What's the (**dark**) matter with dwarf galaxies?

Ferah Munshi

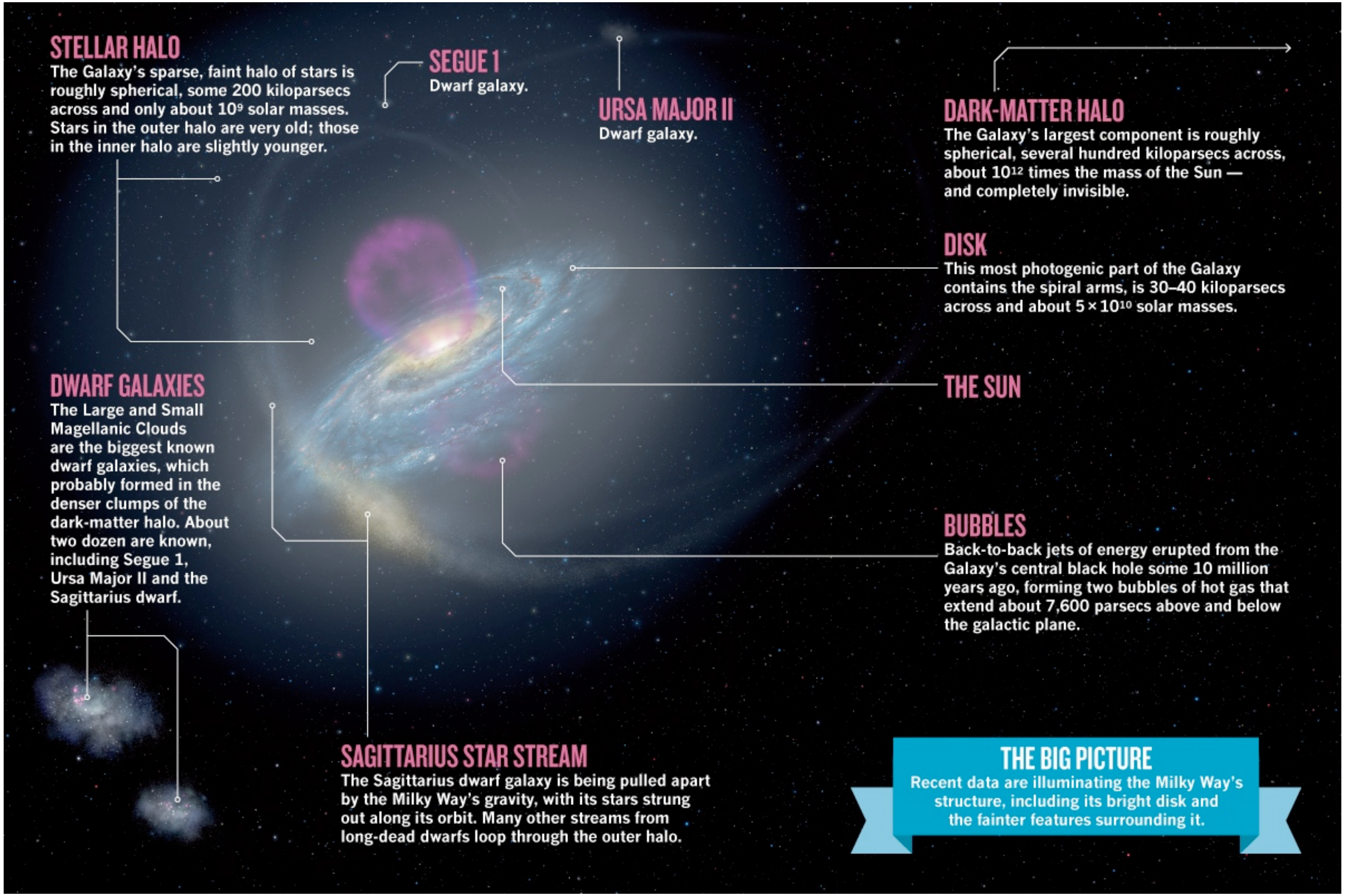
Assistant Professor, University of Oklahoma

In collaboration with: Alyson Brooks (Rutgers), Jillian Bellovary (QCC/AMNH), Kelly Holley-Bockelmann (Vanderbilt) , Charlotte Christensen (Grinnell), Michael Tremmel (Yale) + UW N-body Shop

Student work highlighted: Elaad Applebaum (Rutgers—> data science), Serena Sligh (OU—> industry), Jordan Van Nest (OU), Claire Riggs (OU —-> Rutgers PhD)

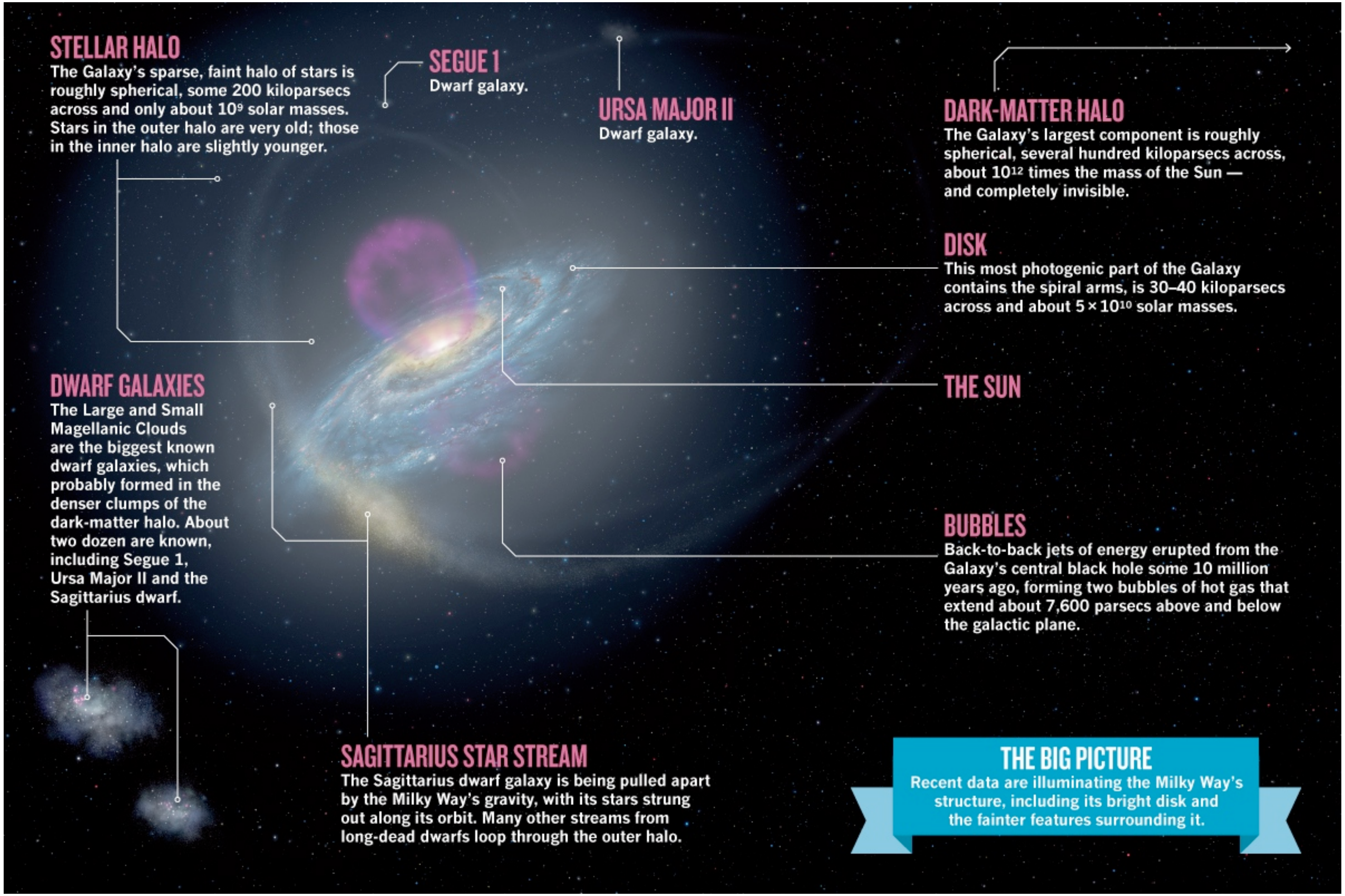
Wellesely College 12/6/2021

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



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

Dwarf galaxies are galaxies smaller than the Milky Way



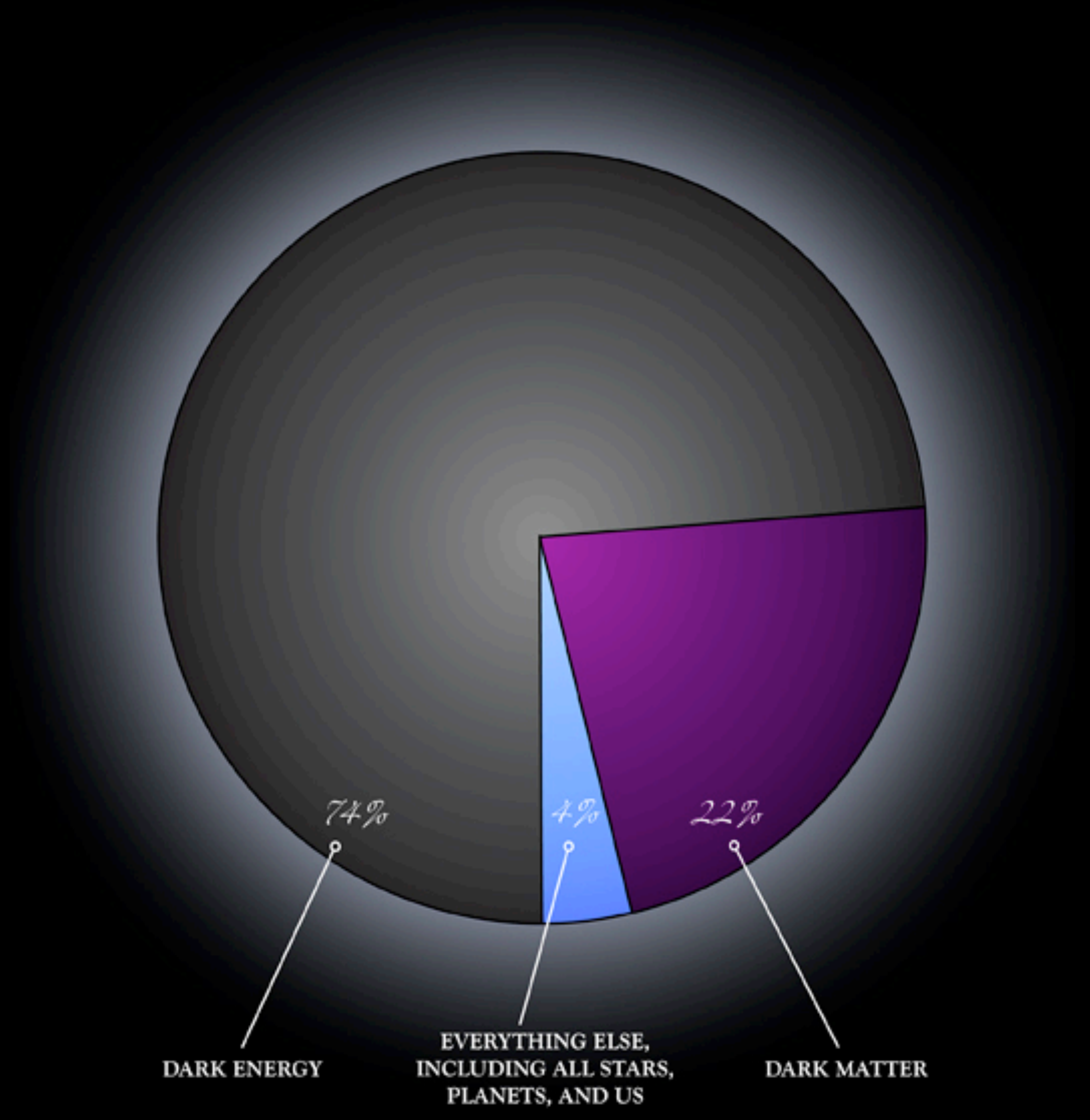
http://www.nature.com/news/galaxy-formation-the-new-milky-way-1.11517

