Title: Understanding Dwarf Galaxy Evolution to understand Dark Matter

Speakers: Ferah Munshi

Series: Cosmology & Gravitation

Date: October 24, 2023 - 11:00 AM

URL: https://pirsa.org/23100108

Abstract: Low mass galaxies challenge our picture of galaxy formation and are an intriguing laboratory for the study of star formation, feedback and dark matter physics. I will present results from high resolution, cosmological simulations that contain many (isolated) dwarf galaxies [the MARVEL dwarfs] as well as satellite dwarf galaxies [the DC Justice League]. Together, they create the largest collection of high-resolution simulated dwarf galaxies to date and the first flagship suite to resolve ultra-faint dwarf galaxies in multiple environments. This sample spans a wide range of physical (stellar and halo mass), and evolutionary properties (merger history). I will present results and predictions constraining star formation, feedback and dark matter physics soon testable by telescopes like JWST, Rubin's LSST and the Roman Space Telescope. Finally, I will present new work on measuring galaxy shapes and the diversity of rotation curves in the dwarf galaxy mass regime which may be used to distinguish dark matter model.

Zoom link: https://pitp.zoom.us/j/99038411436?pwd=OFd1SEdUUXJkd0NLeWtrTUxGR0FCUT09

Understanding Dwarf Galaxy Evolution to Understand Dark Matter

THE N-BODY SHOP

@theNbodyShop
nbody.shop

GEORGE MASON UNIVERSITY

PI PERIMETER INSTITUTE

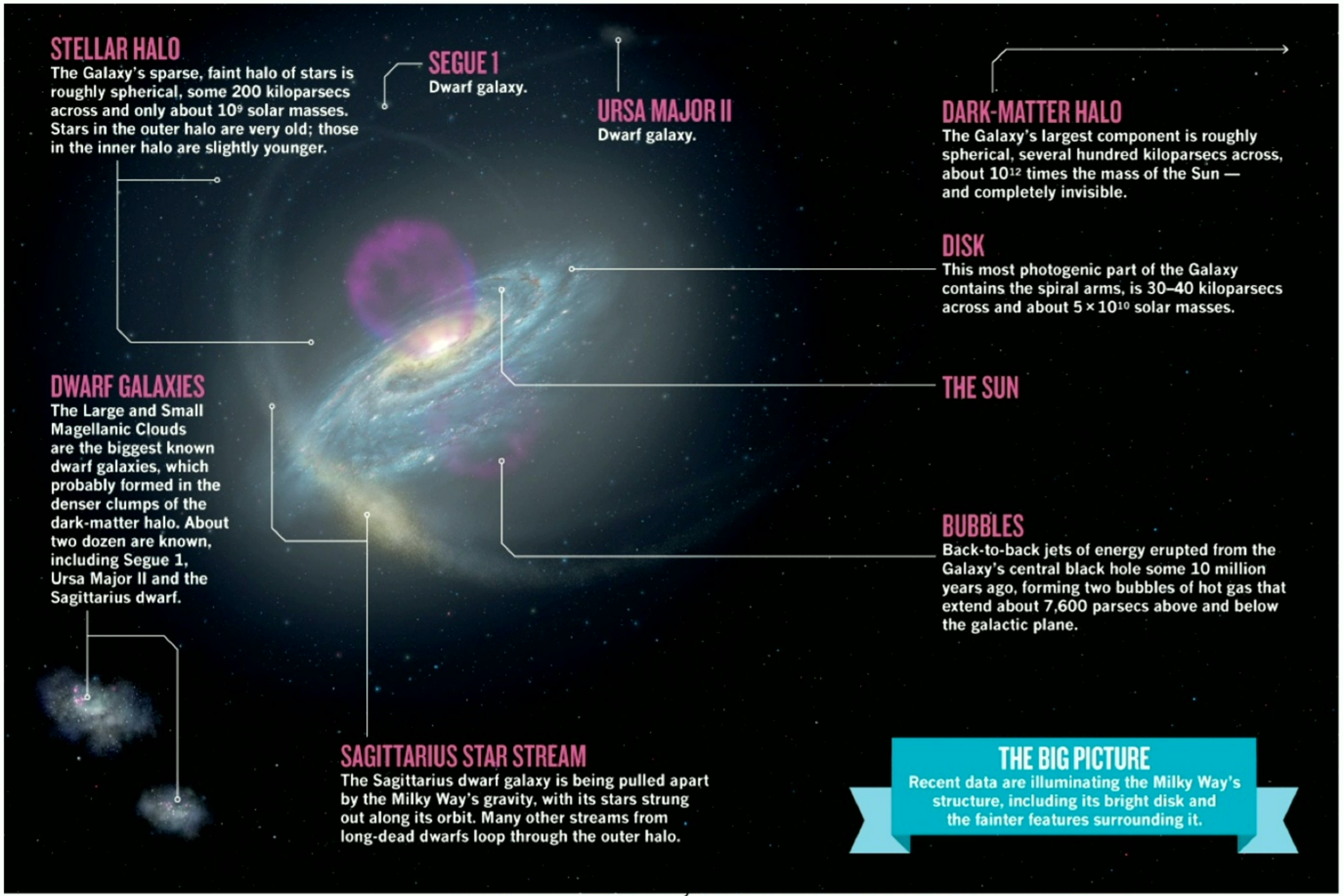
Ferah Munshi

Assistant Professor, George Mason University
Simons Emmy Noether Fellow, Perimeter Institute

In collaboration with: Alyson Brooks (Rutgers), Jillian Bellovary (QCC/AMNH), Kelly Holley-Bockelmann (Vanderbilt), Charlotte Christensen (Grinnell), Ben Keller (Memphis) + UW N-body Shop
Student work highlighted: *Claire Riggs* (OU—>Rutgers), Elaad Applebaum (Rutgers—>data science), Jordan Van Nest (OU), *Bianca Azartash*(OU), *Anna Engelhardt* (GMU)

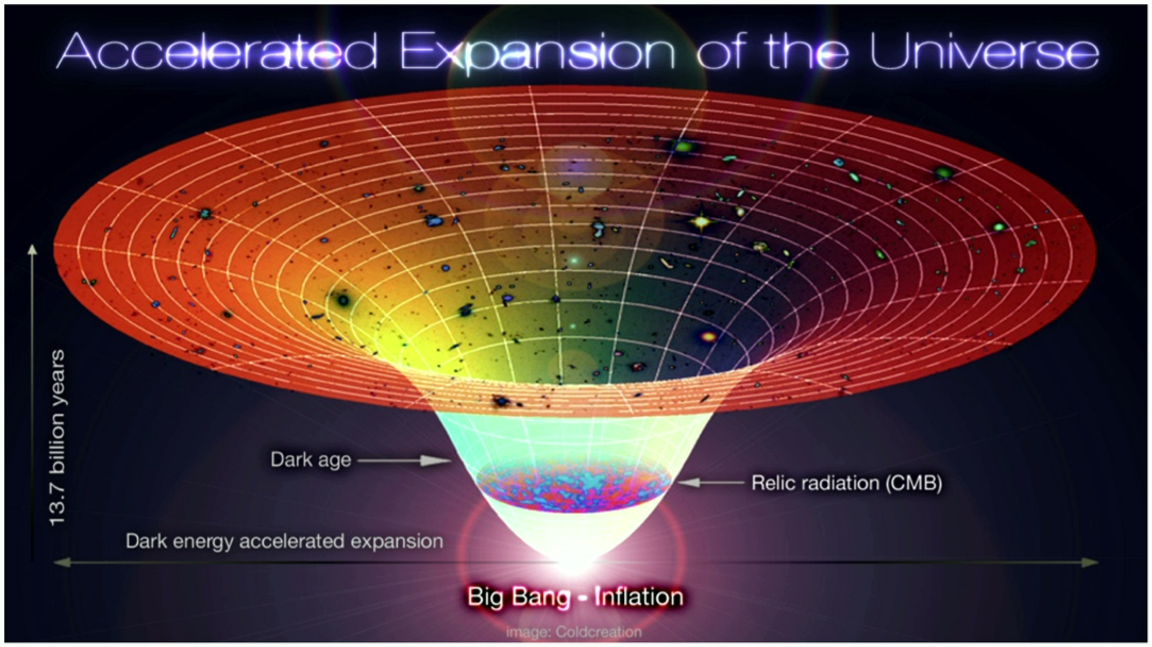
Perimeter Institute 10/24/2023 fmunshi@gmu.edu

Galaxies are collections of stars, gas ("baryons") and dark matter



http://www.nature.com/news/galaxy-formation-the-new-milky-way-1.11517

What is (L)CDM?



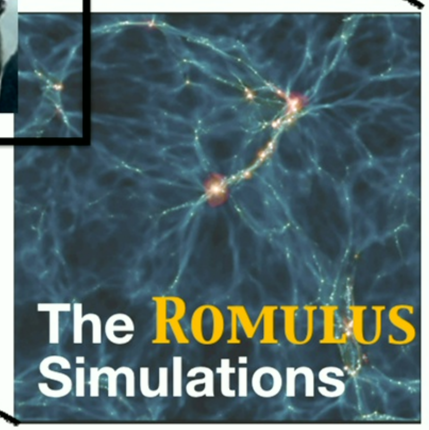
- **Non-baryonic**= made up of matter other than protons, neutrons
- **Cold**= velocity far less than the speed of light (slow)
- **Dissipationless**= cannot cool via radiation
- **Collisionless**= particles interact via gravity

Simple model with a few assumptions that describes many scales- from large scale structure to individual galaxies- "self-similar" across scales

In the N-body Shop, there's been an explosion of dwarf galaxy simulations

Ultra-faints in isolation

Ultra-faints in the vicinity of a MW

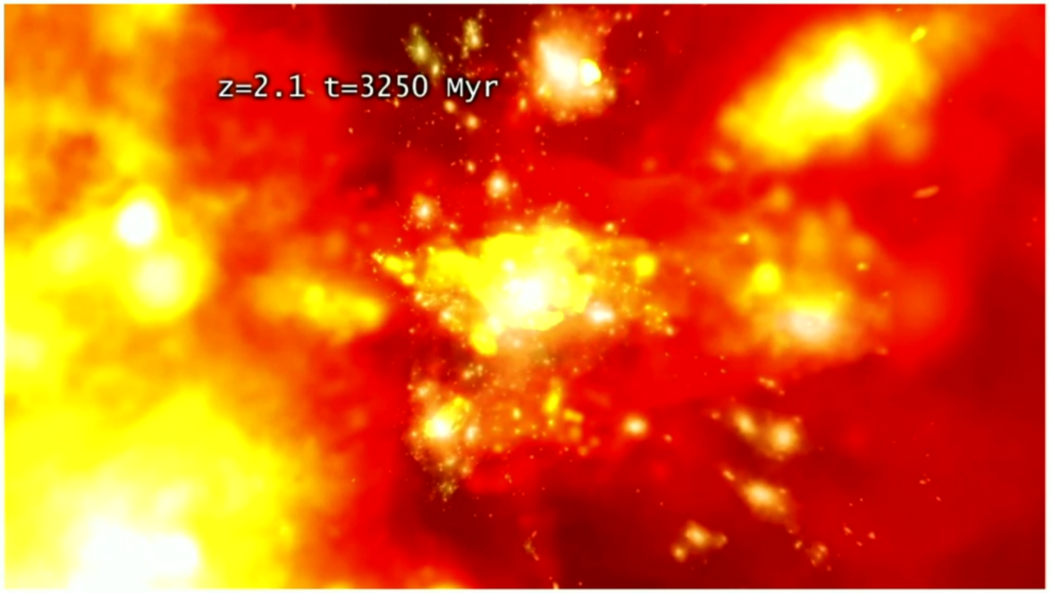


Dwarfs (and UDGs) across environments

MARVELous Dwarf Volumes + Justice League Dwarfs = **211 High-resolution simulated dwarfs**

In mass, the majority of a galaxy is dark matter; dwarfs are ***dominated*** by dark matter

FEEDBACK (baryonic physics/galaxy formation) can imprint its affects on all three components



