A Lonely Giant: The Sparse Satellite Population of M94 Challenges Galaxy Formation

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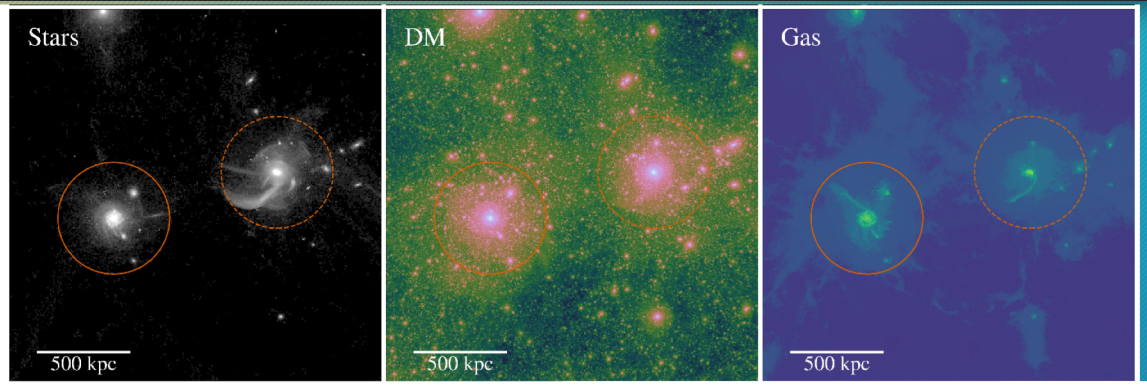
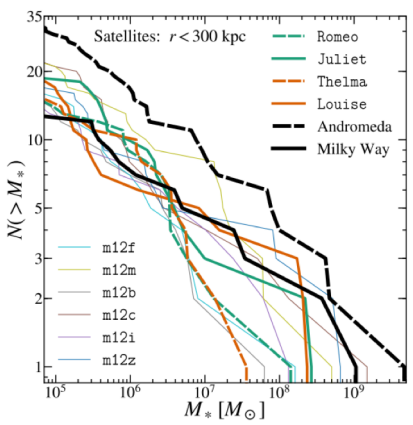
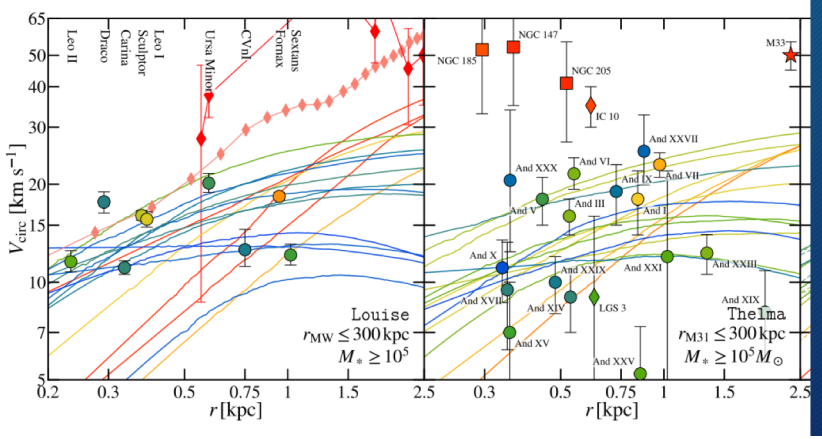
Reionization, feedback, tides can solve missing satellites and too big to fail. Were models ‘overfit’ to the LG?