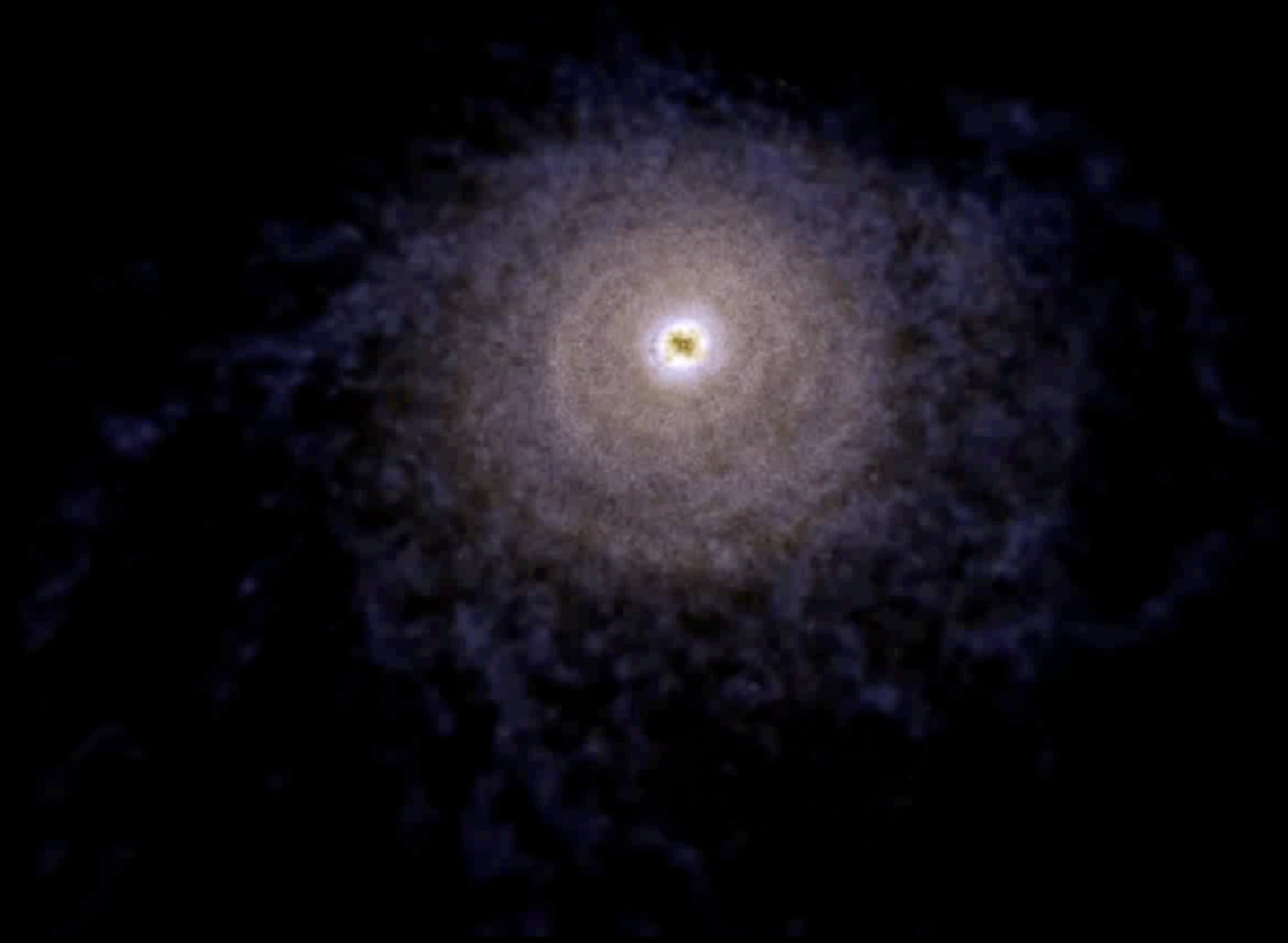
I use galaxy simulations to figure out how galaxies form and evolve- i.e., how they come to look as they do today.

This includes understanding the **dark matter** halos in which they form.

Components of the Universe

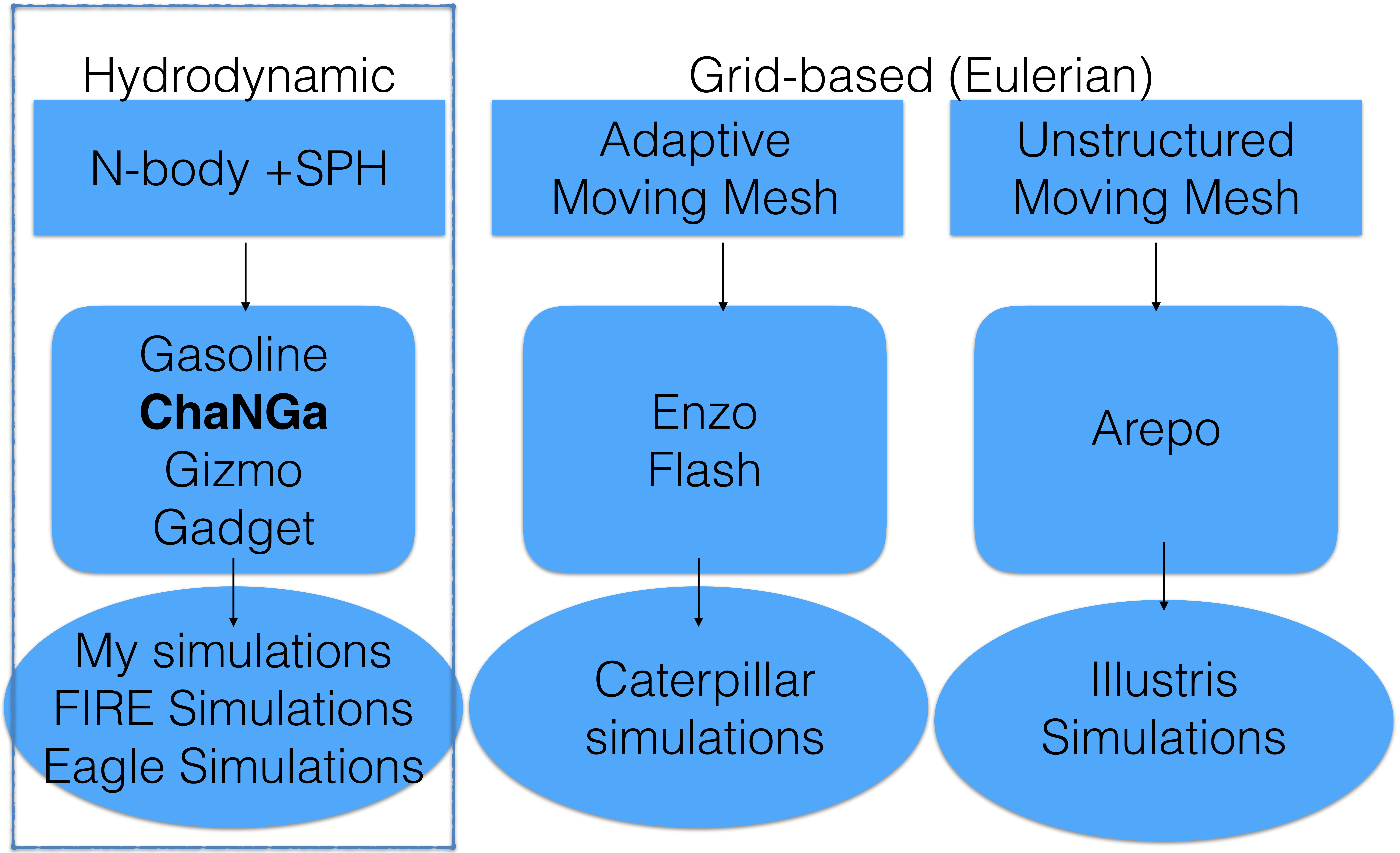
- **Radiation**: light (photons)
- **Baryonic matter** (BM): "ordinary matter" like you and me and stars and galaxies
- **Dark matter** (DM): "Exotic" non-baryonic matter (we have no idea).
- **Dark energy**: bizarre form of matter that causes the expansion of the universe to accelerate



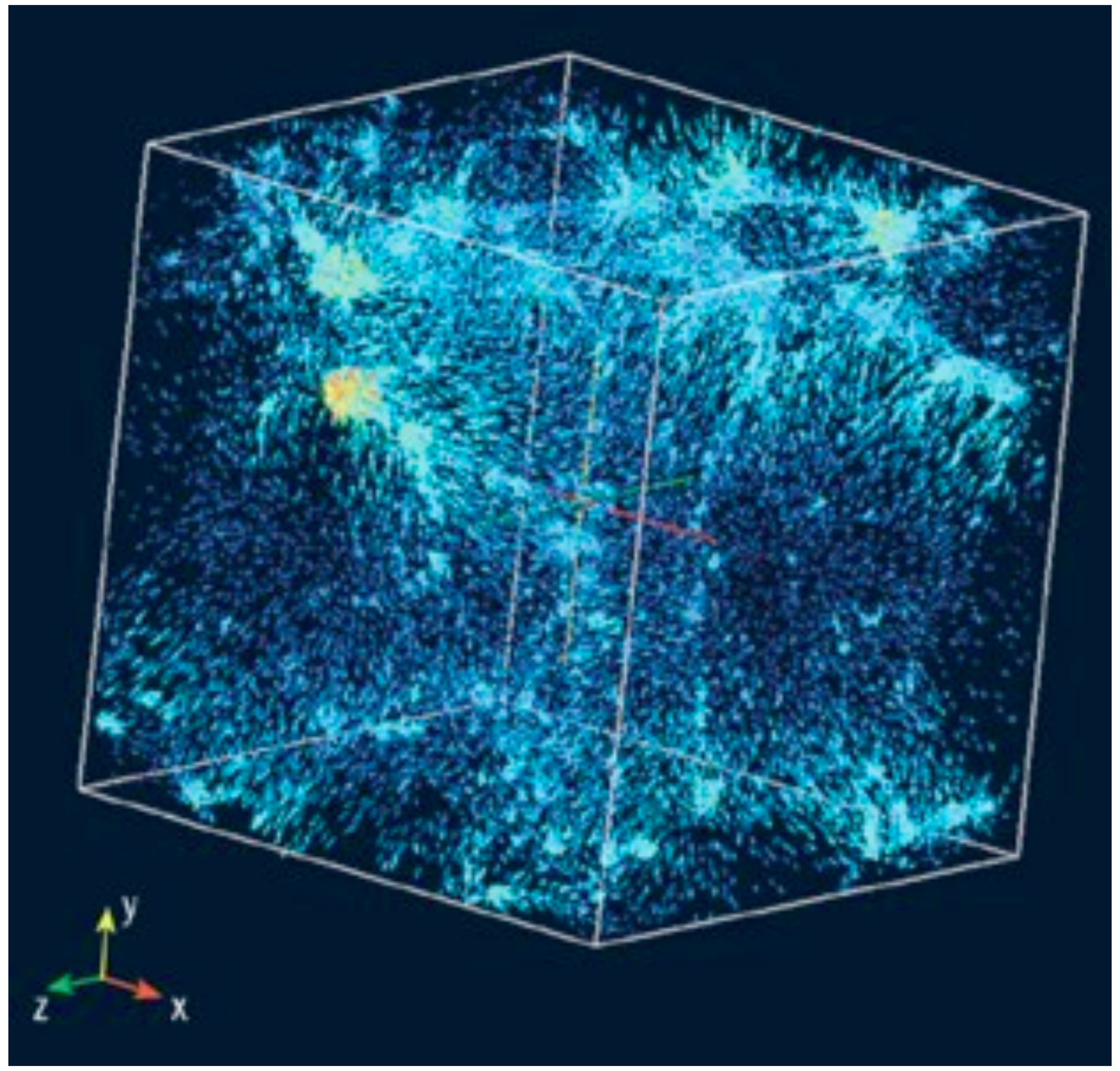


Video courtesy of A. Pontzen

Types of galaxy simulations



What is a (N-body) Simulation?