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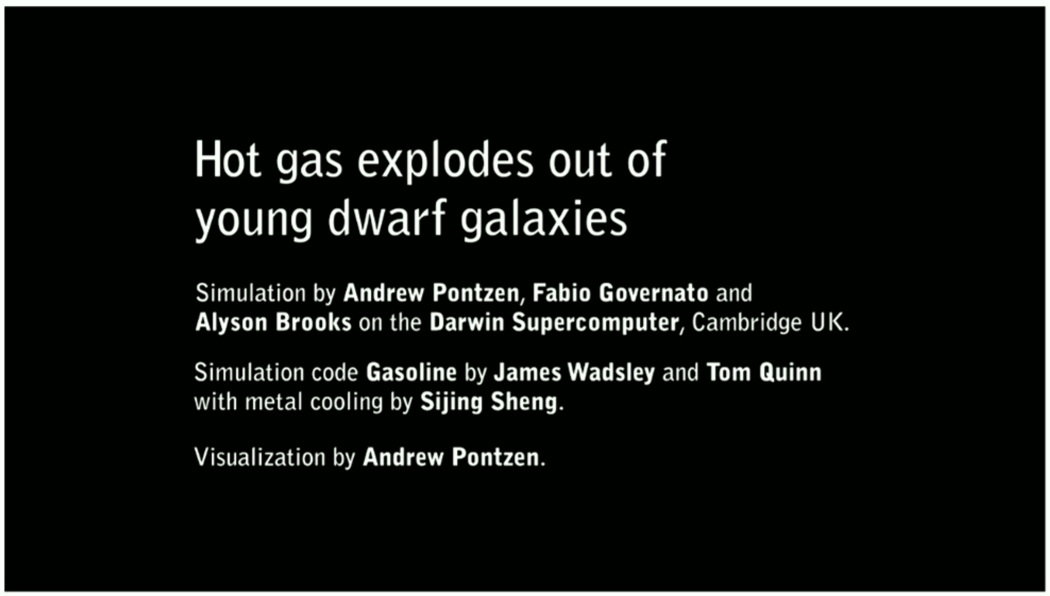
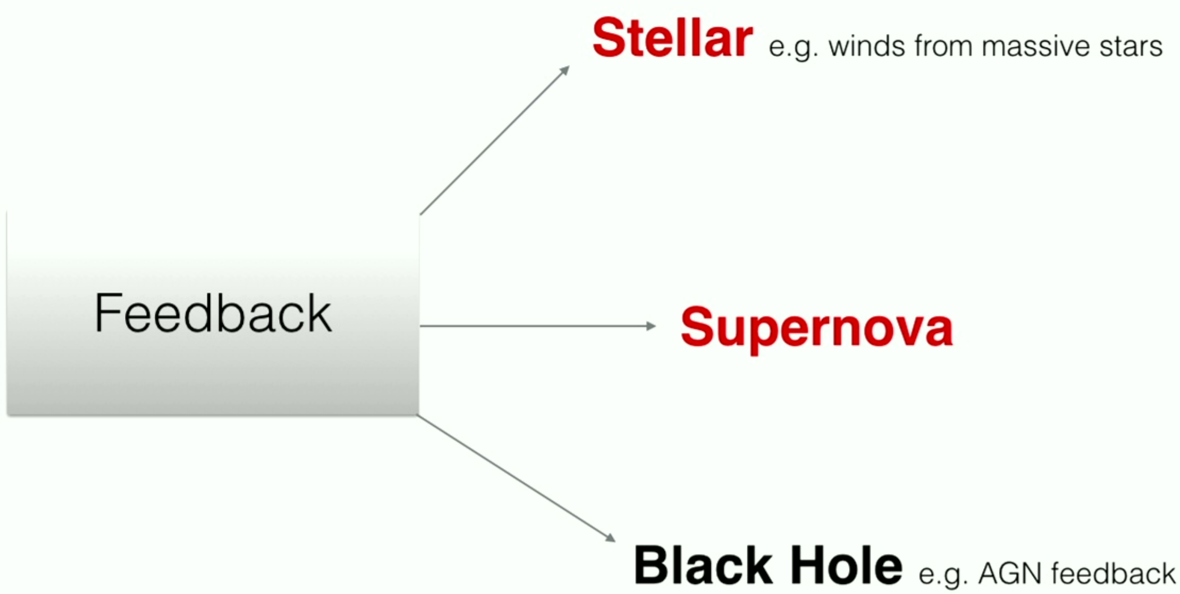


Feedback is necessary to form realistic* galaxies.

*realistic= look like observed galaxies in basic properties



Depending on mass of galaxy, different sources have varying importance

Dwarf galaxies are though to challenge the accepted paradigm for dark matter: cold dark matter (CDM).

“small-scale challenges to CDM”

There is No Small Scale “Crisis” for CDM

CDM= cold dark matter, WDM= warm dark matter, SIDM= self-interacting dark matter

“challenge”	CDM+ baryons	WDM	SIDM	
Bulge-less disk galaxies	✓			Governato+ 2010; Brook+ 2011
The Cusp/Core Problem	✓		✓	Pontzen & Governato+ 2012; Chan+ 2015
Too Big to Fail	✓	✓	✓	Zolotov+ 2012; Garrison-Kimmel+ 2015
Missing Satellites	✓	✓		Brooks+ 2013; Buck+ 2019
Missing Dwarfs	✓	✓	✓	Maccio+ 2016; Brooks+ 2017
Diversity	✓?		✓	Santos-Santos+ 2018; Munshi+ 2021
Planes of Satellites	Still to be explored/contentious			Buck+ 2016; Ahmed+ 2017

**Scorecard adapted from A. Brooks

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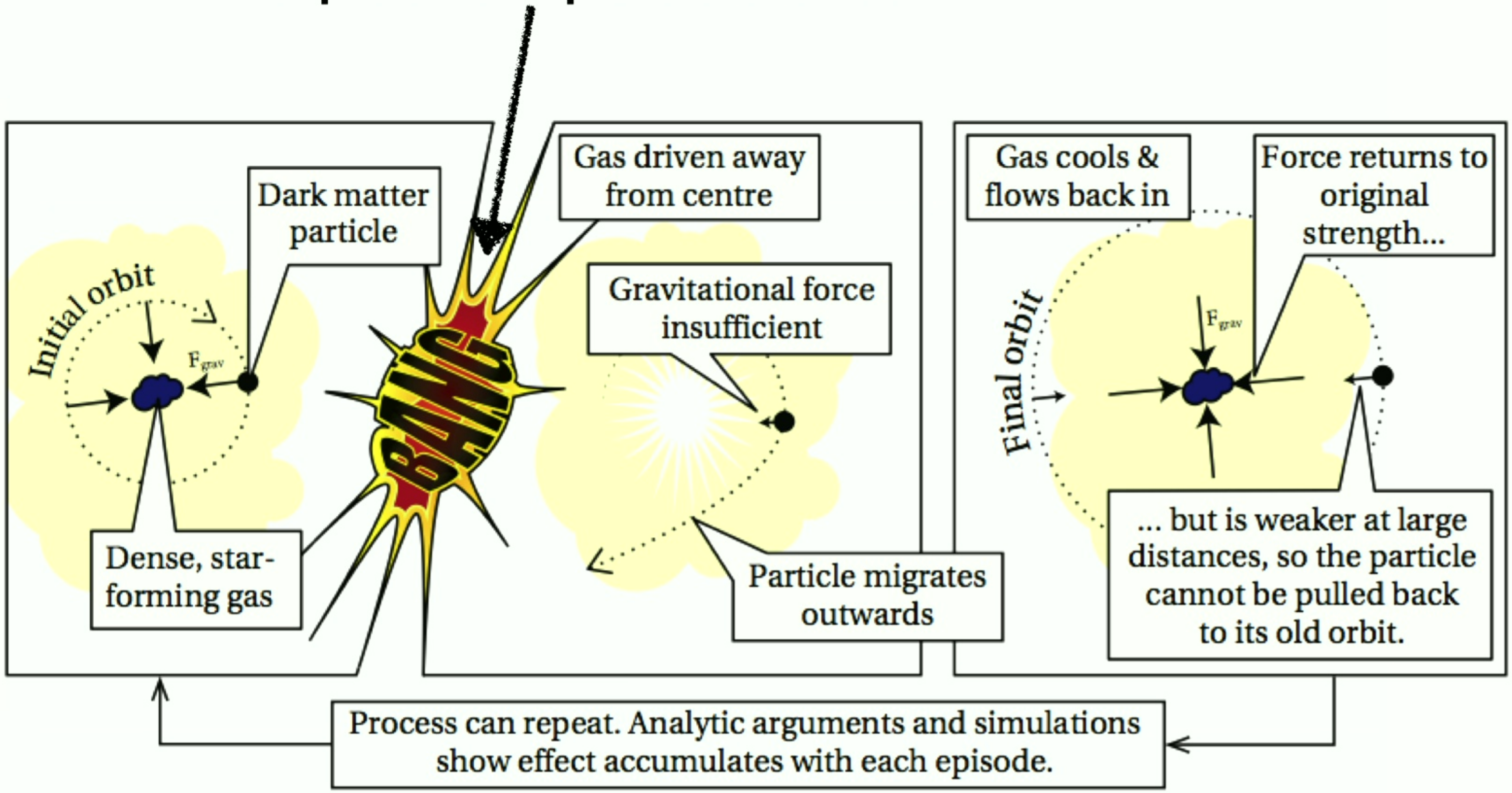
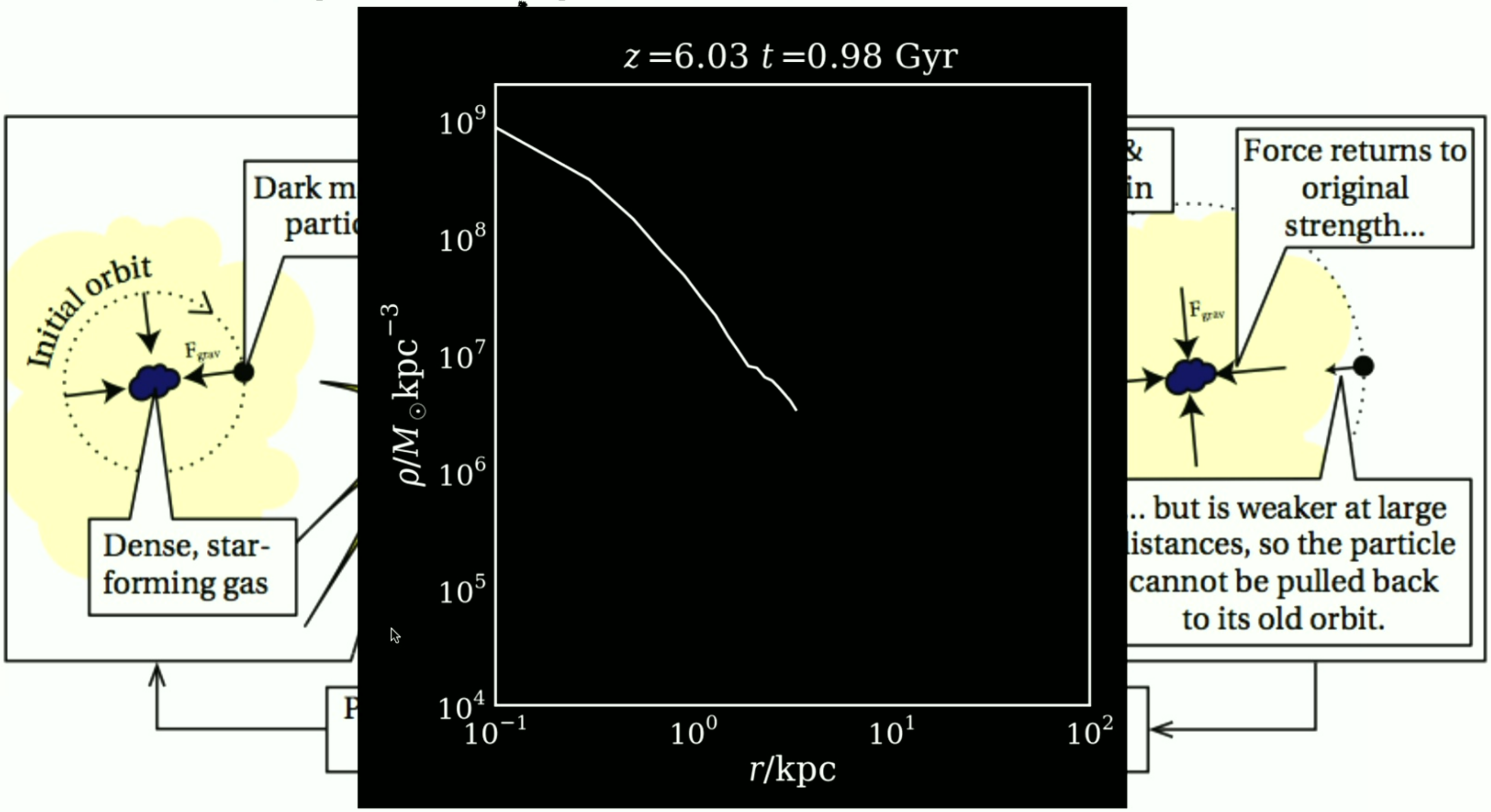
Supernova explosion/feedback