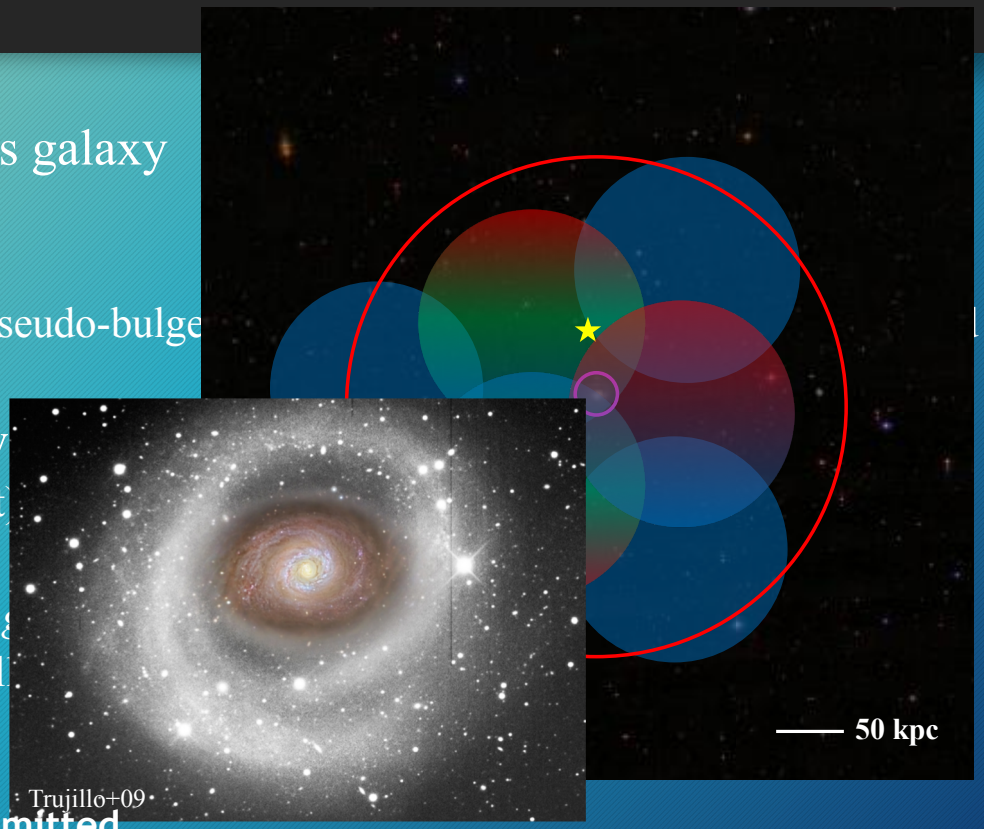
FIRE :
Garrison-Kimmell et al. 2018





We survey smaller areas than spectroscopic or integrated light searches in order to resolve RGB stars.

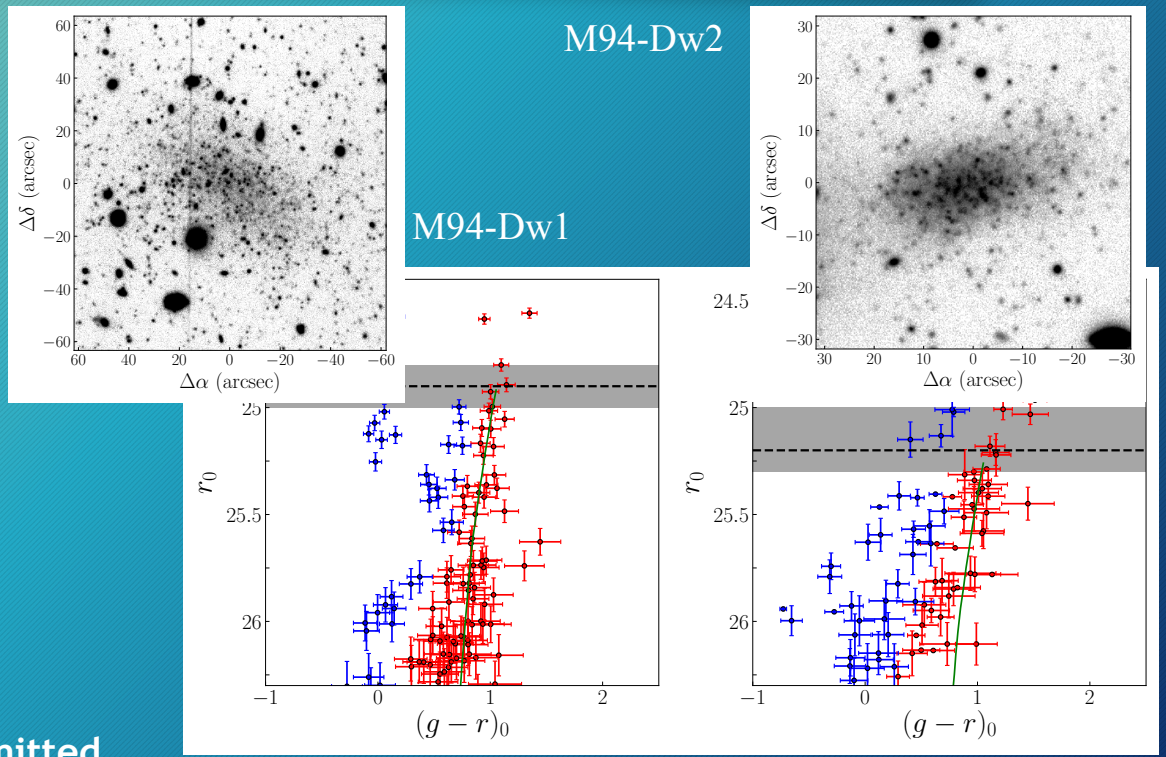
- M94: An isolated MW-mass galaxy
  - Mass: $M_* \sim 4 \times 10^{10}\, M_\odot$
  - Distance: 4.2 Mpc
  - Interesting features: Large pseudo-bulge
    spiral arms.
- 3 filters (*gri*), 6 pointings w
  - 2 *deep* pointings (2h/filter/pt
  - 4 shallower pointigs
  - ~150 kpc radial coverage in g
  - Discovered 2 low-mass satel