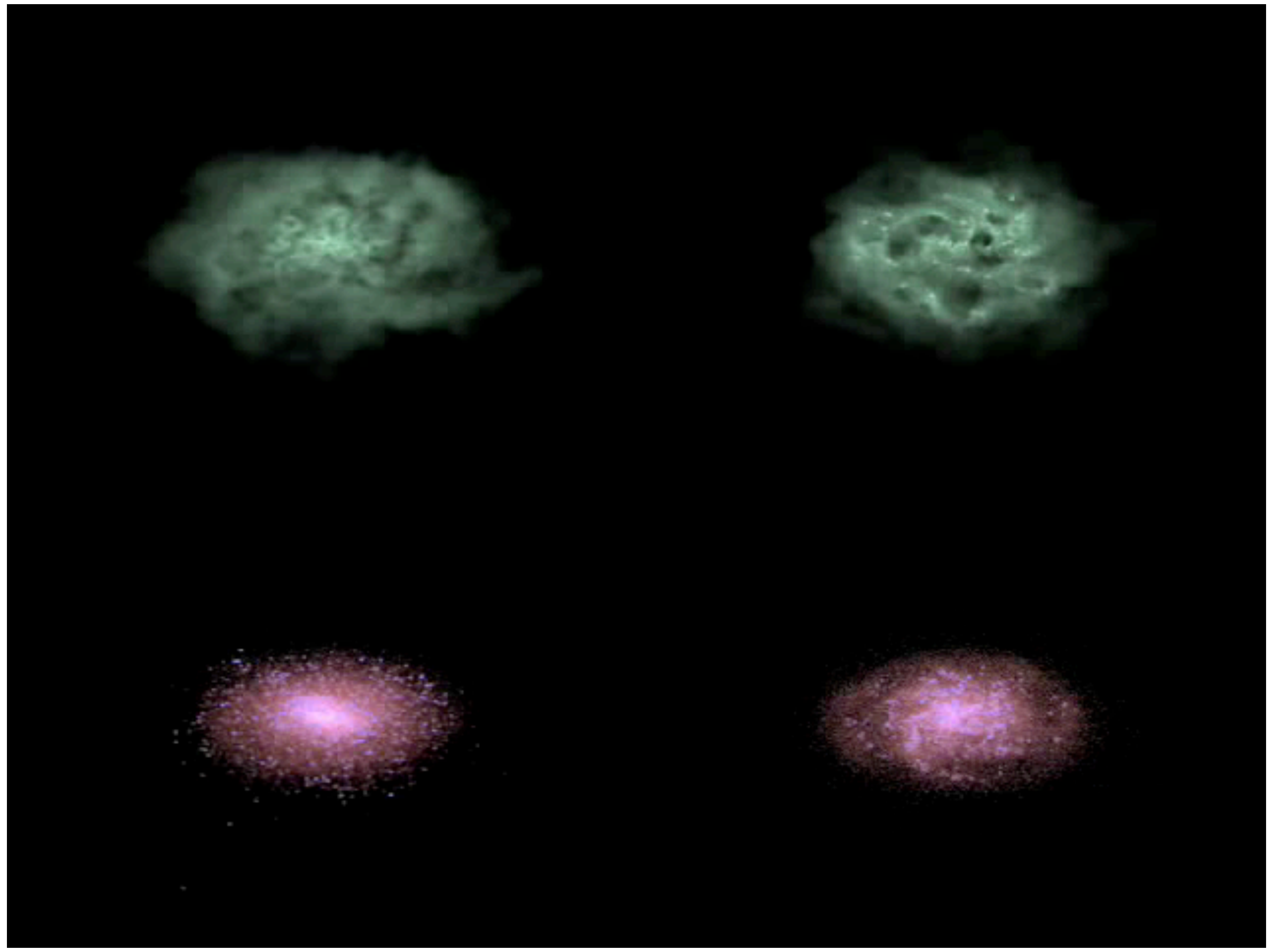


Modeling a dynamical system of particles, usually under the influence of physical forces, in this case: **gravity**

For me: *stars* + *dark matter*, acting under the influence of **gravity**, within a galaxy

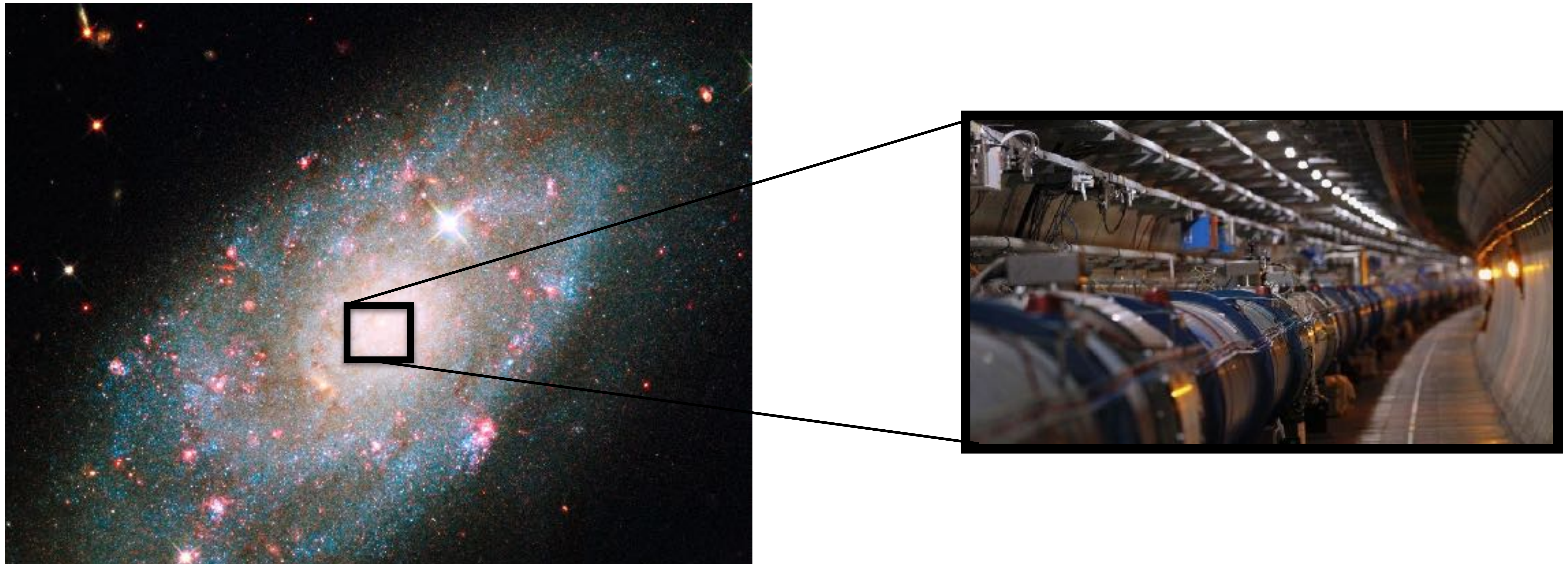
What is an N-body + SPH Simulation?

- SPH= "smoothed particle hydrodynamics"
- computational method used for simulating fluid flows- ie, gas
- Gas is divided into a set of discrete elements, referred to as "particles"
- "cosmological"= from early times all the way to present day



Dwarf galaxies are fantastic astrophysical particle accelerators.

…and we can place constraints on DM by studying them.



Dwarf galaxies have challenged our accepted paradigm for dark matter: cold dark matter (CDM).

“small-scale challenges to CDM”

Fundamental Q1: How do feedback and star formation affect the dark matter in dwarf galaxies?

Fundamental Q2: What challenges remain to be solved?

Galaxies are made up of stars, gas and dark matter (the majority of a galaxy is in dark matter; dwarfs are ***dominated*** by dark matter)

FEEDBACK can imprint its affects on all three components

In dwarf galaxies, feedback is key to understanding (solving?) the small-scale challenges to CDM

All feedback mechanisms have this in common:

They **heat gas**, **drive outflows,** and **suppress star formation**

In order to simulate a galaxy, you must be able to model feedback.

Feedback is necessary to form realistic* galaxies.

*realistic= look like observed galaxies in basic properties

Feedback

Stellar e.g. winds from massive stars

Supernova

Black Hole e.g. AGN feedback

Depending on mass of galaxy, different sources have varying importance

What are the “small-scale challenges” to CDM?

1. **Missing Satellite Problem**
- CDM predicts more small satellites around Milky Way than actually observed

Bullock (2010)

2. **Cusp/Core Problem**
-“Cuspy”, high density peaks expected for dark matter distribution, but instead find flat “cored” centers

Navarro + (2006)

3. **To-big-to-fail problem**
- CDM predicts satellites which are too massive

Boylan-Kolchin + (2013)