Pontzen & Governato 2012 & 2014

Supernova explosion/feedback

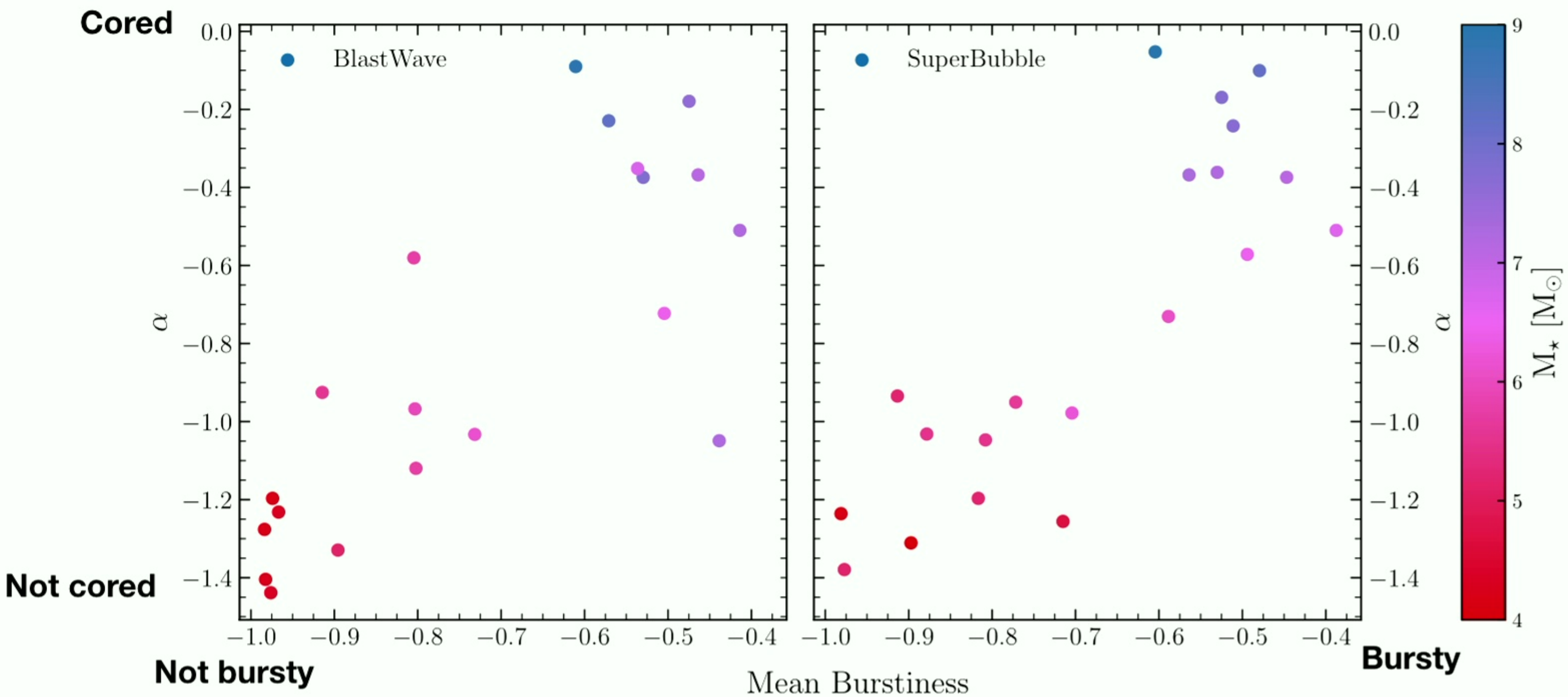


Pontzen & Governato 2012 & 2014

Repeated feedback events => flattening of DM core

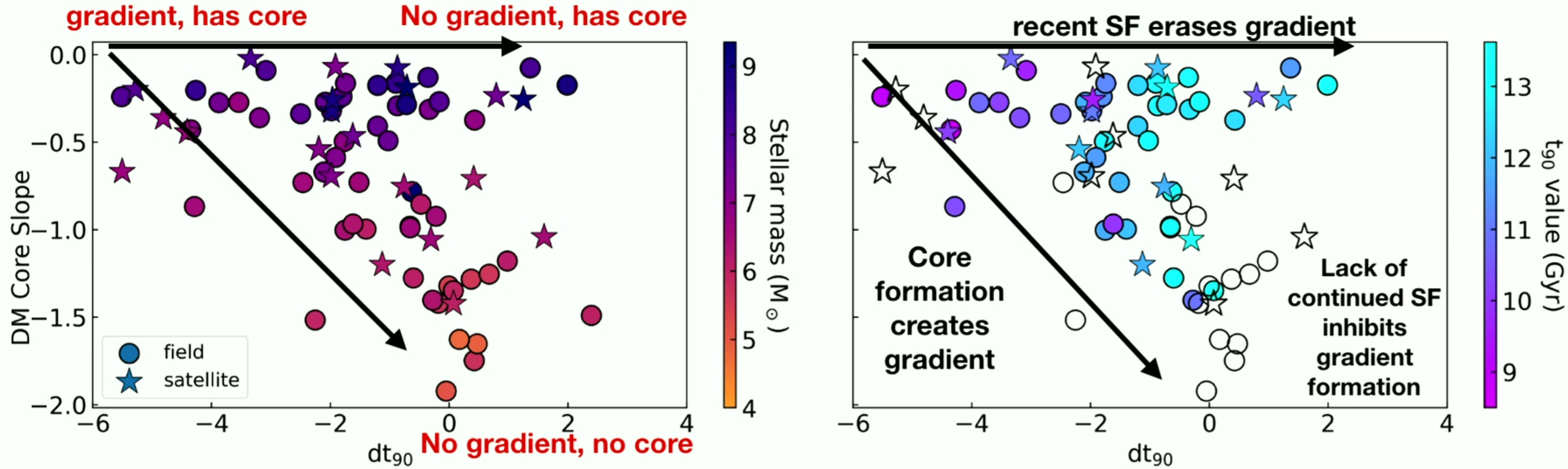
Does average burstiness of star formation history (SFH) correlate with DM slope?

Yes, if you consider all of cosmic history; depends on feedback model



Results from OU grad Bianca Azartash and GMU grad Anna Engelhardt

Relation to Age Gradients in Dwarfs?



Core formation is the result of continued bursty SF. This drives age gradients in dwarf galaxies. However, dwarfs with **recent** SF can have their age gradients erased, despite having a core.

Lack of age gradient does not mean the galaxy does not have a core

See also Graus+ 2019, El-Badry 2016

Comparison to obs, metallicity gradients in: Taibi+ 2022

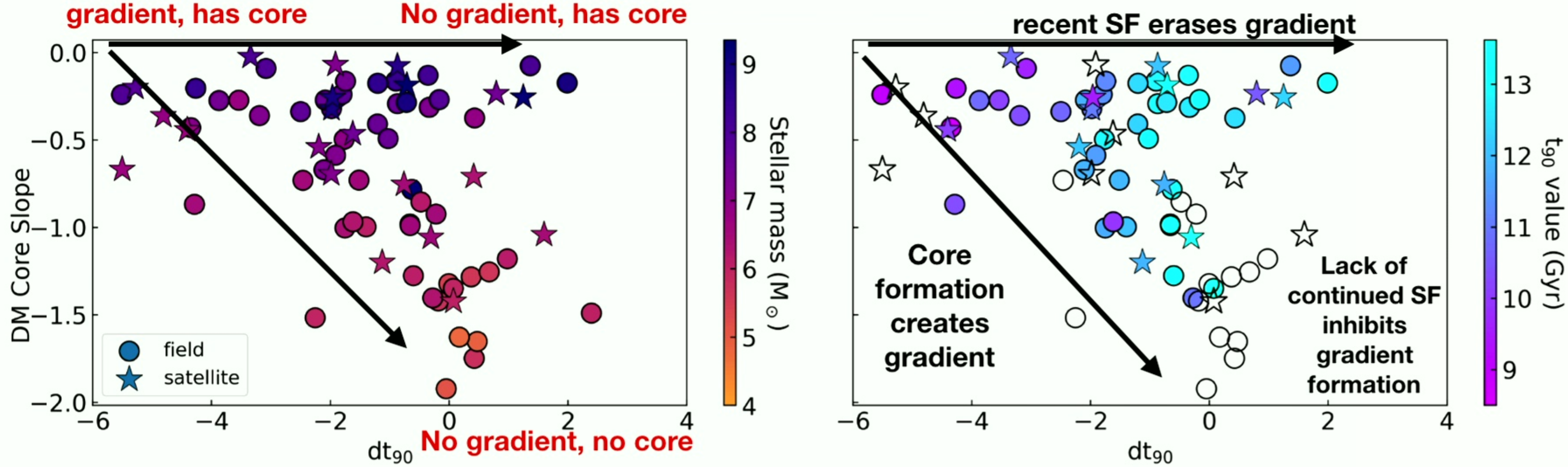
Riggs, Munshi & Brooks, in-prep

Key Problems

Can we continue to understand the formation and evolution of dwarf galaxies in a vanilla CDM + baryons model?

With baryons, many DM models can solve all the problems. Can we find a way to distinguish them?

Relation to Age Gradients in Dwarfs?



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Key Problem #1

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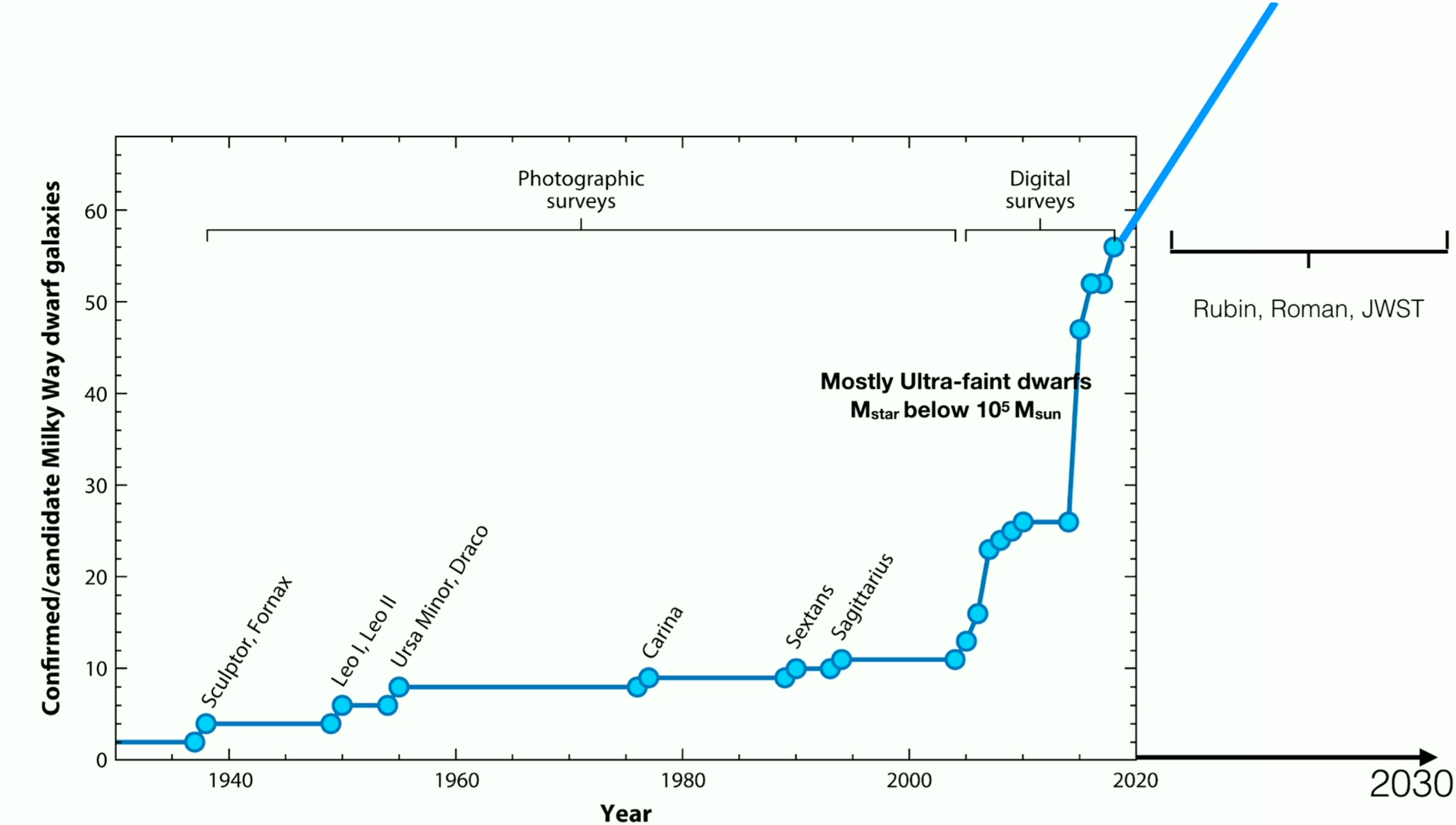