Smercina et al. 2018; ApJ, submitted

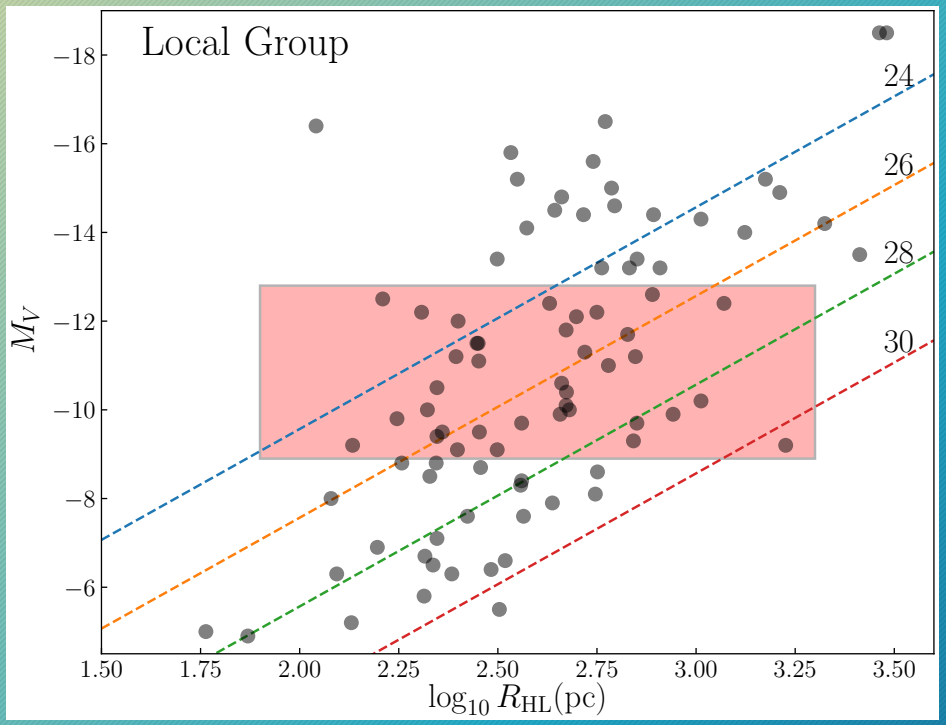
Visual inspection reveals two new M94 satellites with D~4.2 Mpc, M_V~-10, M* ~ $10^6 M_\odot$

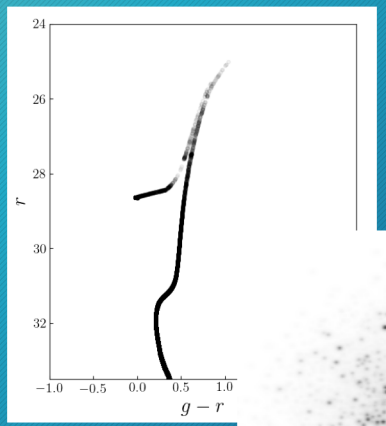
- M94-Dw1:
  - $M_* \sim 9.7\times10^5\, M_\odot$
  - $M_V = -10.1$
  - $\mu_V = 27.4$ mag arcsec^{-2}
  - $D_{\rm TRGB} = 4.1 \pm 0.6$ Mpc
  - $R_{\rm p} \sim 69$ kpc
- M94-Dw2:
  - $M_* \sim 6.7\times10^5\, M_\odot$
  - $M_V = -9.7$
  - $\mu_V = 26.4$ mag arcsec^{-2}
  - $D_{\rm TRGB} = 4.8 \pm 0.6$ Mpc
  - $R_{\rm p} \sim 38$ kpc