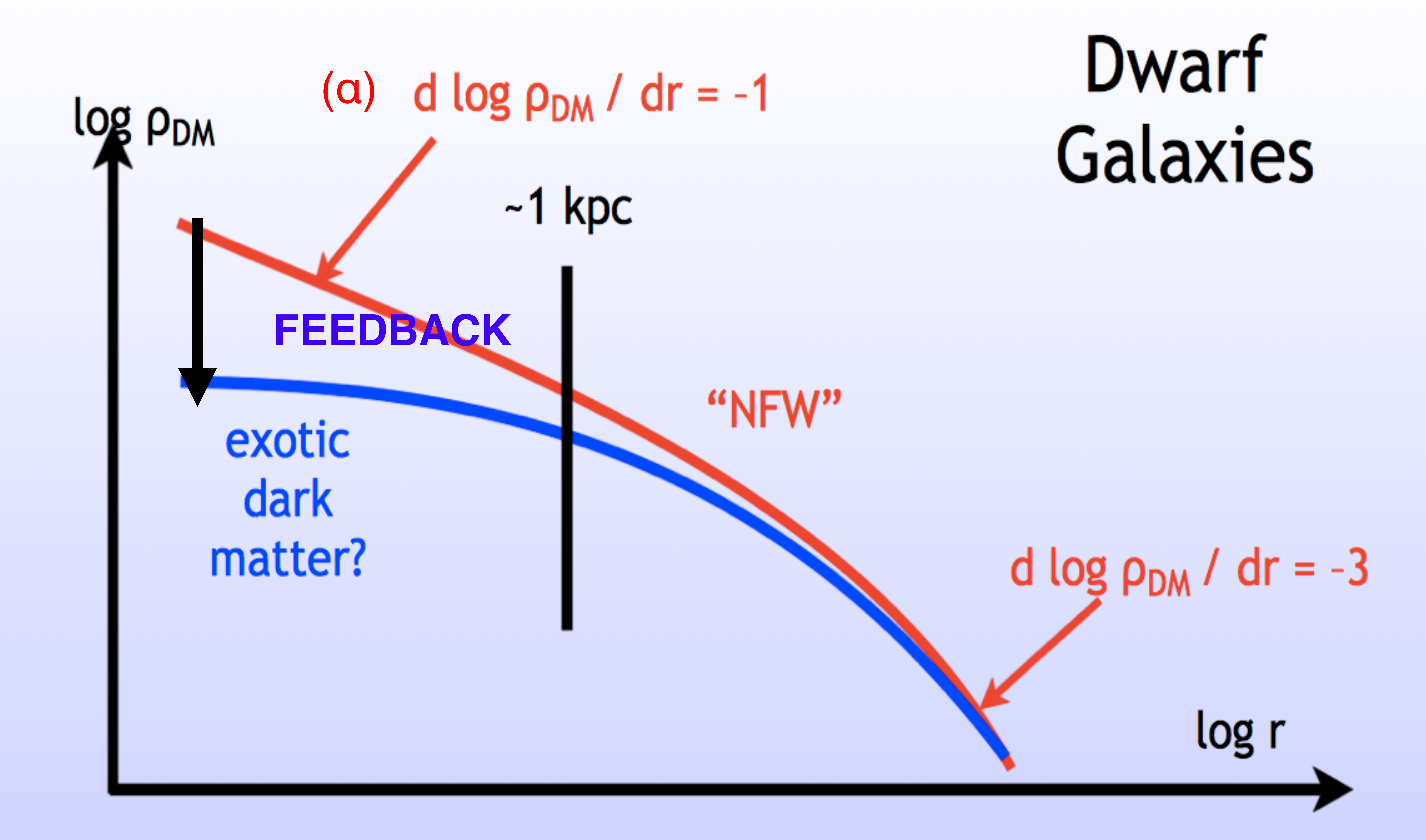
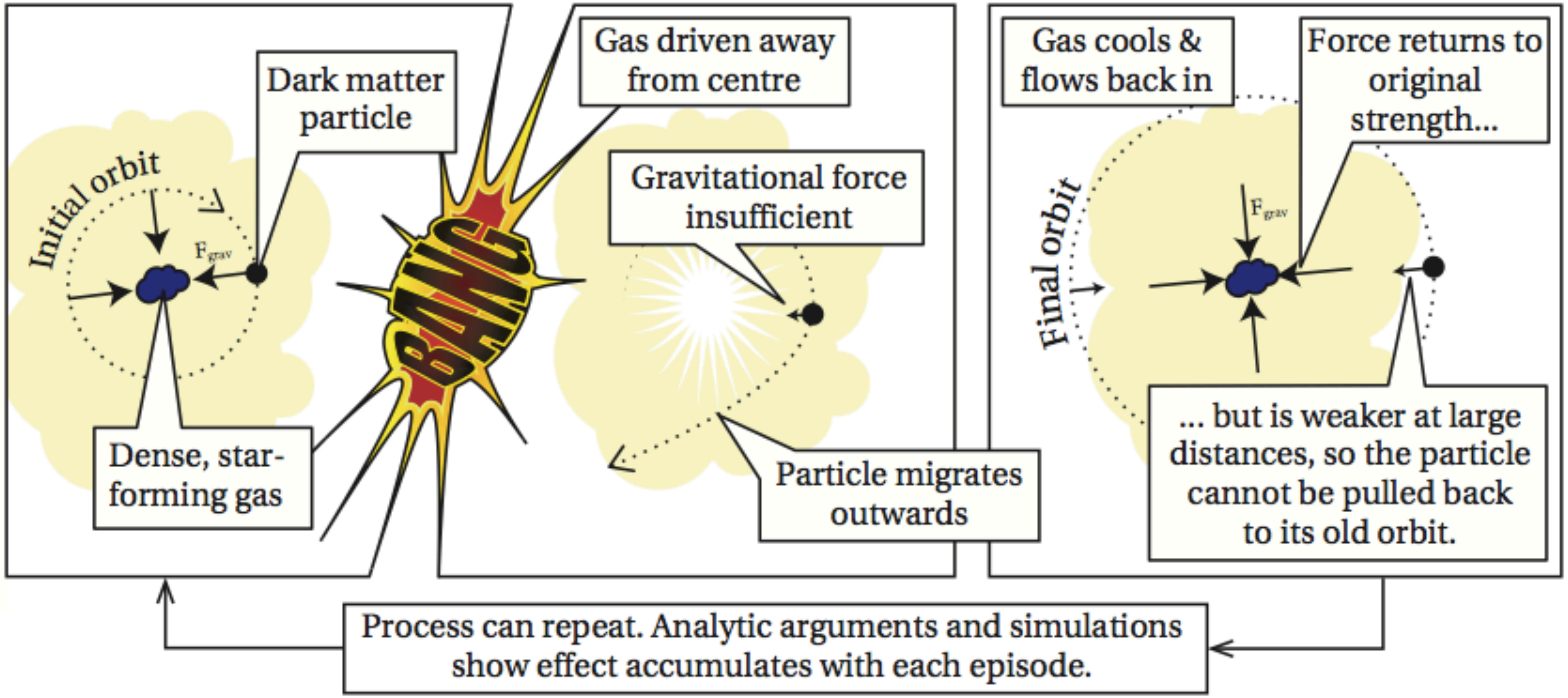
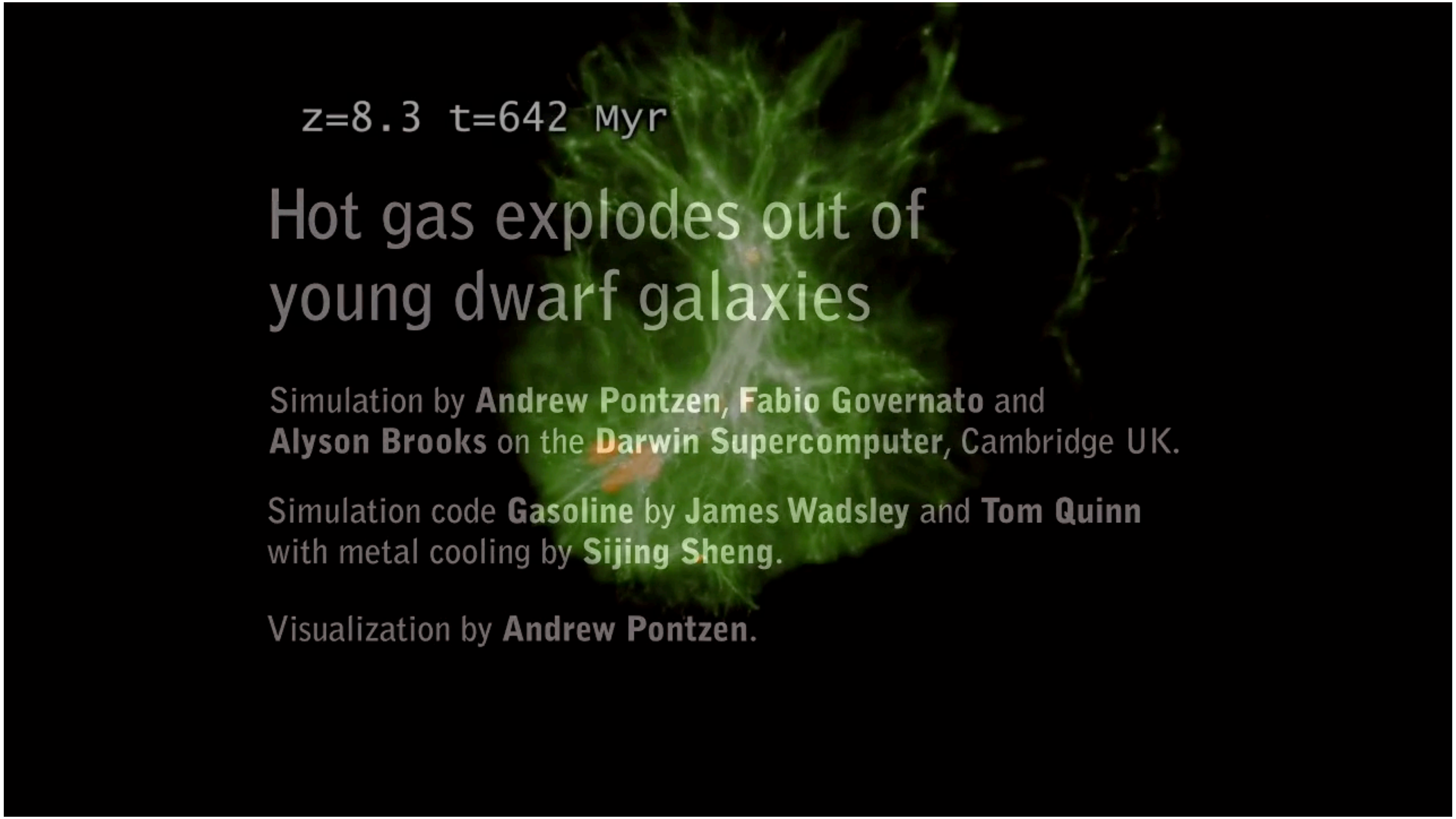


Figure courtesy of F. Governato



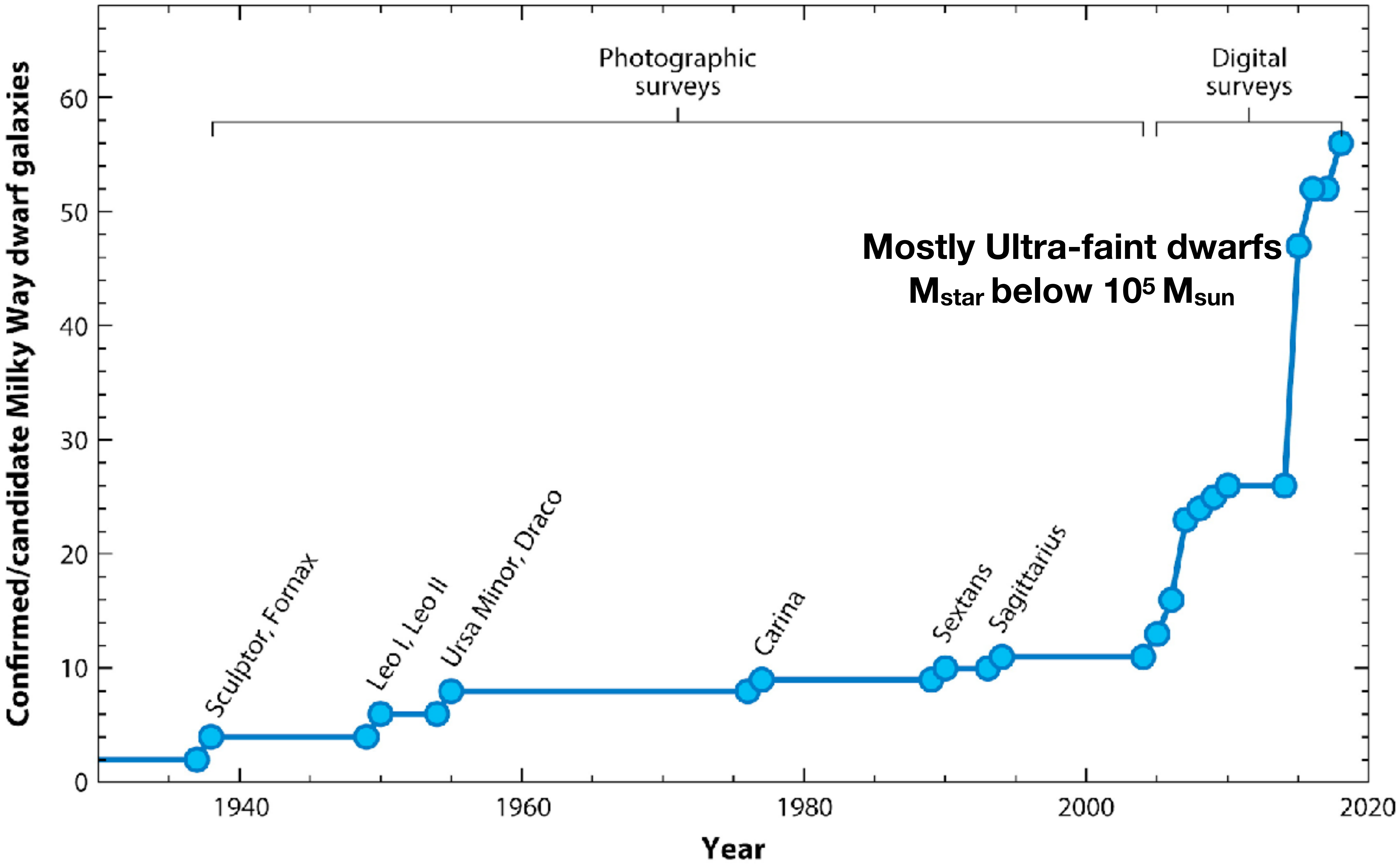
Pontzen & Governato 2012 & 2014


z=8.3 t=642 Myr
Hot gas explodes out of young dwarf galaxies
Simulation by Andrew Pontzen, Fabio Governato and Alyson Brooks on the Darwin Supercomputer, Cambridge UK.
Simulation code Gasoline by James Wadsley and Tom Quinn with metal cooling by Sijing Sheng.
Visualization by Andrew Pontzen.