Photographic surveys
Digital surveys
Rubin, Roman, JWST
Mostly Ultra-faint dwarfs
M_{star} below 10^5 M_{sun}
Sculptor, Fornax
Leo I, Leo II
Ursa Minor, Draco
Carina
Sextans
Sagittarius
Confirmed/candidate Milky Way dwarf galaxies
0
10
20
30
40
50
60
1940
1960
1980
2000
2020
2030
Year

It is commonly assumed that ultra-faint dwarfs are "simple" systems

- They're old- reionization truncated their star formation
- The least massive/faintest live in the least massive dark matter halos, but they are extremely dark matter dominated.
- Their abundance can tell us something about dark matter- the smallest halo that can host a galaxy depends on DM model

Astrophysical constraints on dark matter: the importance of UFDs

If galaxies in this mass range are observed to have large cores, then maybe something beyond CDM is necessary

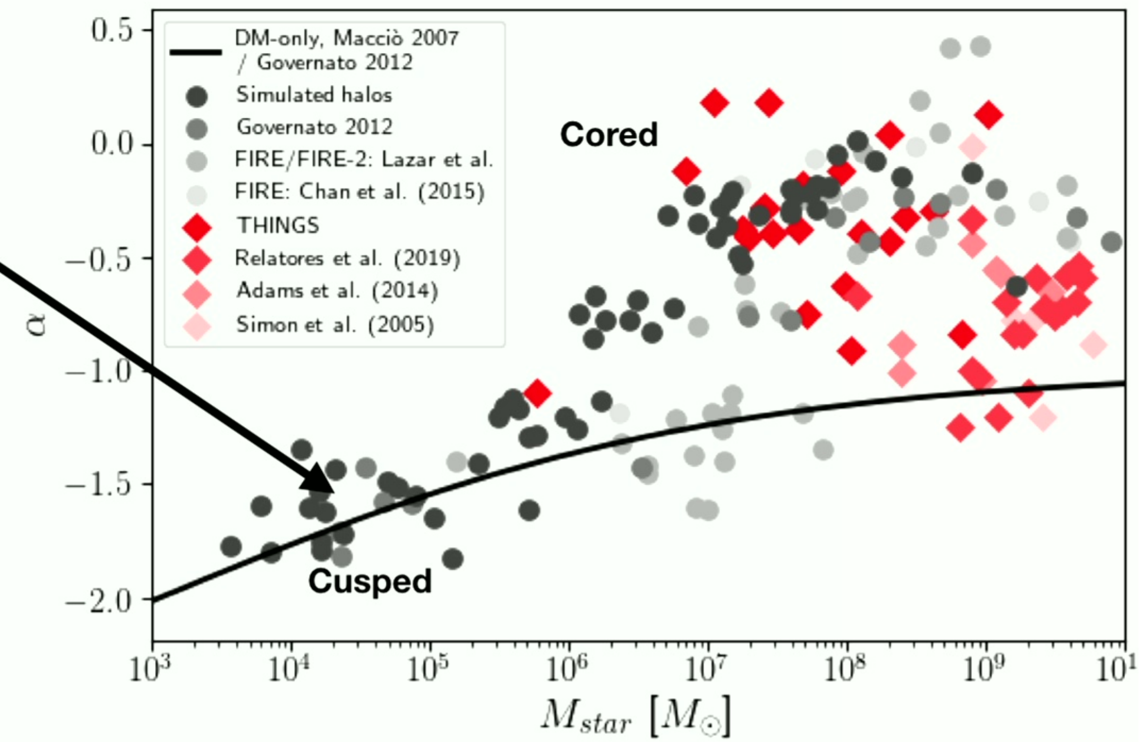
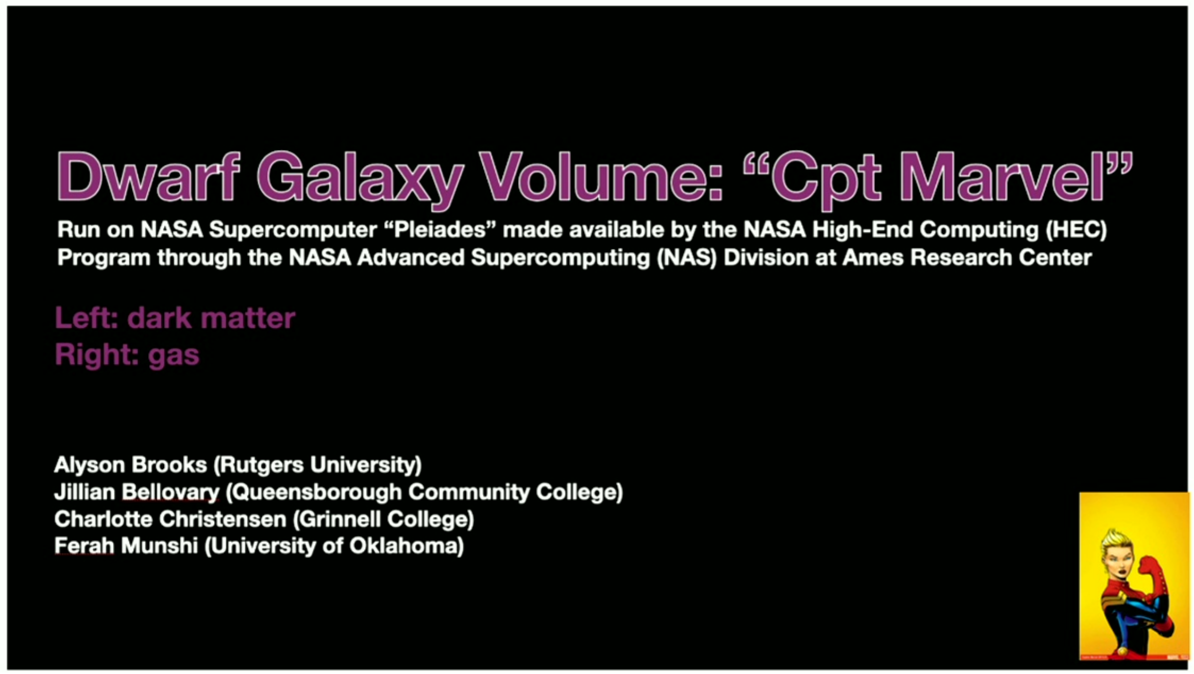
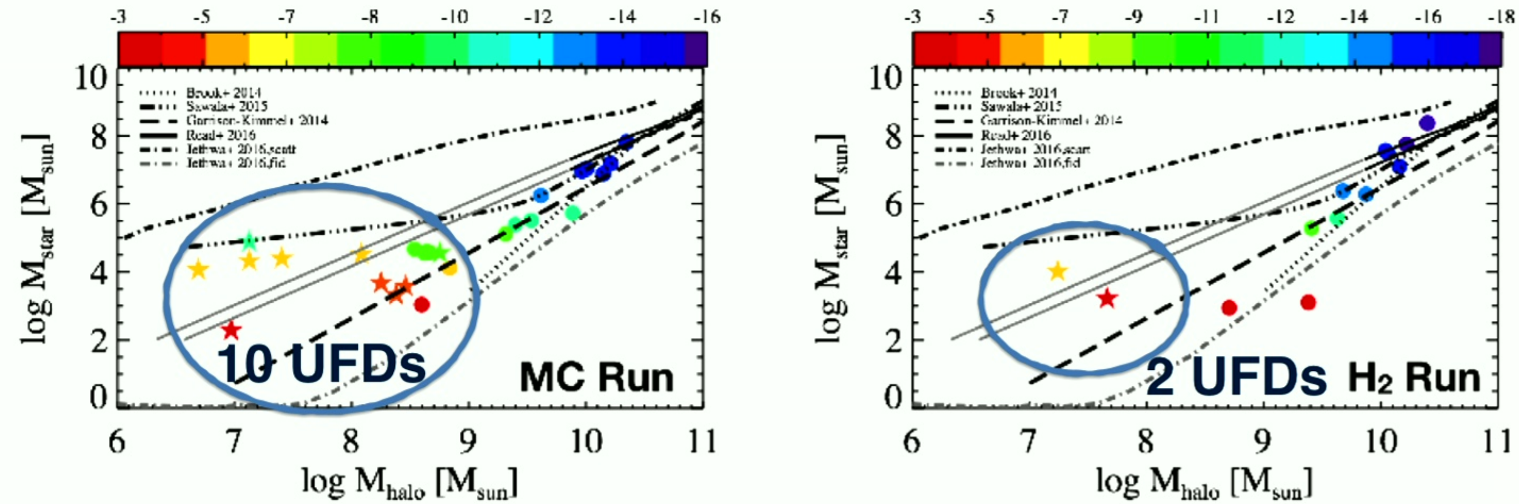


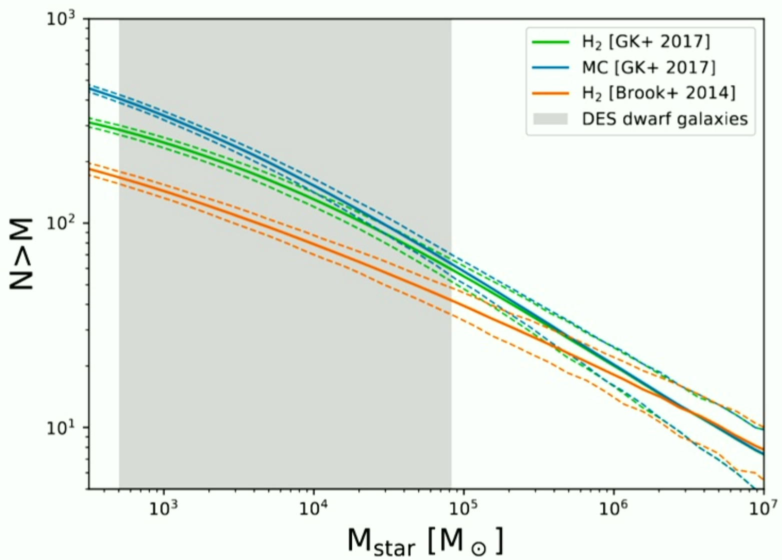
Figure from my grad student, J. Van Nest

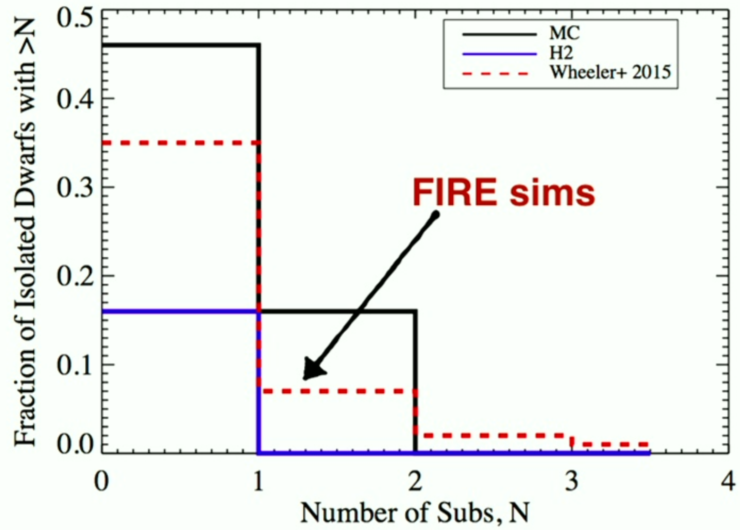
With a simulation sample like this, we can begin to constrain:

1. The abundance of ultra-faint dwarfs
2. How they populate dark matter halos





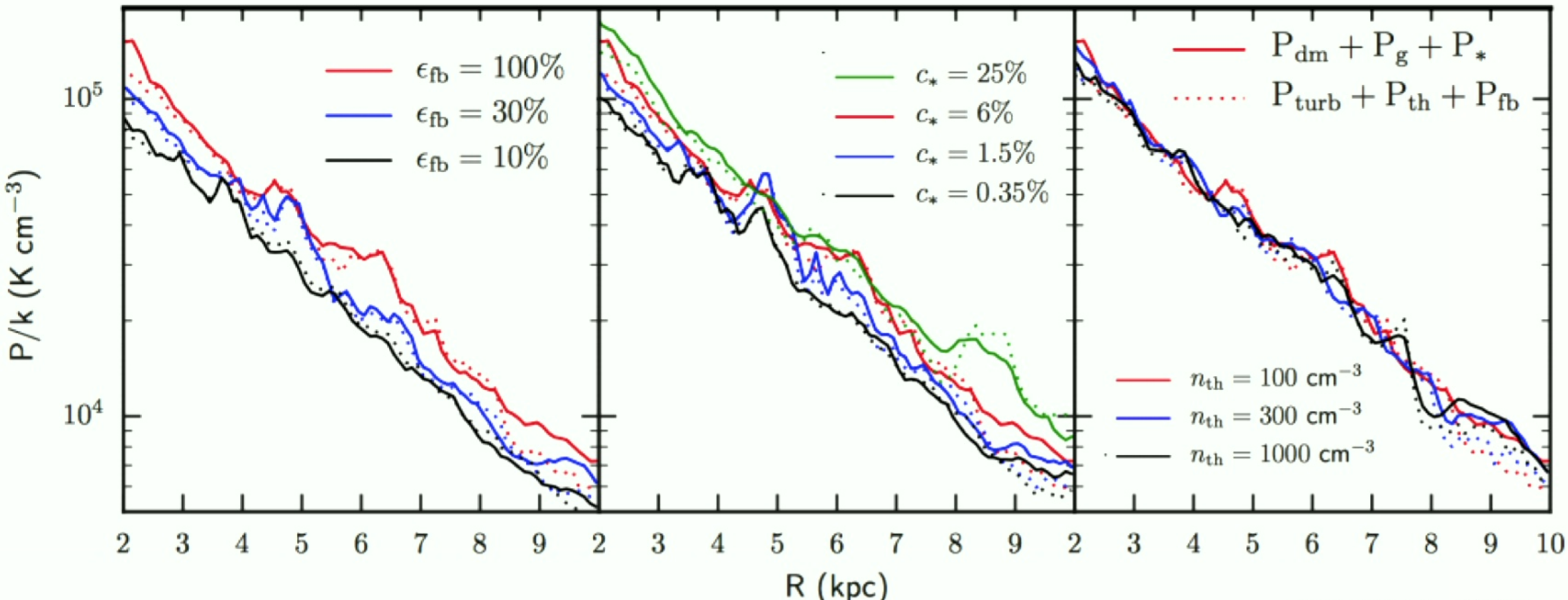




Any predictions you make depend on your star formation and feedback model

Munshi+ 2019

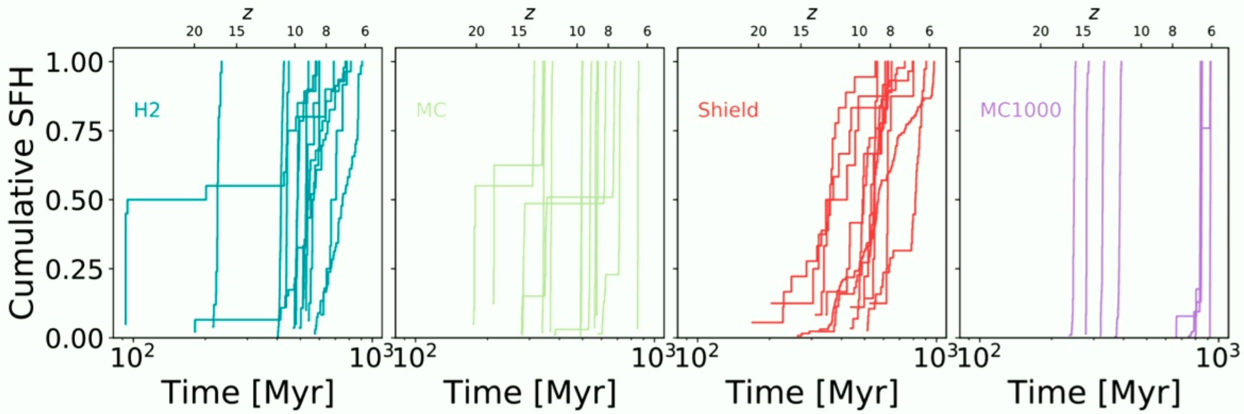
Why haven't we worried before?

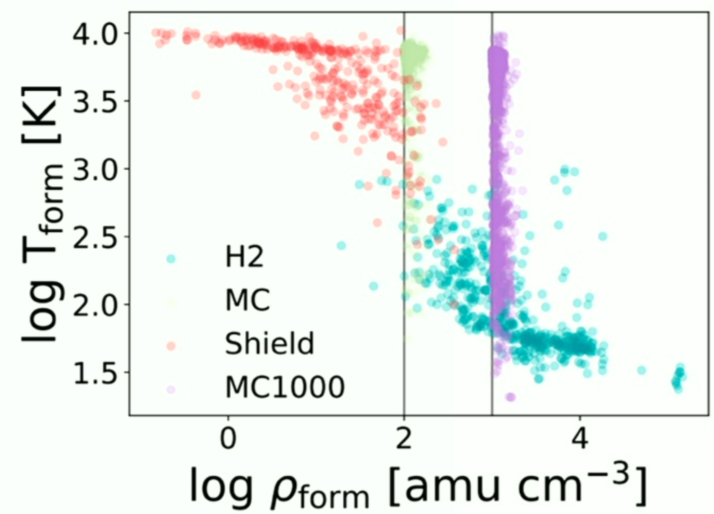


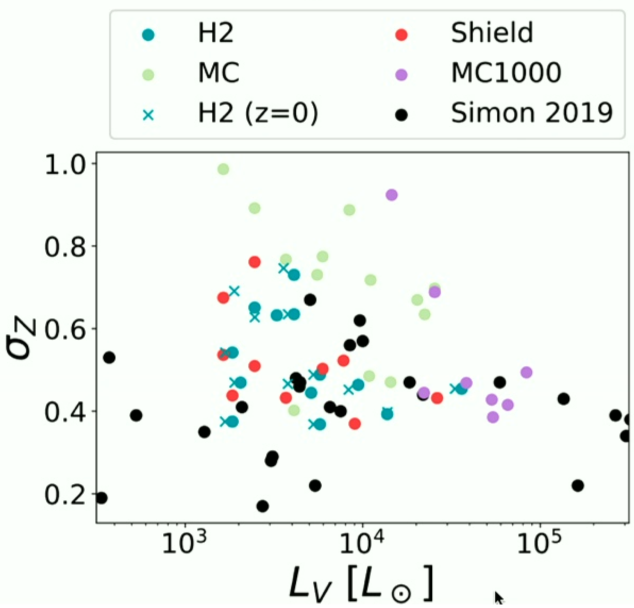
Benincasa+ 2016

Star formation and feedback self-regulate at classical dwarf masses and above.

Is there a way to differentiate SF models?

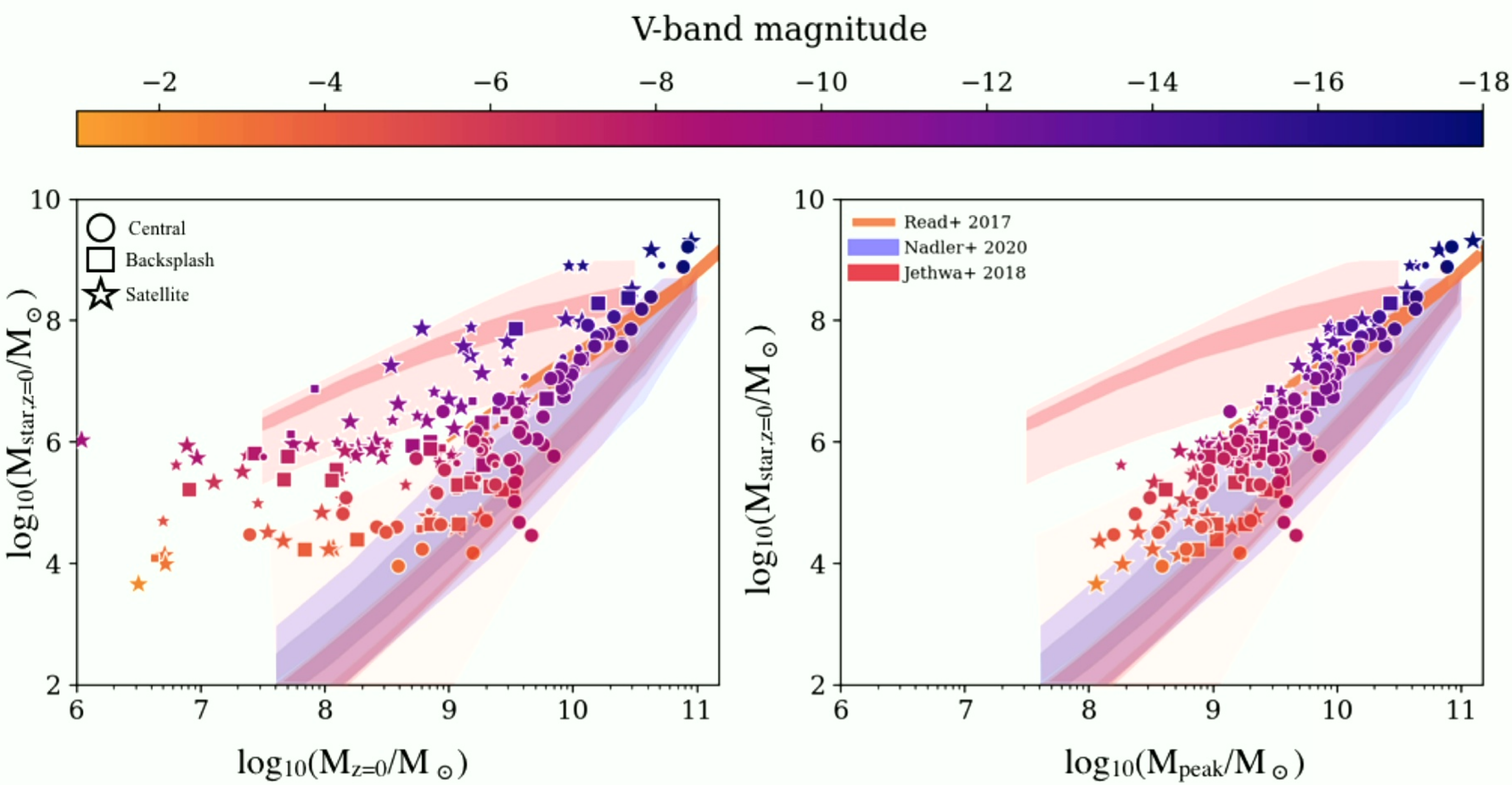




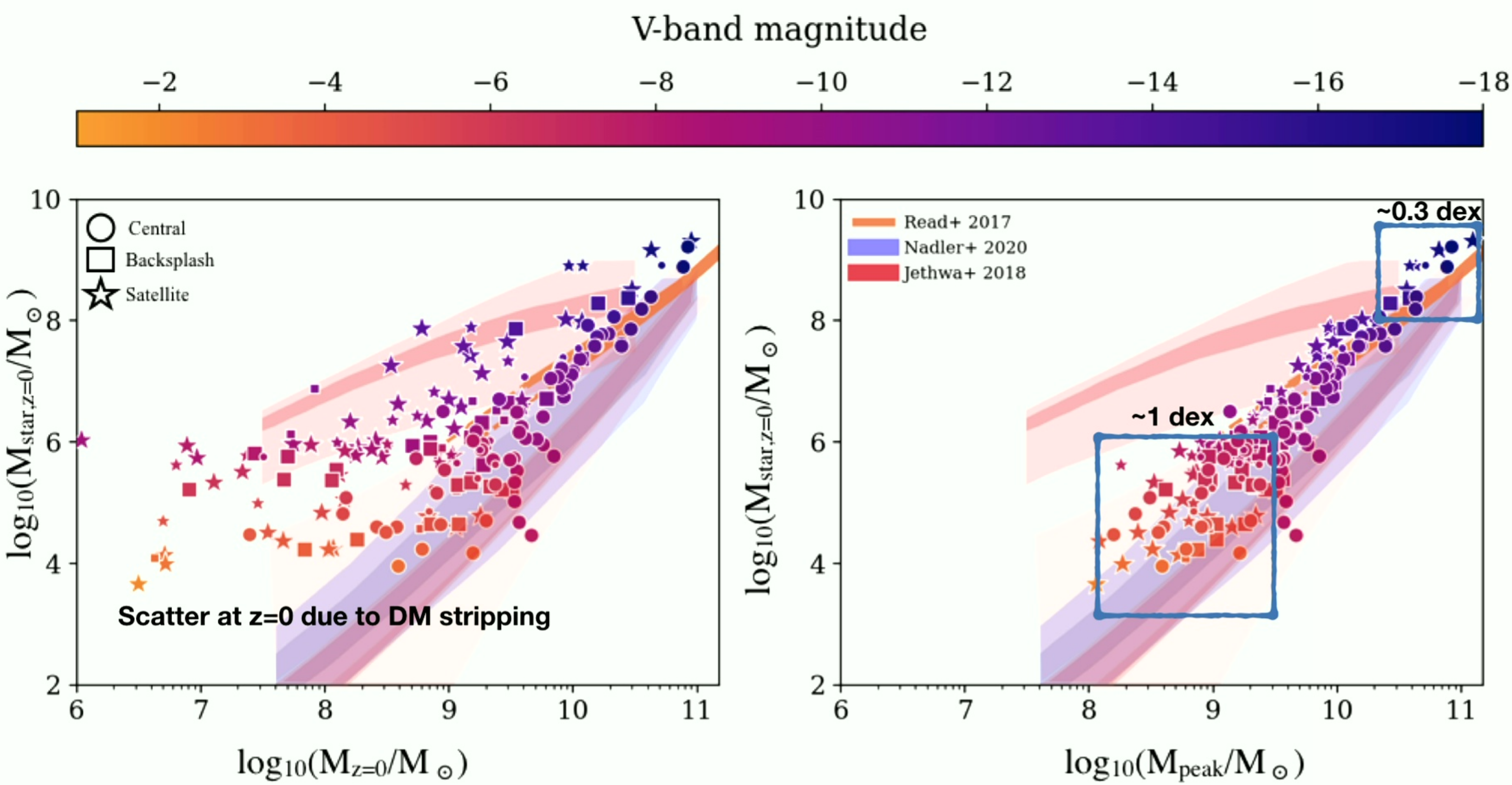


- SFHs in UFDs vary between SF recipes due to varying thresholds for forming stars
- This isn't detectable but, **width of MDF may differentiate SF models**!