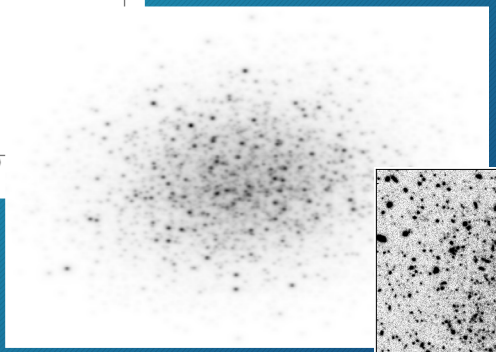


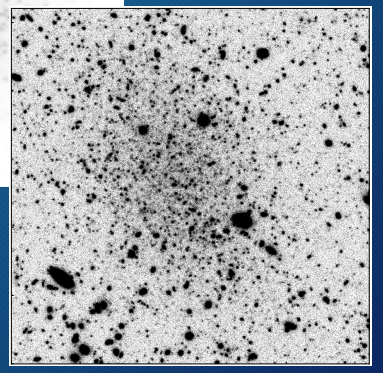
Smercina et al. 2018; ApJ, submitted

We quantify survey efficiency using simulations of dwarfs like similarly bright Local Group satellites.



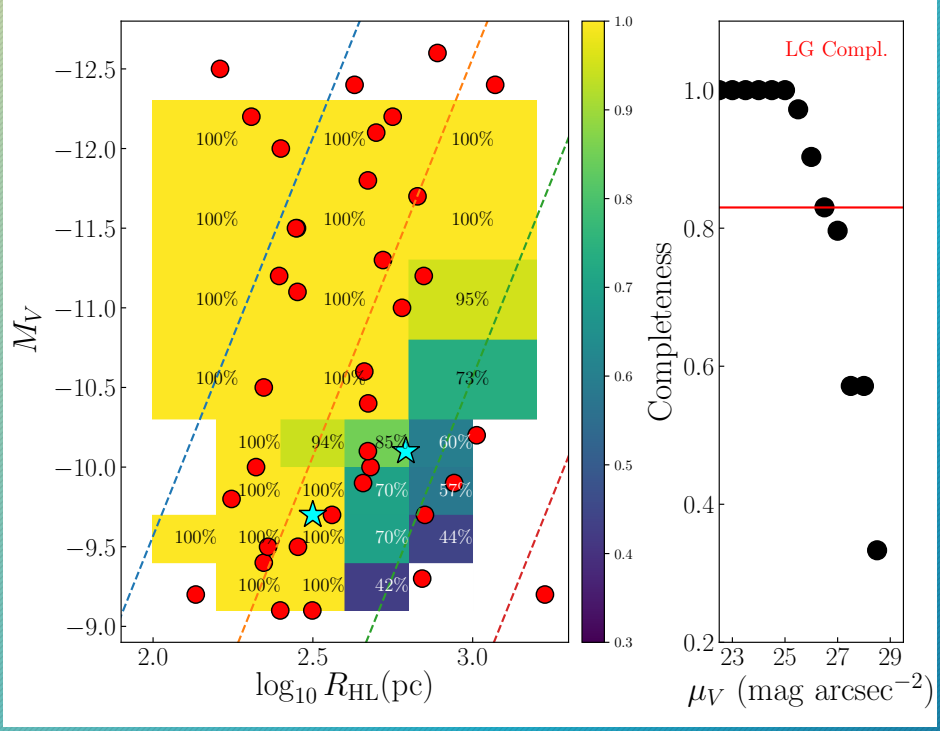






McConnachie 2012

Completeness varies primarily with surface brightness and implies M94 has two M_V<-9.1 satellites at r<150 kpc



- Completeness is ~smooth function of surface brightness
  - >99% complete for $M_V < -10.3$
  - 85% complete for LG satellites in test range
- 85% complete down to $M_V < -9.1$
  - $M_* \sim 4\times10^5\, M_\odot$

There are only 2 satellites >$4\times10^5\, M_\odot$!