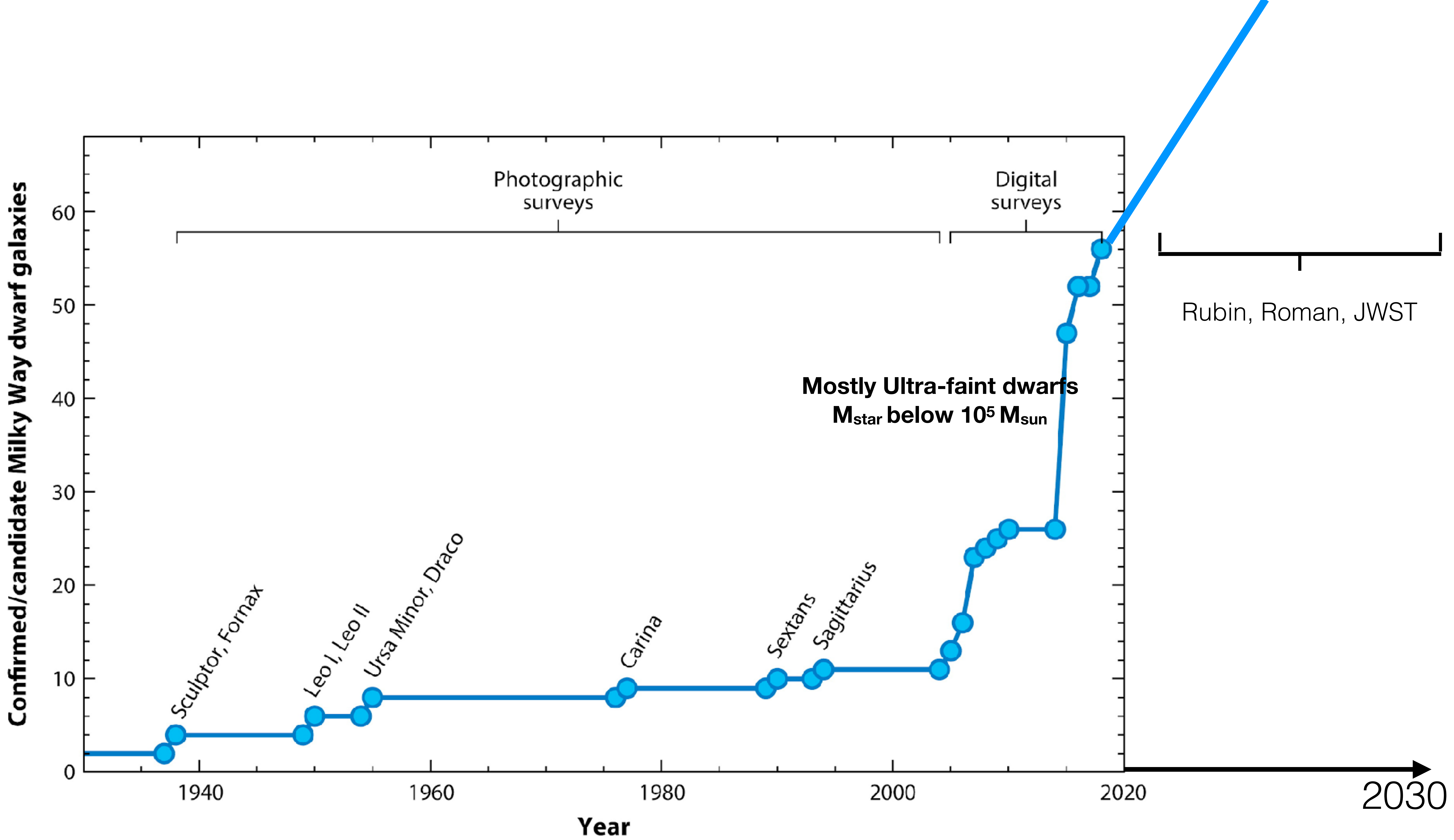
Big question #1: How do feedback and star formation affect the dark matter in dwarf galaxies?

We constrain our simulations by comparing to observations and simulations can make predictions for observations.

There has been an explosion in finding fainter and fainter dwarfs



Simon JD. 2019.
Annu. Rev. Astron. Astrophys. 57:375–415


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

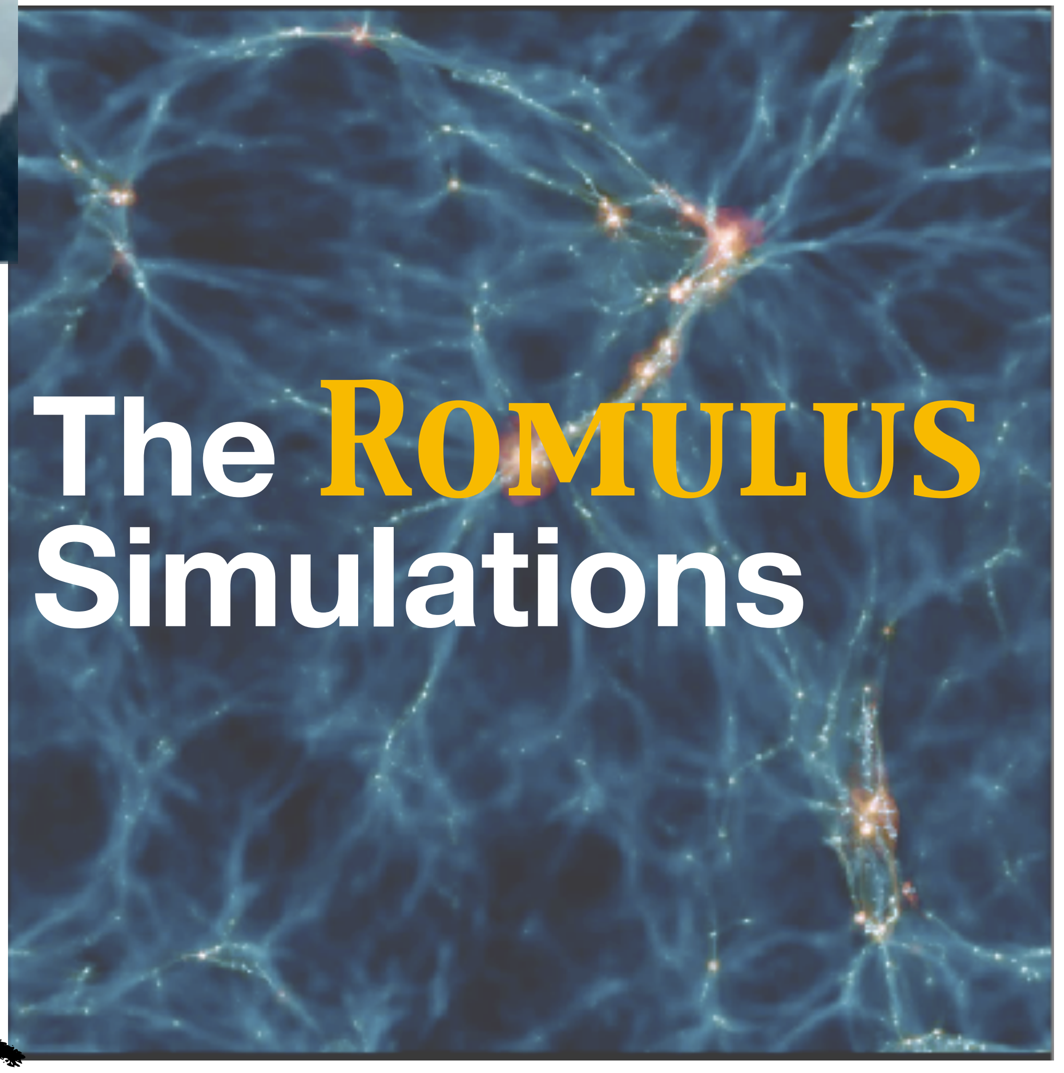
- They’re old- reionization truncated their star formation
- The least massive/faintest live in the least massive dark matter halos, but they are extremely dark matter dominated.
- Their abundance can tell us something about dark matter