Engelhardt, Brooks, Munshi & Applebaum to be submitted

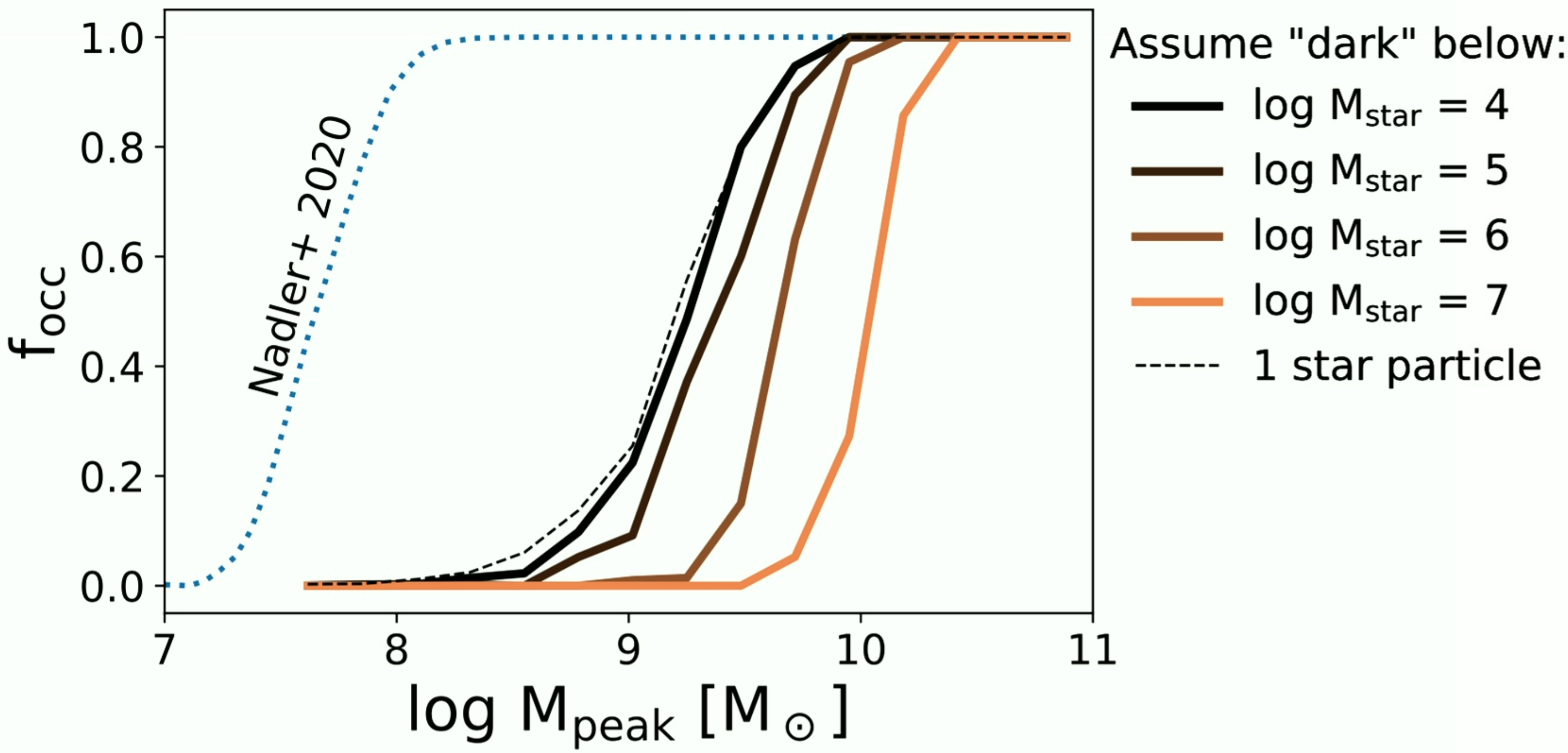


Munshi, Brooks, Applebaum+, 2021



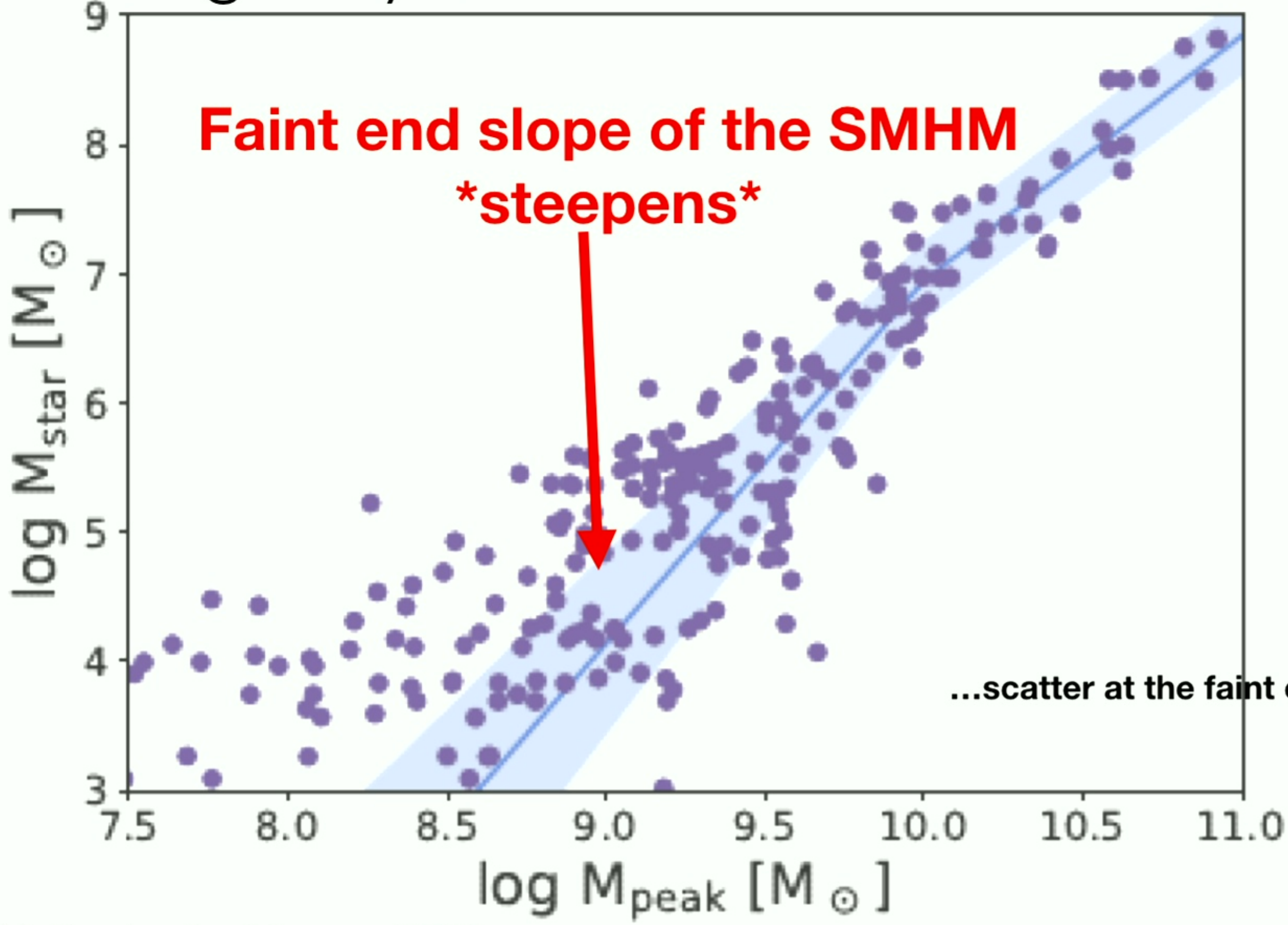
Munshi, Brooks, Applebaum+, 2021

In simulations, occupation fraction is inherently resolution dependent.



Munshi, Brooks, Applebaum+ (2021)

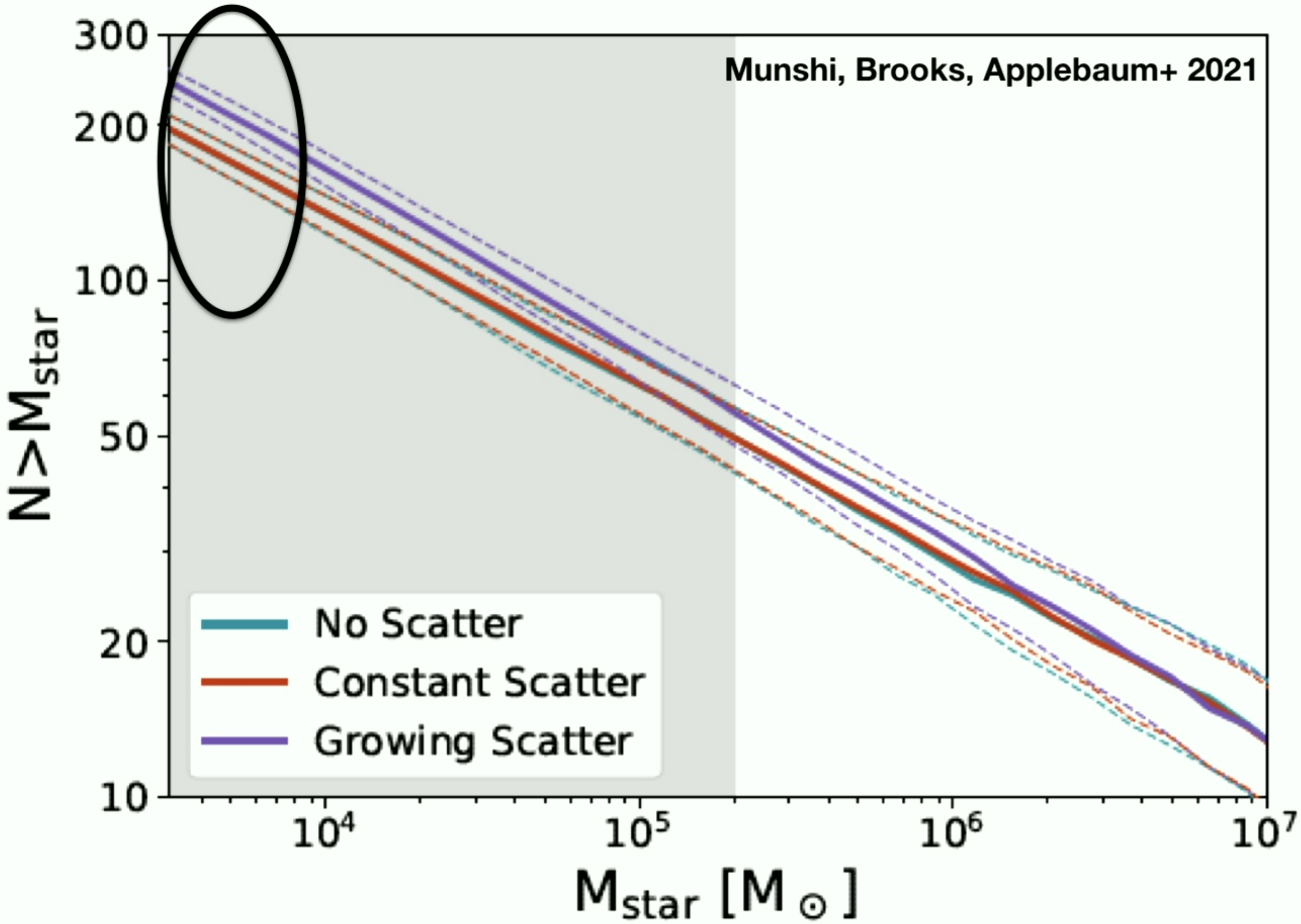
If we assume that halos that are "dark" are actually host a galaxy below our resolution limit..