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M94, with only 2 satellites within 150kpc, has a satellite system unlike any other Milky Way-mass galaxy

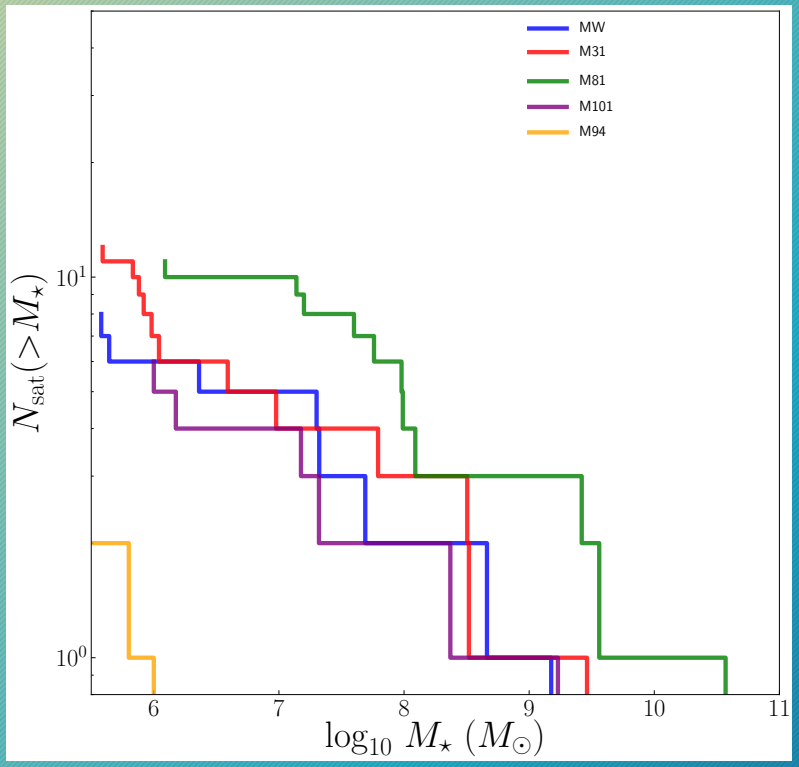


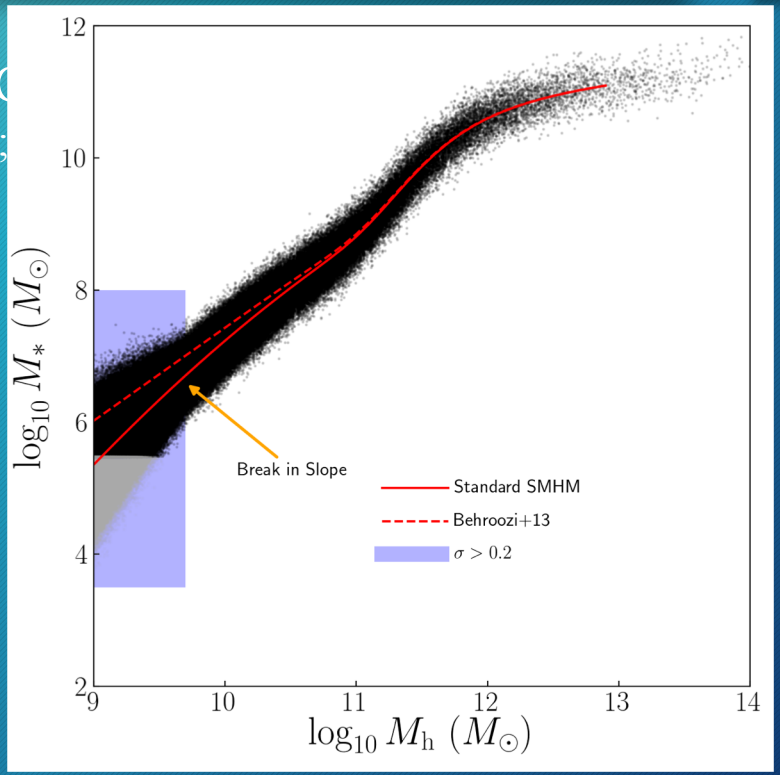
Figure: Satellite stellar mass functions for galaxies within 150 kpc projected distance from nearby MW-mass centrals.

Though this is a puzzle for (us) observers, is it a problem for galaxy formation models?