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

Ultra-faints in isolation

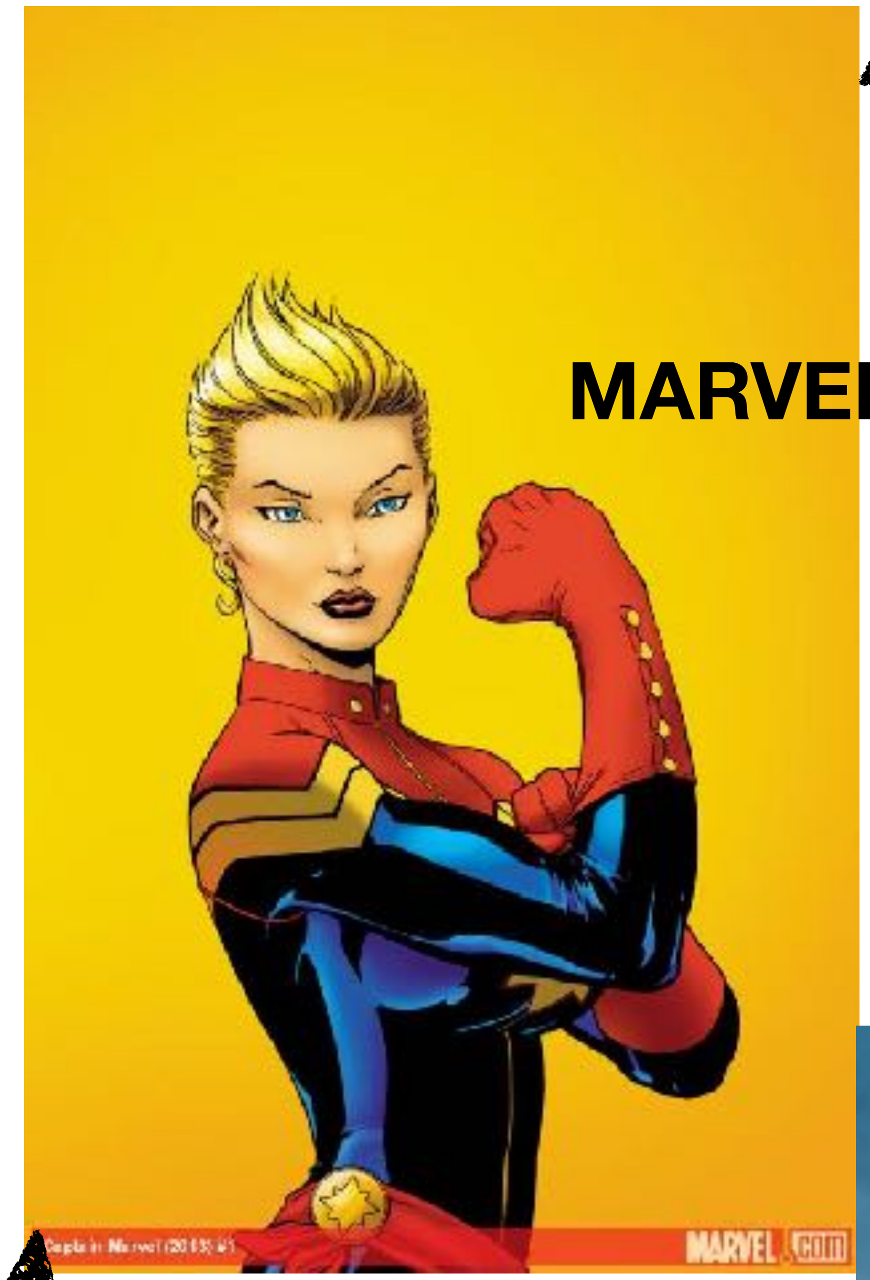
MARVELous Dwarfs

Ultra-faints in the vicinity of a MW



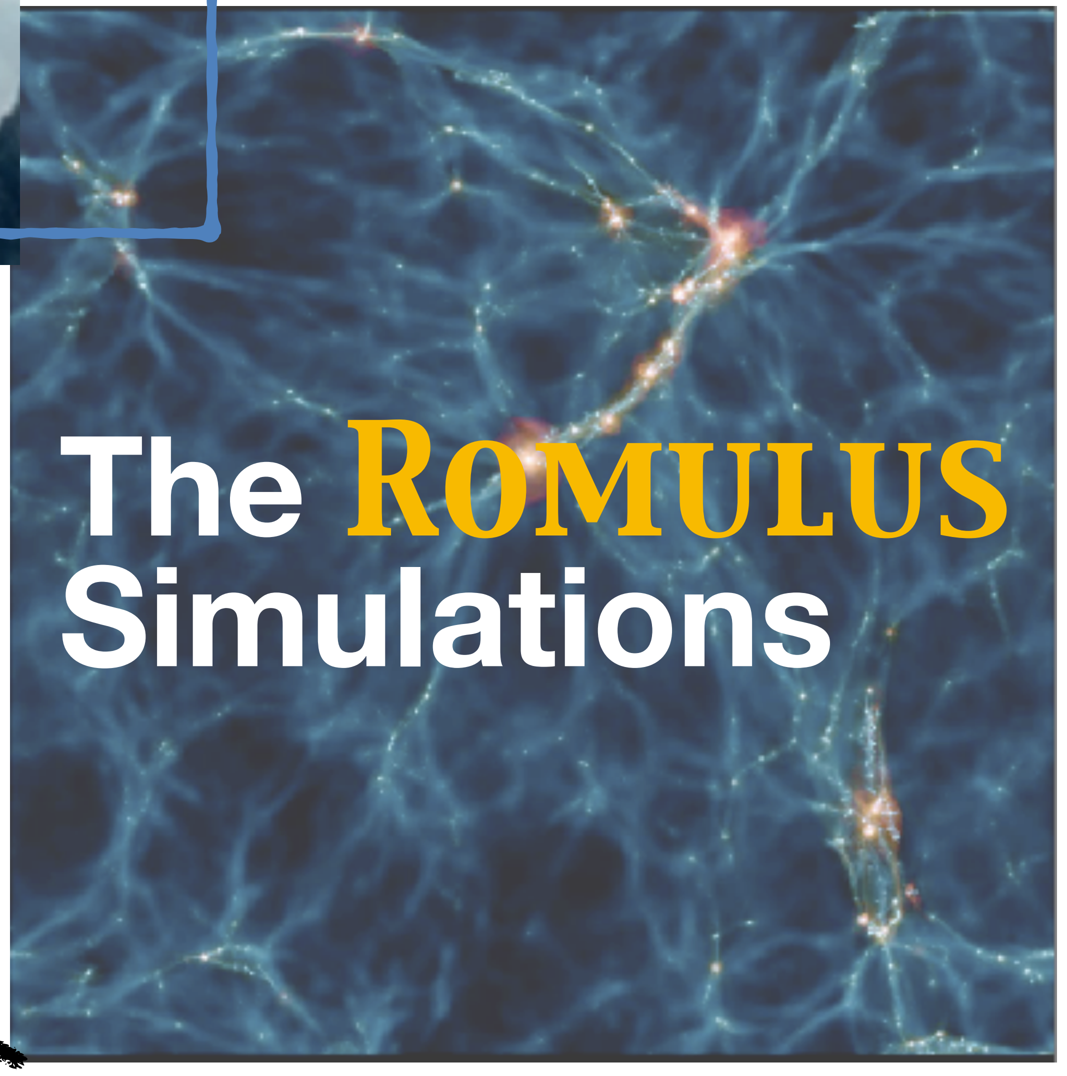
Dwarfs (and UDGs) across environments

Ultra-faints in isolation



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

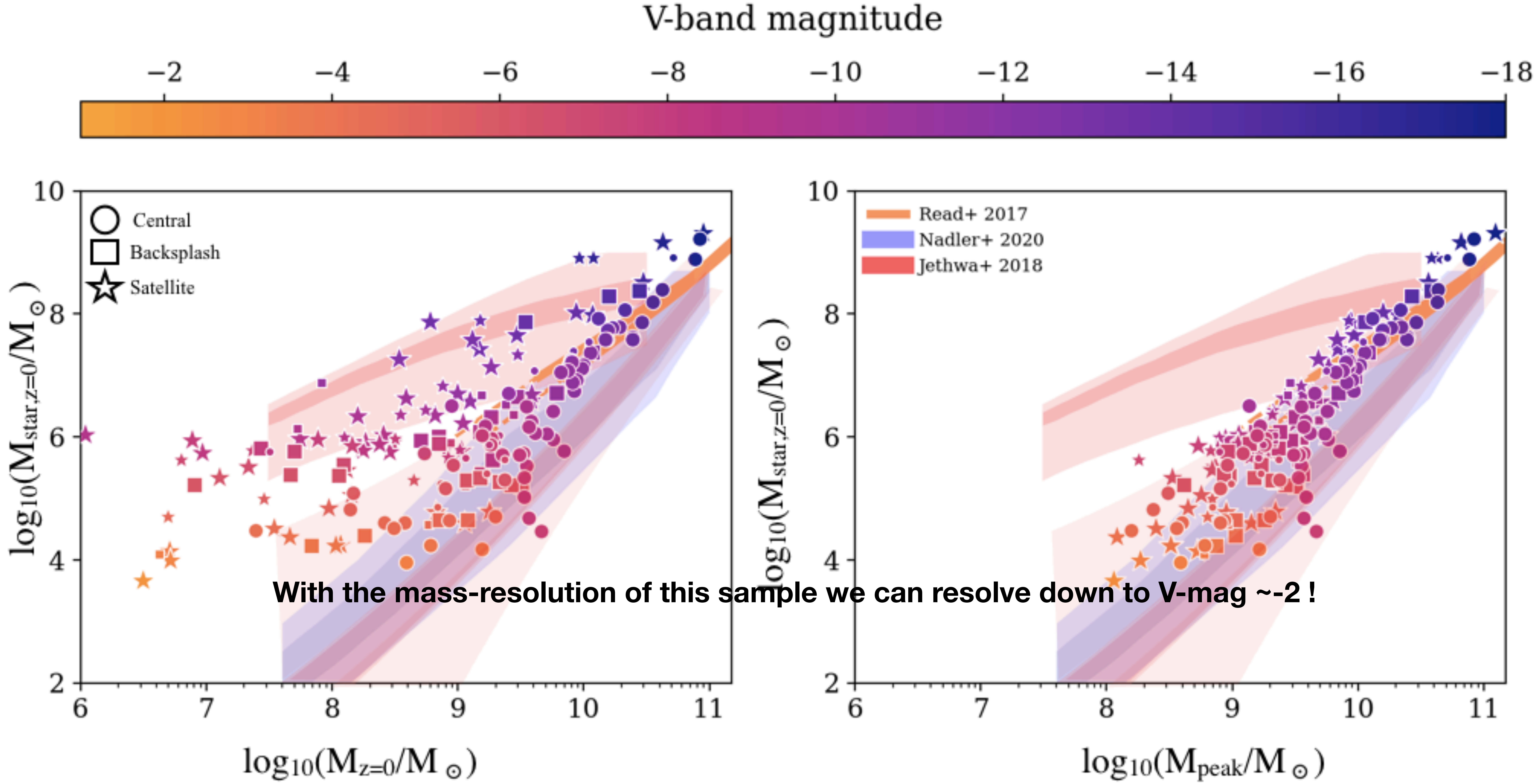
Ultra-faints in the vicinity of a MW



Dwarfs (and UDGs) across environments
My student Jordan Van Nest has been working on this

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

The largest sample of high resolution dwarf galaxies- down to unprecedented low masses

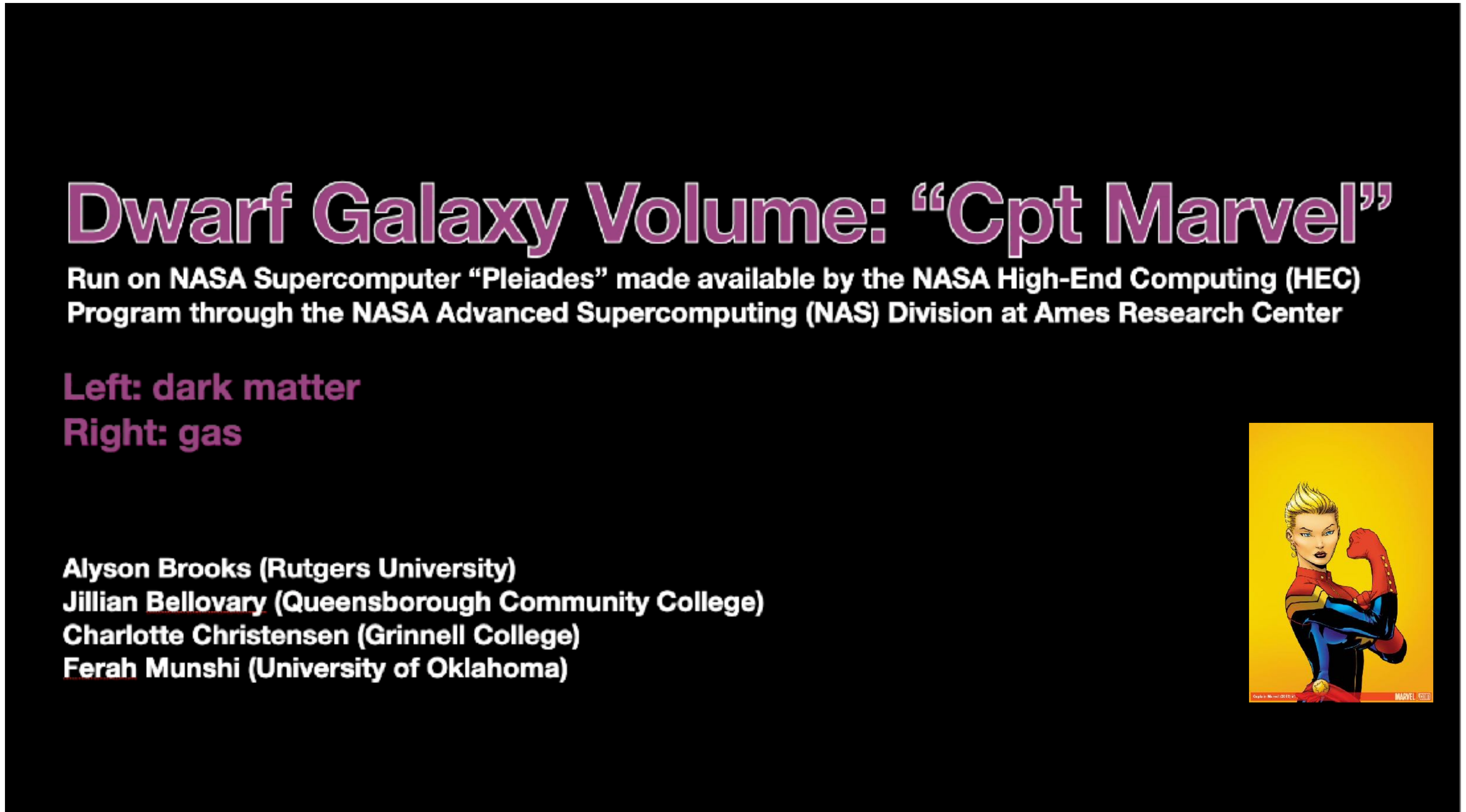


With the mass-resolution of this sample we can resolve down to V-mag ~-2 !