...scatter at the faint end remains similar

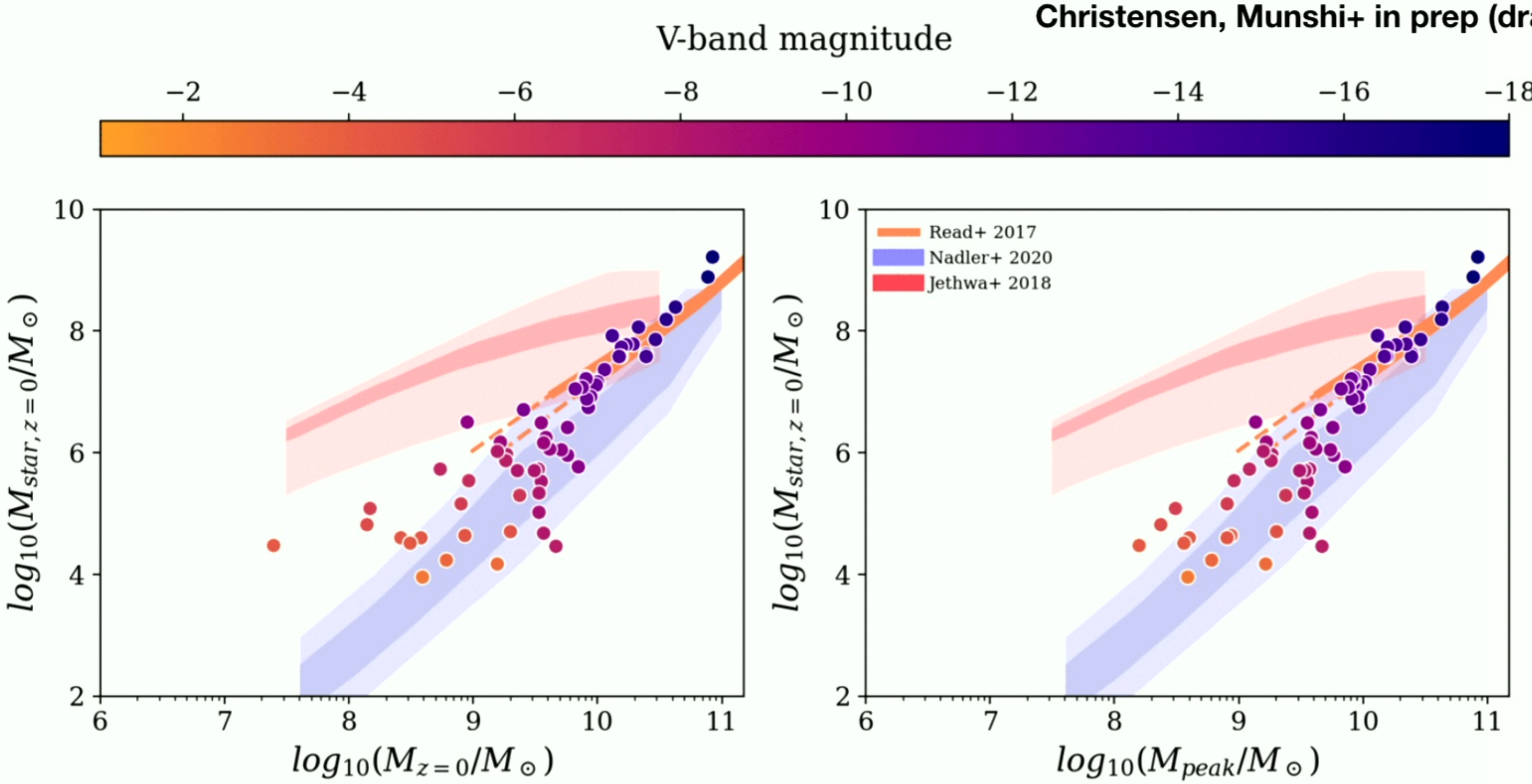
Munshi, Brooks, Applebaum+ (2021)

Growing Scatter in the SMHM steepens the faint-end SMF!



Upcoming: Effect of Environment

Christensen, Munshi+ in prep (draft circulating!)



This is in tension with previous work at lower resolution!

Can we continue to understand the formation and evolution of dwarf galaxies in a vanilla CDM + baryons model?

I have created a statistical sample of simulated dwarf galaxies in order to interpret Local Volume observations and prepare for JWST/Roman/Rubin/LISA in the context of DM science

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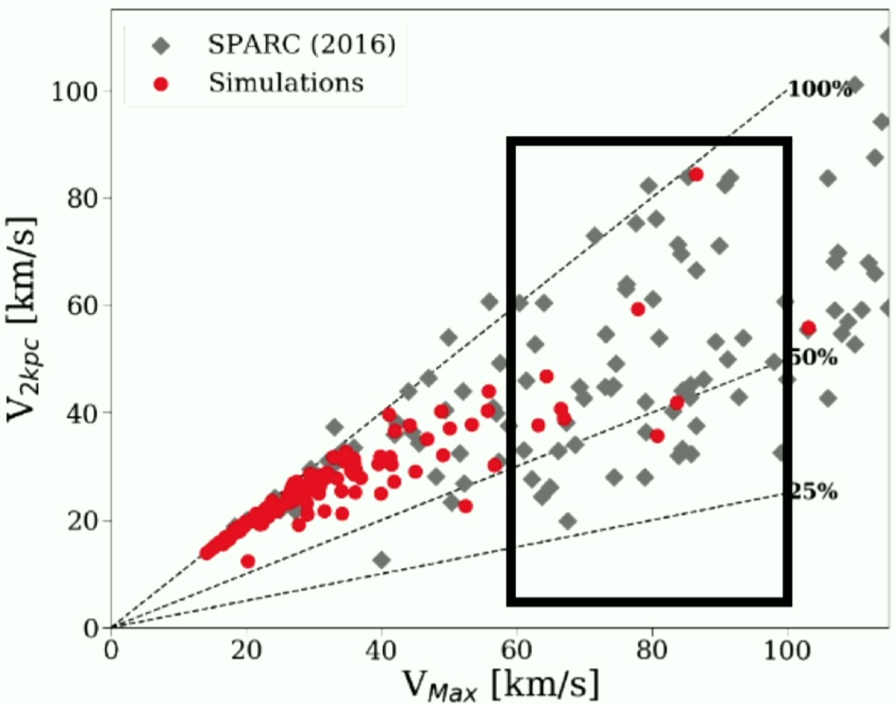
To constrain DM model, we must understand the impact of baryonic physics on galaxy formation:

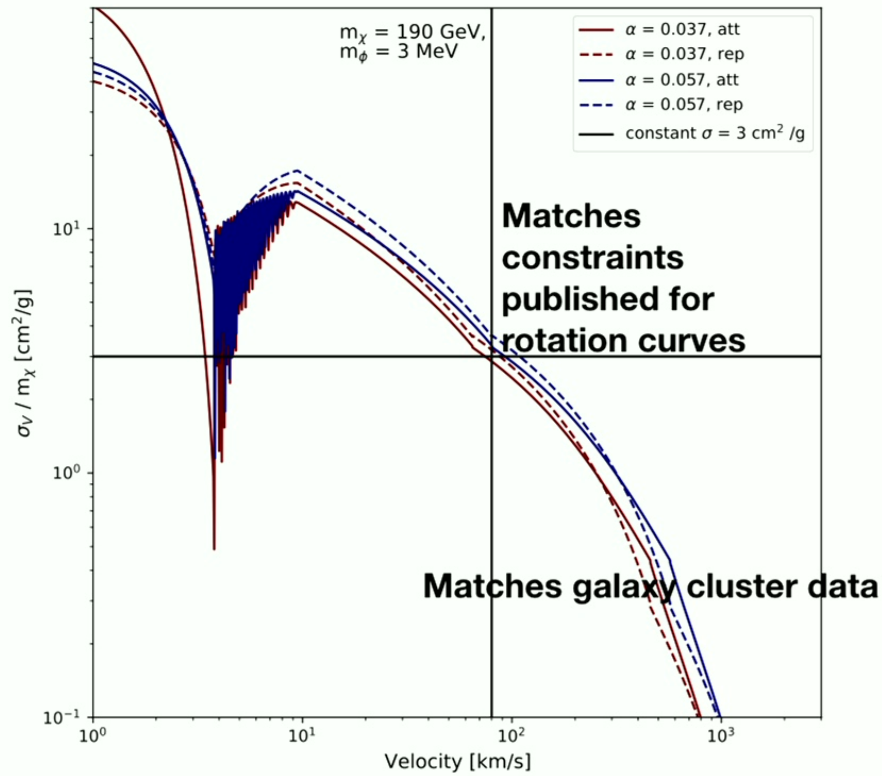
- interplay between star formation and feedback has ramifications on: stellar to halo mass relationship- its form and scatter, satellite mass functions, stellar mass function

SIDM Dwarfs: smoking gun in rotation curves?

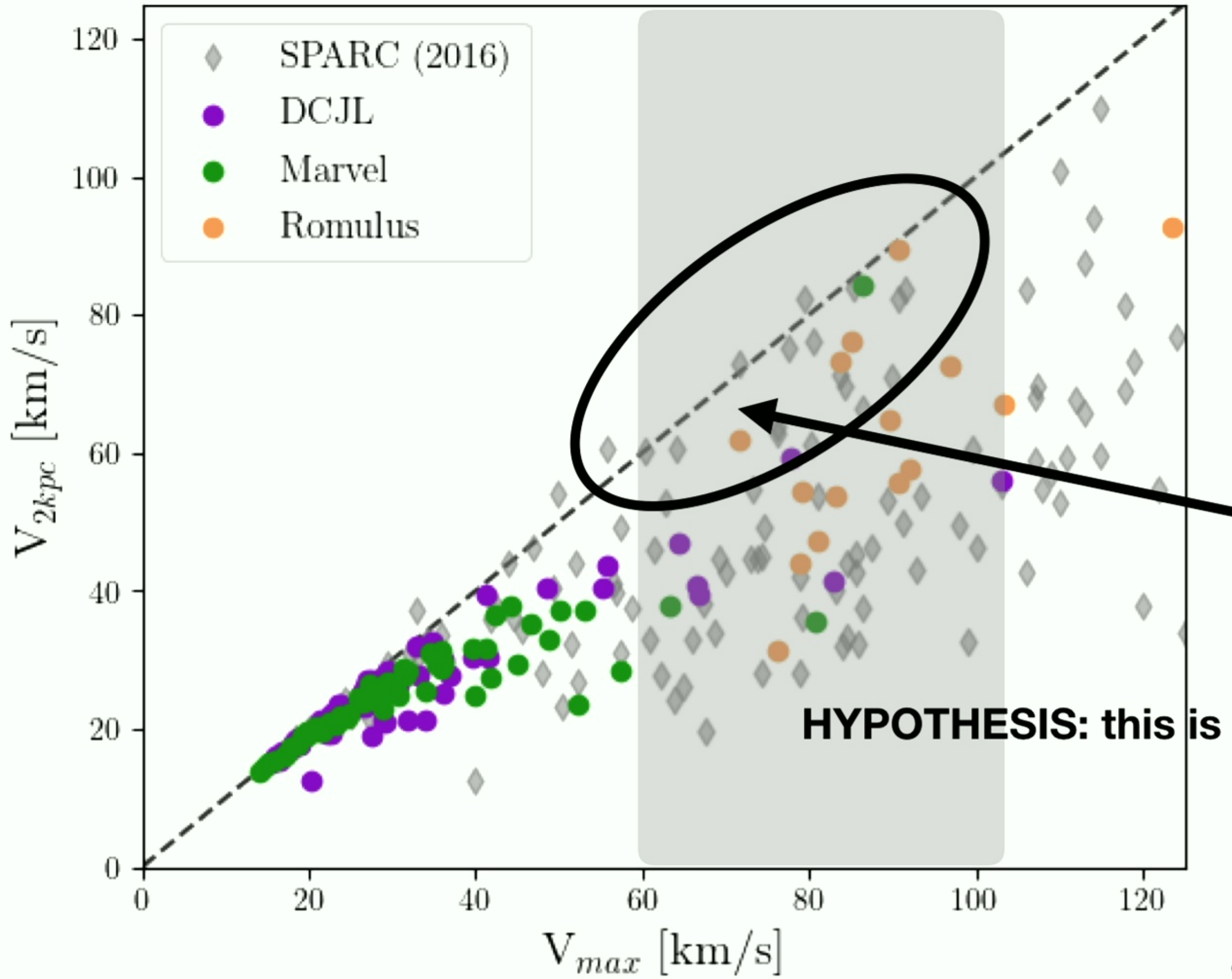
New velocity dependence based on latest literature

New CDM/SIDM dwarfs fill in parameter space: **MARVELous Merian Magellenics**





Corresponds to a light mediator model/Yukawa potential [att=attractive, rep=repulsive] *preliminary result



New Romulus Zooms seem to “solve” the diversity problem in CDM+ baryons

HYPOTHESIS: this is due to subgrid SF modeling

Cruz, Munshi, Brooks + in prep

The Future is Dwarfy

Merian Survey

PIs: Alexie Leauthaud (UCSC) and Jenny Greene (Princeton)

NSF-funded NOIRLab survey on DECam

100,000 star forming dwarf galaxies with $10^8 < M_{star} < 10^9 M_\odot$
$0.06 < z < 0.1$

→ Galaxy-Halo connection at ~LMC mass for the first time!