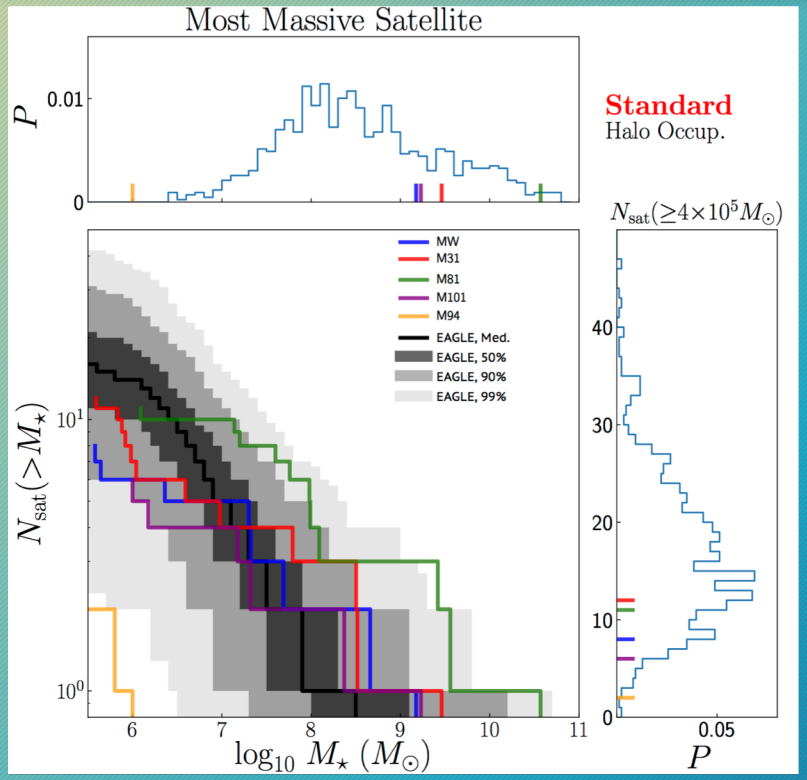
MW+M31: McConnachie 2012
M81: Karachentsev & Kudrya 2014
M101: Danieli et al. 2017
M94: Smercina et al. 2018

EAGLE permits modeling of Milky Way-mass central galaxies in a ‘Standard’ Halo Occupation Context

- Take all halos with $M_h > 10^9\ M_\odot$ from EAG
  - Pros: diverse population of MW-mass centrals; realistic tidal field from galaxies.
- Adopt a ‘standard’ halo occupation model.
  - Behroozi+13 + Munshi+17
  - Populate halos with galaxies.
- Identify ‘MW-mass galaxies’ as:
  - $6\times10^{11}\ M_\odot < M_h < 3\times10^{12}\ M_\odot$
  - $M_* > 4\times10^{10}\ M_\odot$
- Identify ‘satellites’ as:
  - ≤150 kpc in projection (X & Y)
  - ≤1 Mpc ΔZ (LOS)