Munshi, Brooks, Applebaum+, in-press arXiv:2101.05822

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

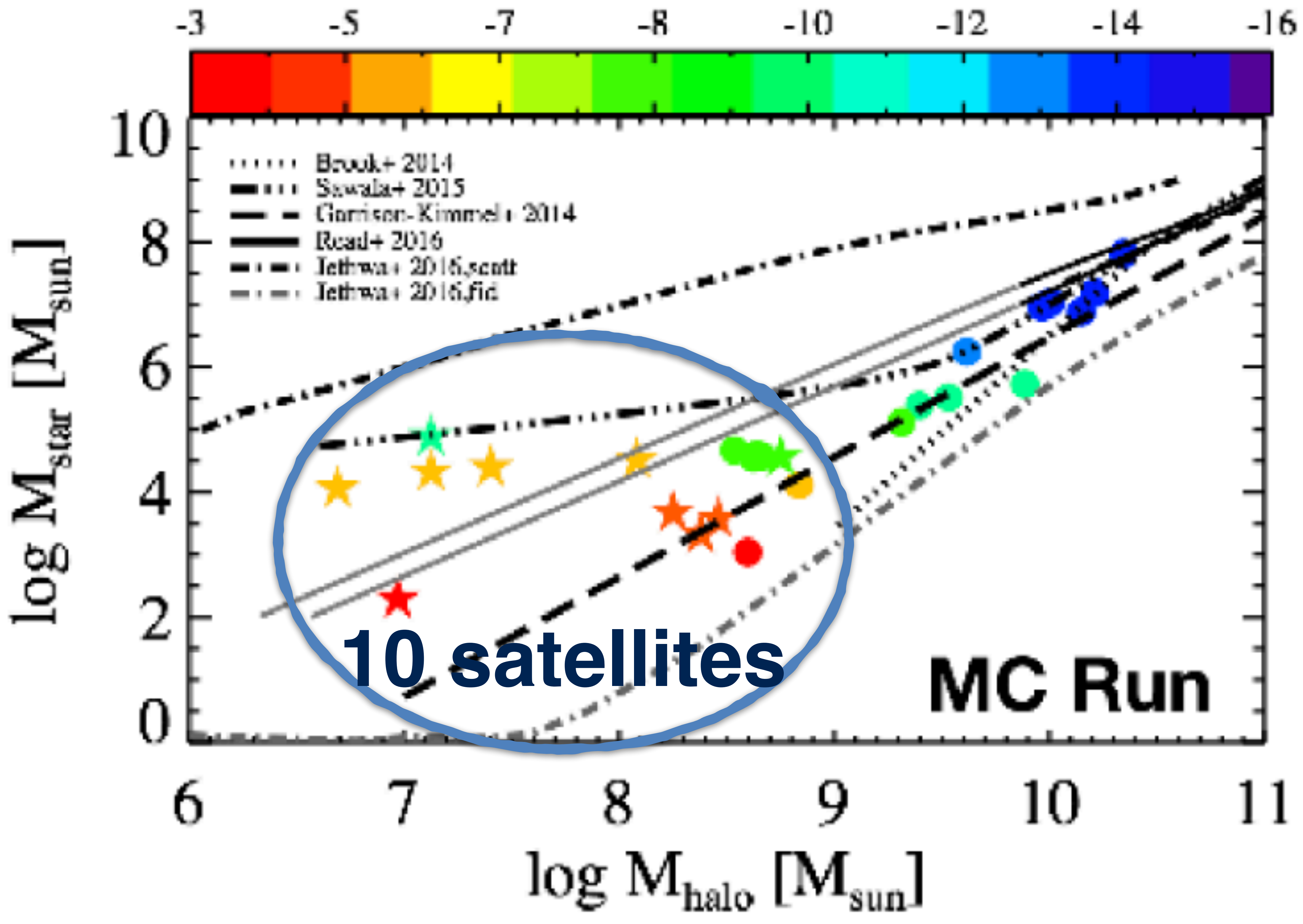


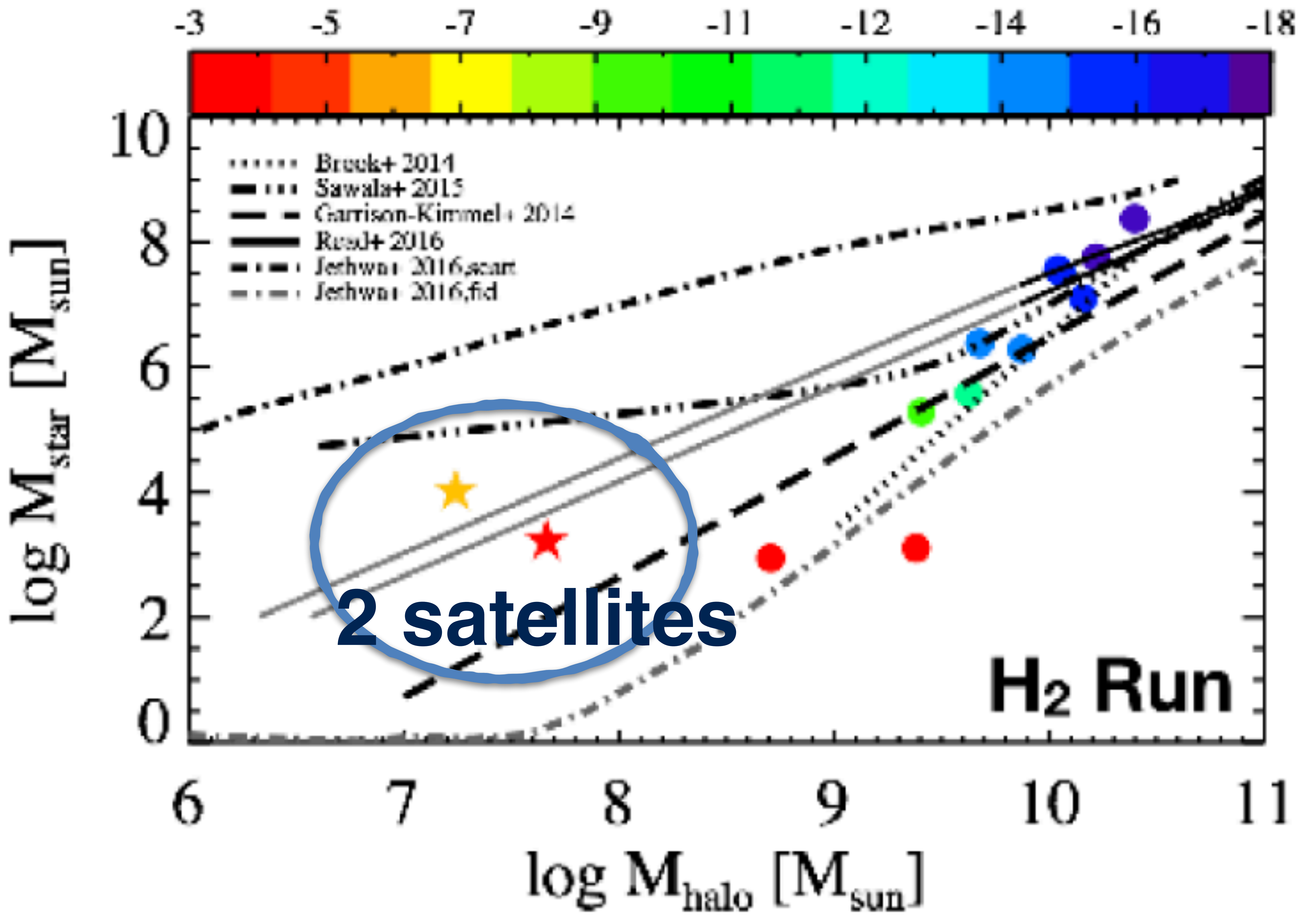
Why do we care?

At ultra-faint masses, the number of halos that host a galaxy (may) drop low. How low and at what mass this drop occurs shapes the low mass end of the stellar mass function, constrains feedback **(& could distinguish dark matter models!)**

This is important to constrain for upcoming telescopes/missions like JWST, Roman Space Telescope (WFIRST), Vera Rubin Observatory (LSST)

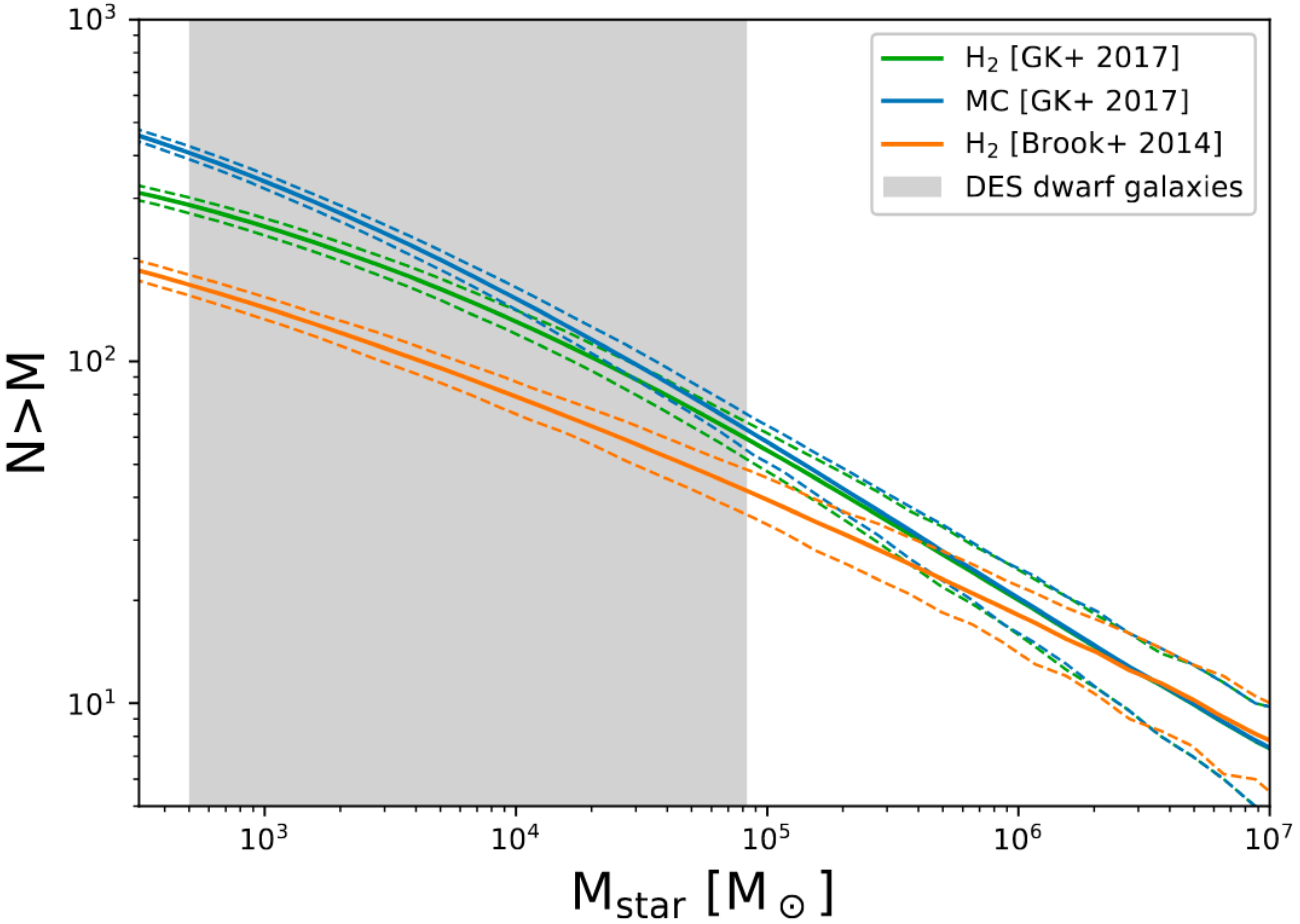
The number of ultra-faints predicted depends on SF model



