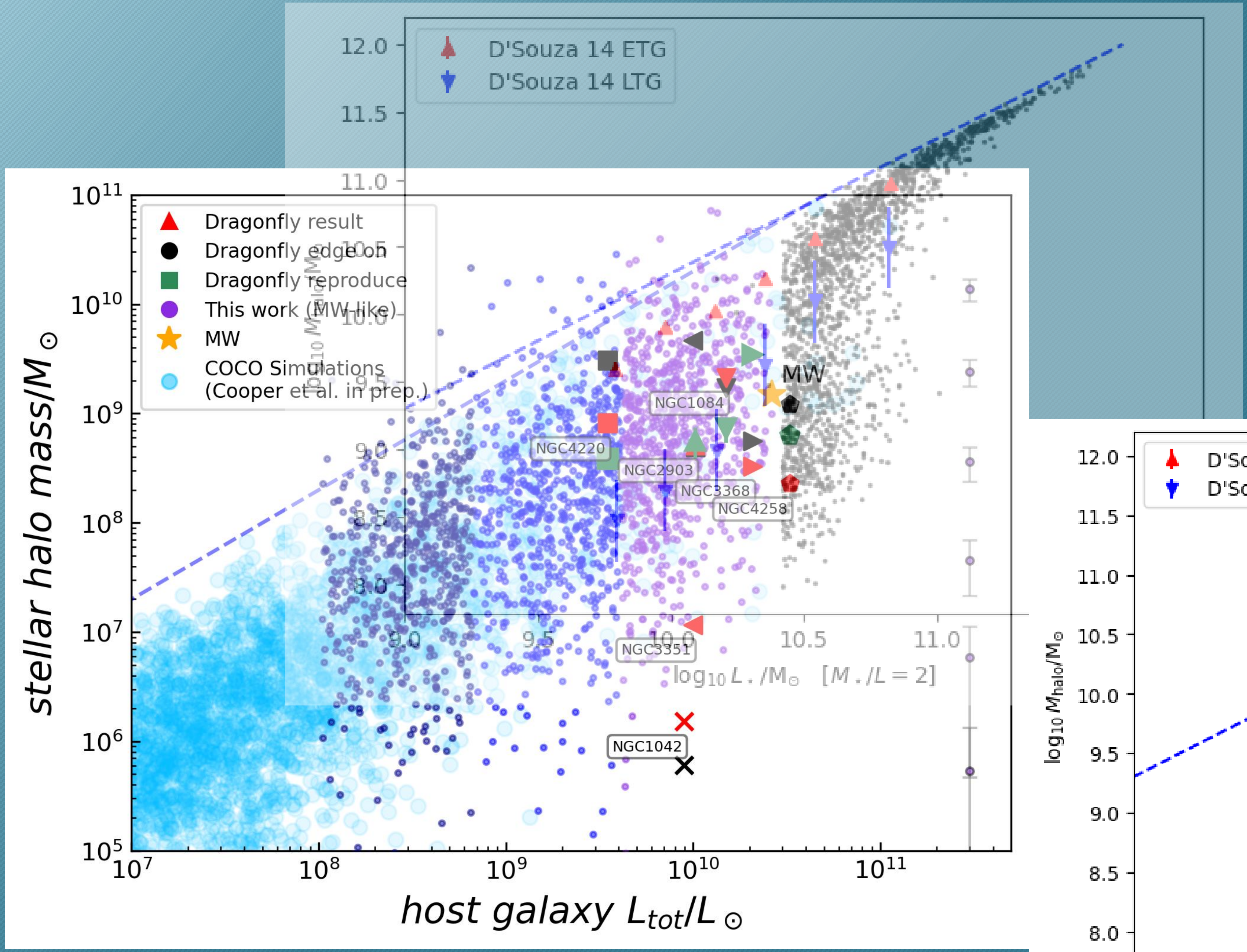
CONTINI ET AL.
Mean
± σ distribution
Proctor+23
Ahvazi+23
TNG50
$c_{200}<6.23$
$6.23<c_{200}<7.18$
$7.18<c_{200}<8.10$
$8.10<c_{200}<9.22$
$c_{200}>9.22$
Deason+19 (MW)
Harmsen+17 (M31)
Kluge+21
Ragusa+23
Only these are observational data
Fraction of DL
0.6
0.5
0.4
0.3
0.2
0.1
0.0
11.5
12.0
12.5
13.0