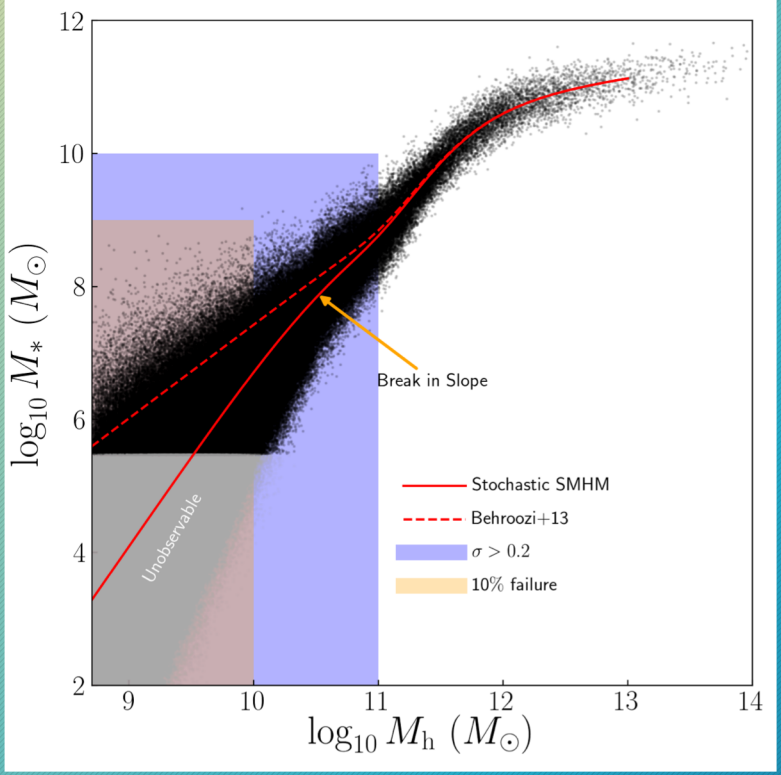


A group like M94 is very unlikely in a 'Standard' Halo Occupation Context



- M94 is *very* unlikely
  - <0.2% of MW-analogs in EAGLE have ≤2 satellites with $M_* \geq 4\times10^5\, M_\odot$
    → <1% in a sample of 5
  - *No systems* host a most massive satellite with $M_* \leq 2\times10^6\, M_\odot$
- Shape of $N_{\rm sat}$ distribution doesn't match known galaxies well.
  - $N_{\rm sat}(\geq 4\times10^5\, M_\odot) = 9 \pm 3$ for 4 known galaxies
  - $\langle N_{\rm sat} \rangle \sim 15$ for galaxies in 'standard' model

We explore a ‘Stochastic’ abundance matching model, and…



- Steeper low-mass slope
  - $\alpha \sim -3$
- *Drastically* increase scatter.
  - ~1 dex for $M_{\rm h} = 10^9\ M_\odot$
- Increased scatter *up to* $M_h = 10^{11}\ M_\odot$
  - An OOM larger than the TBTF mass.
- 10% probability of total galaxy failure for $M_{\rm h} < 10^{10}\ M_\odot$

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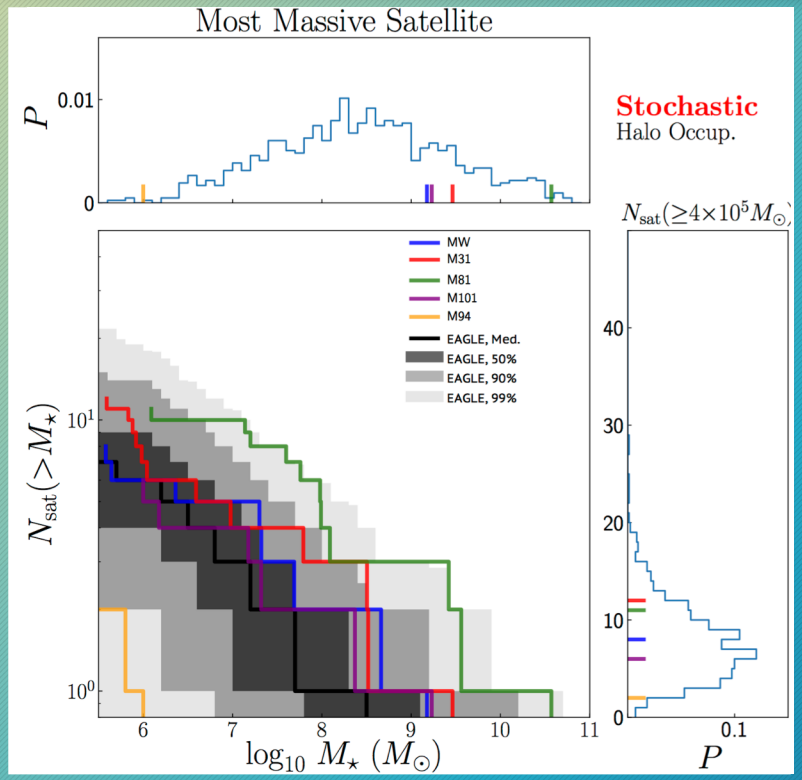
A ‘Stochastic’ abundance matching prescription increases the chances of finding a M94-like system to >~20%



- >5% probability of $N_{\rm sat} \leq 2$
  - →>20% chance in a sample of 5
- ~0.5% probability of most massive satellite $M_* \lesssim 10^6\, M_\odot$
  - Not great, but *better*.
- Shape of distribution correctly spans 5 known galaxies.

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M94's sparse satellite system suggests large scatter in stellar content of even 10^{10} - 10^{11} $M_{\odot}$ halos.

- The MW-mass galaxy M94 hosts only 2 low-mass satellites within 150 kpc, with *no massive companions*.
- This satellite population is in tension with current 'standard' models of dark matter halo occupation.
- In order to alleviate the tension, galaxy formation must be much more stochastic than is currently predicted.
  - Including halos thought to be too massive to suffer from increased stochasticity in hydrodynamic simulations.

This **'Lonely Giant'** advocates for significant modifications to ideas about how low-mass galaxies form.