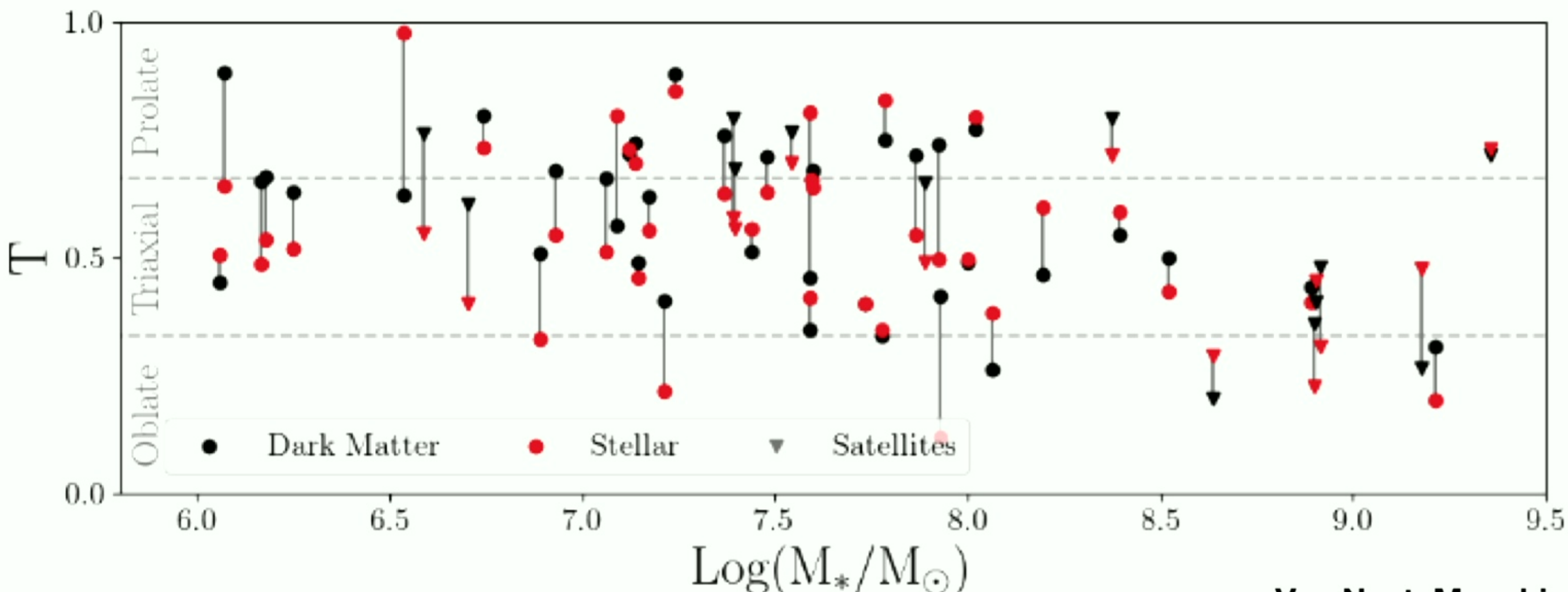
Merian honors 17th century Maria Sibylla Merian (1647, 1717), the first female entomologist and naturalist. Her fascination with the world of tiny things combined with unique observational skills led to a number of important discoveries, including the previously unknown metamorphosis of caterpillars into butterflies.

SIDM Dwarfs: smoking gun in galaxy shapes?

Expectation: SIDM makes spherical galaxies due to interactions in the center; CDM makes triaxial galaxies

Implication: Galaxy shape follows dark matter halo shape (regardless of DM model)

Let's test this



Van Nest, Munshi+, in prep

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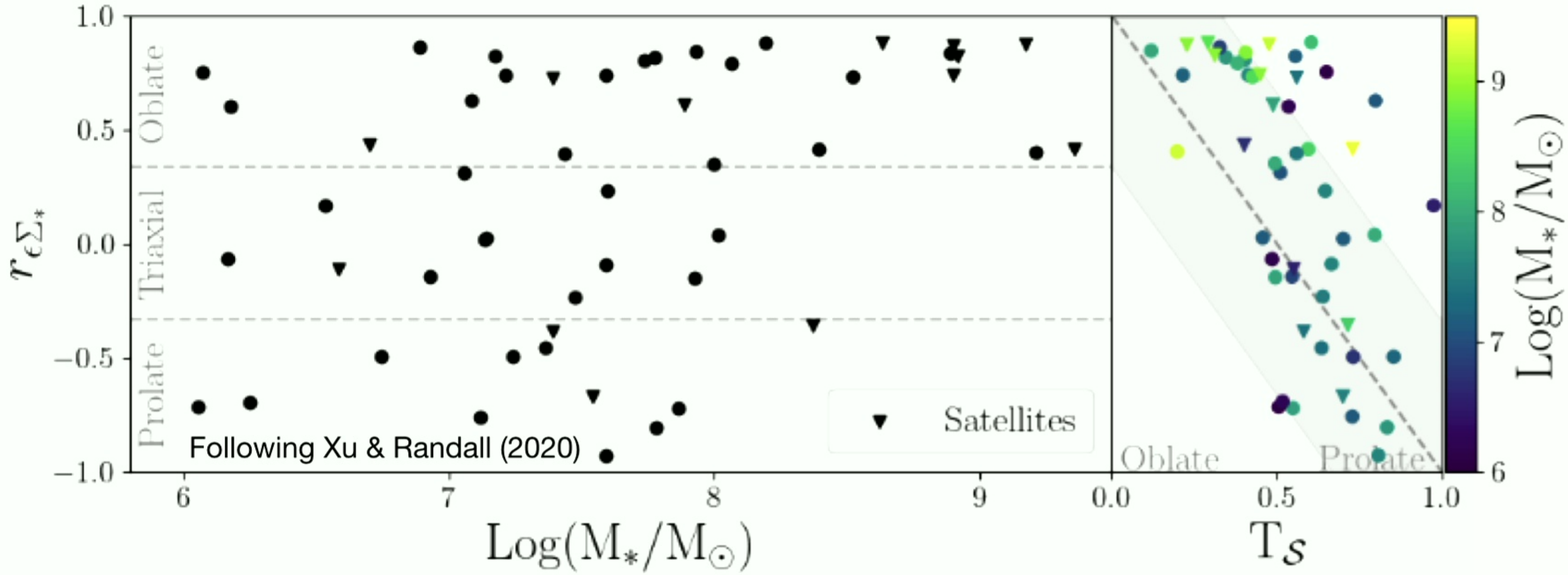
Implication: Galaxy shape differences are *measurable* ← **Let's test this**



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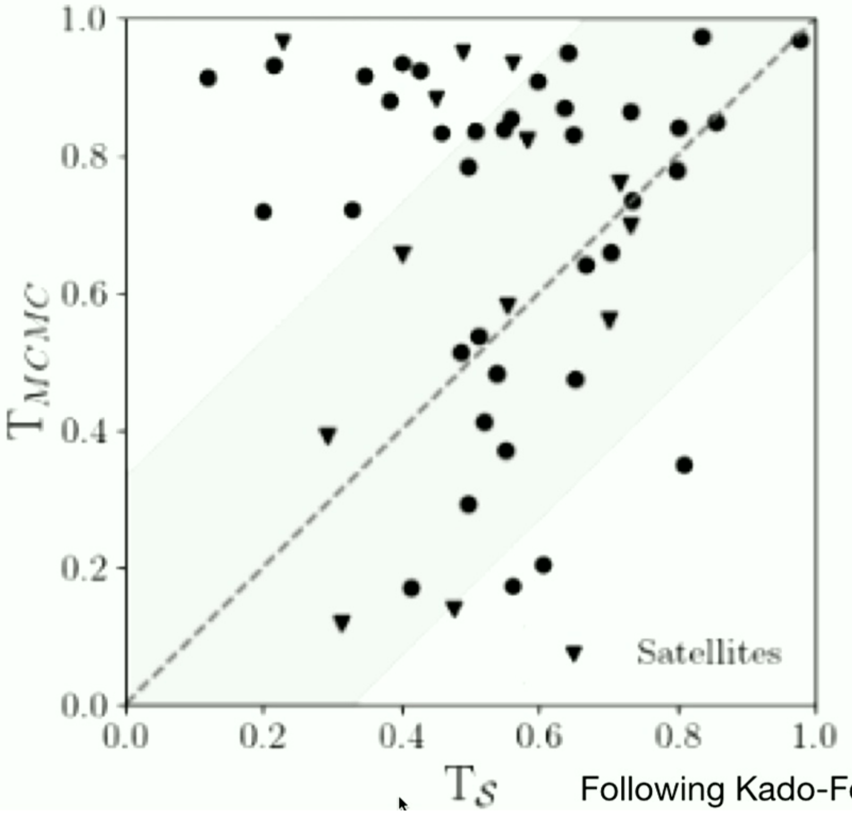


Following Kado-Fong+ 2021

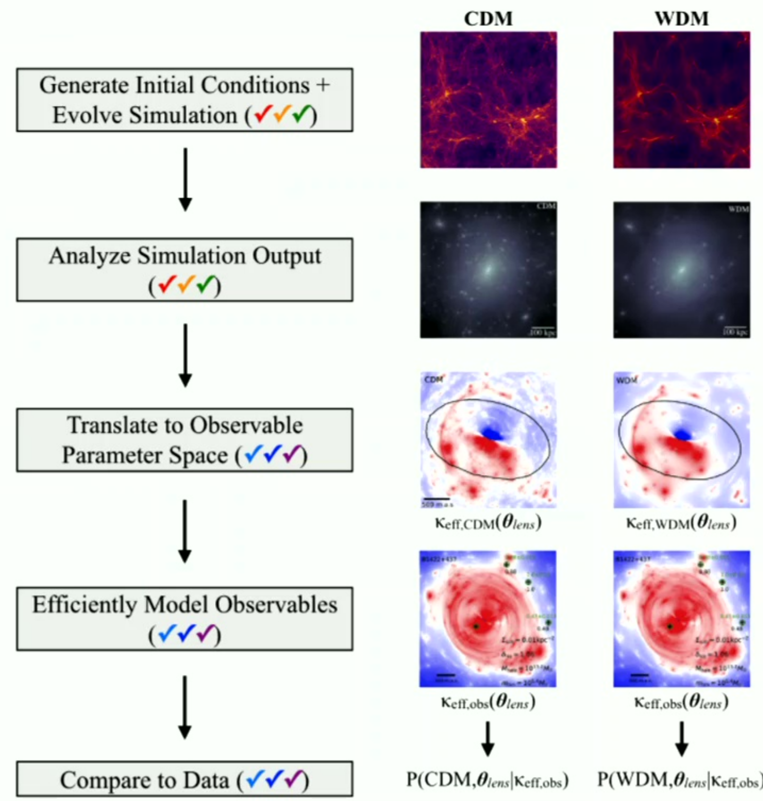
Van Nest, Munshi+, in prep

Take home message: My current generation of simulations has significant predictive power for current & upcoming surveys like JWST, Rubin, Roman over a wide range of galaxy formation topics.

But in order to interpret the upcoming wealth of data, significant study needs to be done to understand galaxy formation in particular to constrain DM. **This is where my work comes in.**

Questions?

Measuring Dark Matter Physics using Cosmological Simulations



Need #1: Collaboration between simulators and particle theorists
Need #2: Algorithm development and code comparison tests
Need #3: Hydrodynamic simulations for observational targets
Need #4: Compare simulations to data in observable parameter space
Need #5: Fast realizations of observed systems to constrain dark matter
Need #6: Provide guidance to observers about dark matter signatures

From the Snowmass cosmic frontier numerical simulation white paper