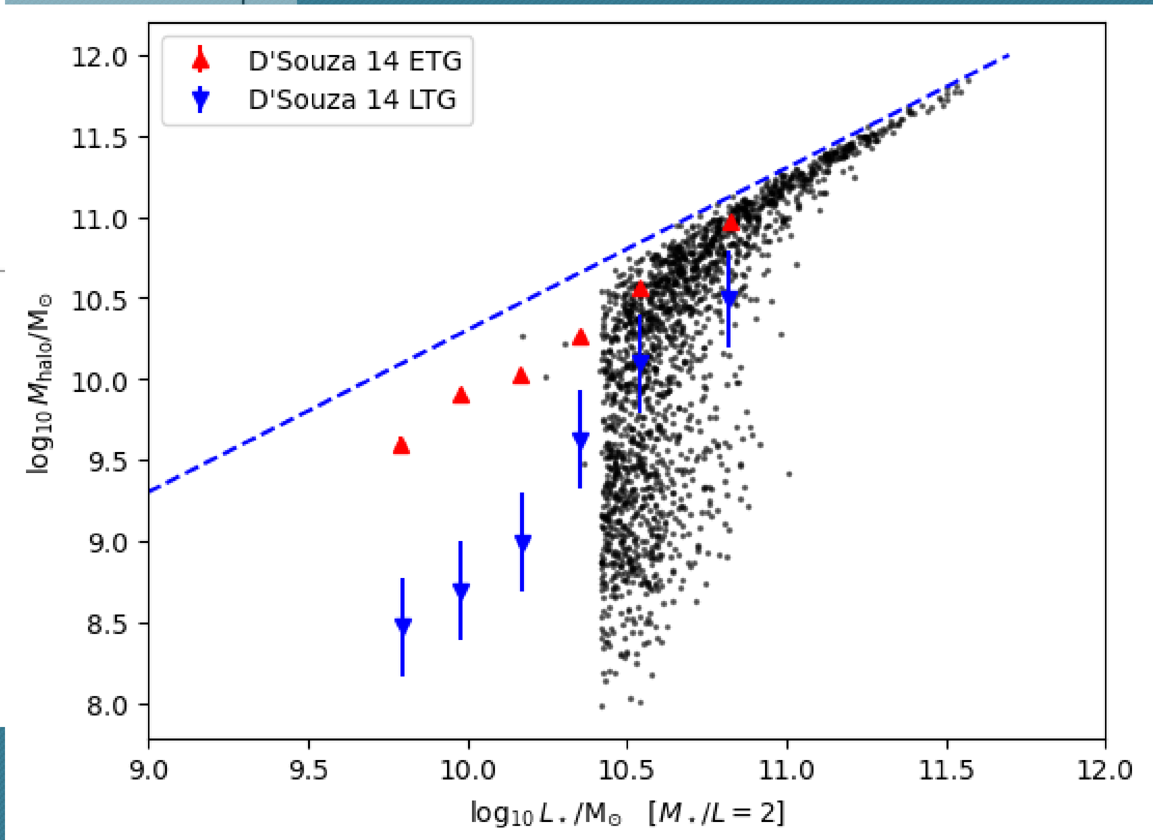


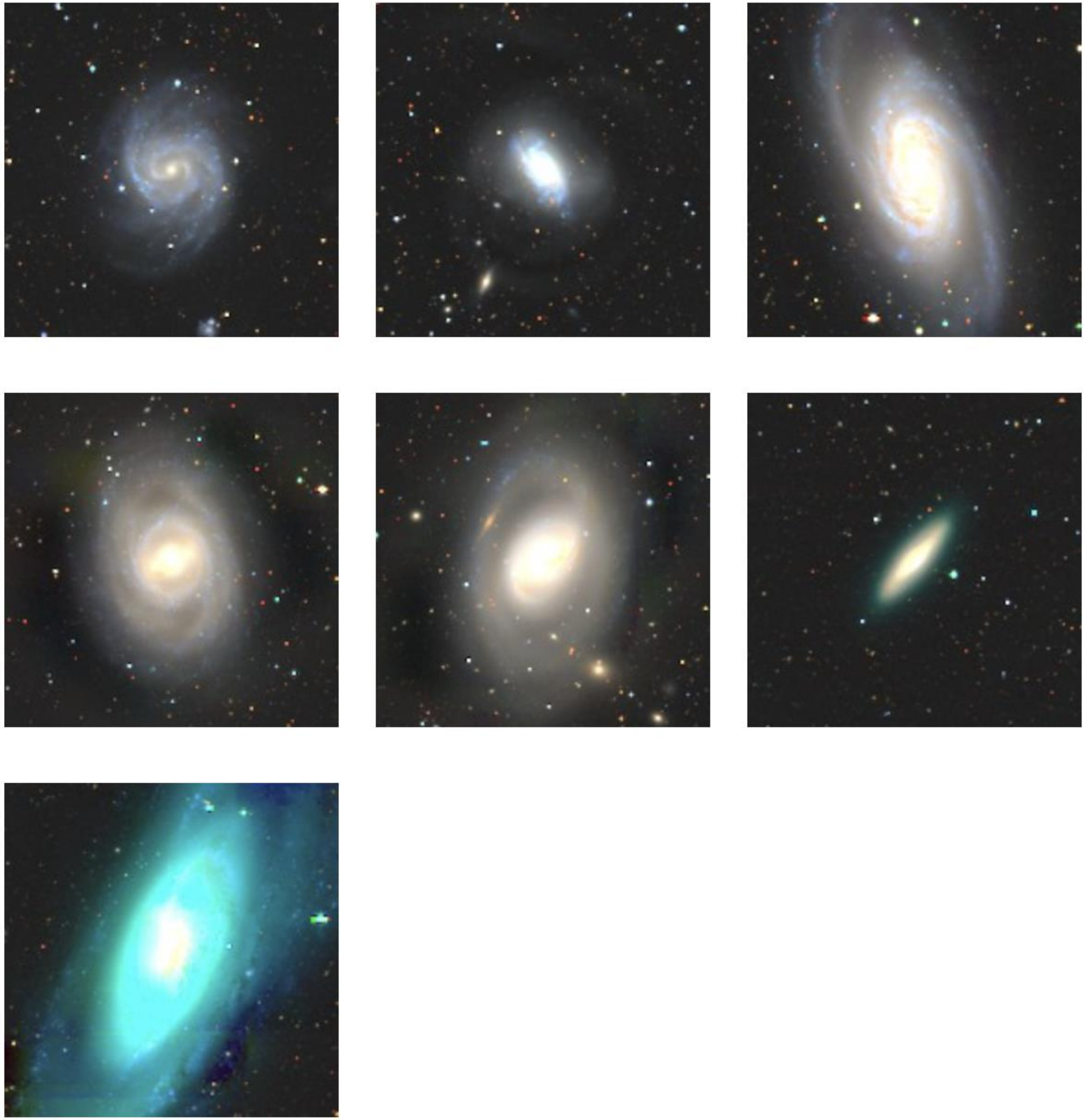
(Merritt et al. 2016)



NGC3351 corner
log_amplitude
r_eff
log_amplitude1
r_eff1
n1
log_const_bkgd
threshold
threshold_width


D'Souza 14 ETG
D'Souza 14 LTG
Dragonfly result
Dragonfly edge on
Dragonfly reproduce
This work (MW-like)
MW
COCO Simulations
(Cooper et al. in prep.)
NGC1084
NGC4220
NGC2903
NGC3368
NGC4258
NGC3351
NGC1042
stellar halo mass/$M_\odot$
host galaxy $L_{tot}/L_\odot$
$\log_{10} L_*/M_\odot$ $[M_*/L = 2]$


D'Souza 14 ETG
D'Souza 14 LTG
$\log_{10} M_{halo}/M_\odot$
$\log_{10} L_*/M_\odot$ $[M_*/L = 2]$



GALAXY	SGA_ID	RA_LEDA	DEC_LEDA
PGC025916	33675	137.915423	64.365986
UGC11127	50134	272.164709	28.060194
PGC172103	56543	6.909903	-8.171083
PGC011251	82857	44.609958	1.872194
PGC026688	105725	141.232349	19.140150
PGC130187	155329	37.968837	-42.757558
PGC016118	166931	72.475041	-10.754303
PGC067520	193265	328.027879	12.675640
PGC003435	244517	14.396245	-5.002481
PGC1062641	255409	143.441603	-4.118018
PGC026646	294501	141.057687	40.637466
PGC031815	338063	160.276754	-2.963694
UGC03581	354549	104.761500	80.003444
UGC04380	373558	126.132710	54.853871
PGC025834	375286	137.454931	19.857462