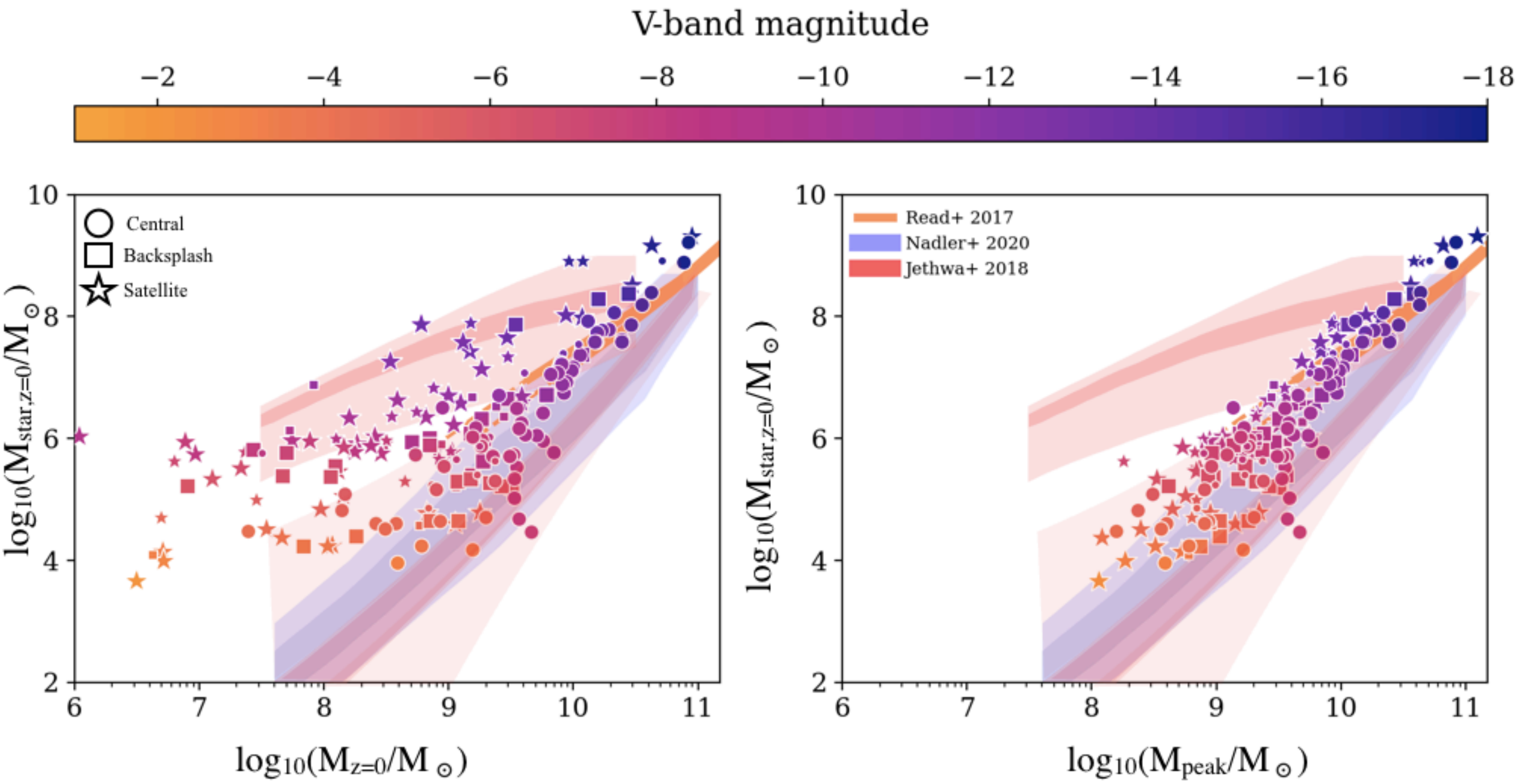


Munshi+ 2019

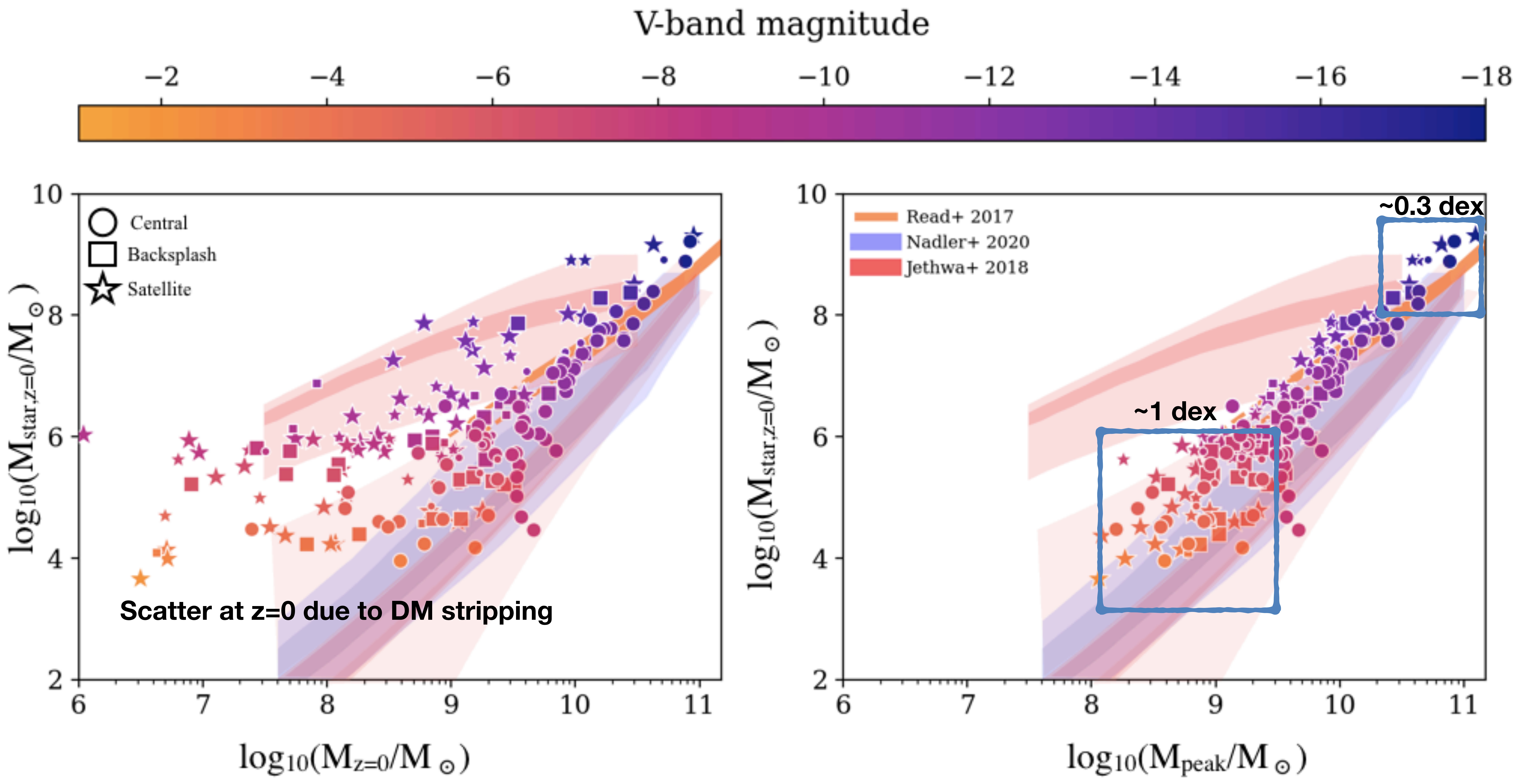
Any predictions you make depend on your star formation and feedback model



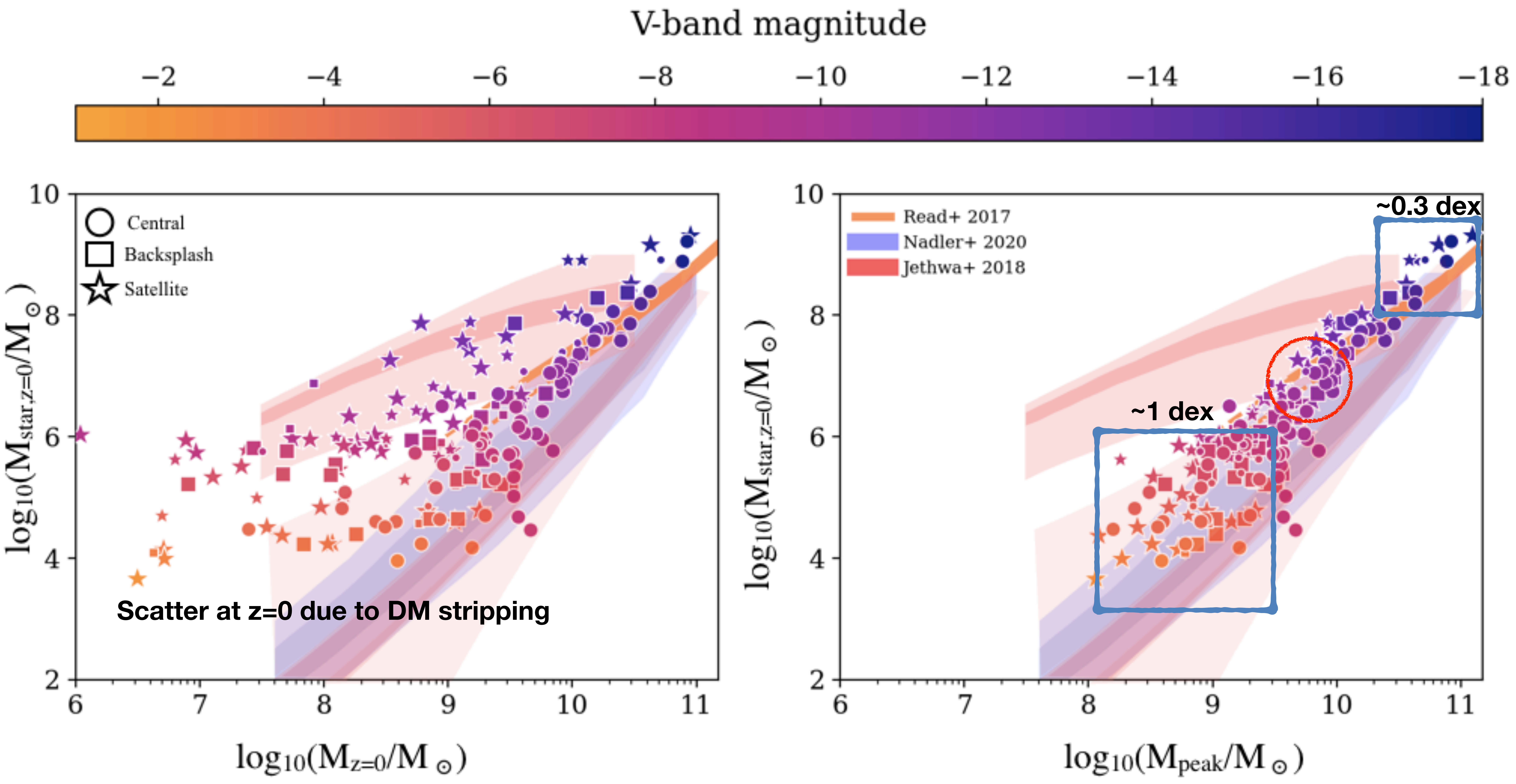
Munshi+ 2019



Munshi, Brooks, Applebaum+, in-press arXiv:2101.05822

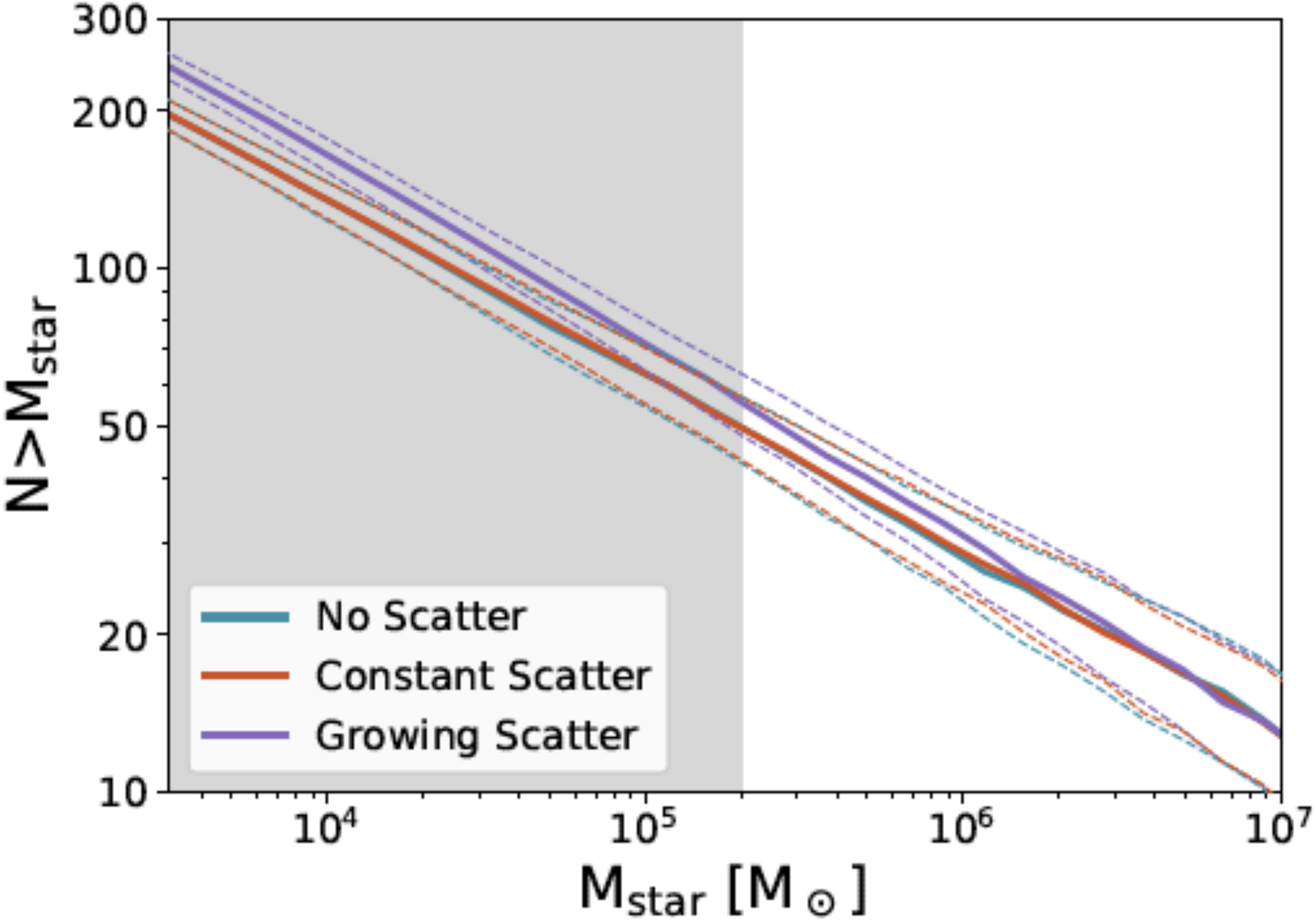


Munshi, Brooks, Applebaum+, in press arXiv:2101.05822



Munshi, Brooks, Applebaum+, in press arXiv:2101.05822

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



How do feedback and star formation affect the dark matter in dwarf galaxies?

Baryons & feedback can alter the dark matter in dwarf galaxies in three ways:

(1) it alters (lowers) the masses of dark matter halos predicted at dwarf galaxy scales and,

(2) it affects how good of a measure the lowest occupied halo is for constraining dark matter models

(3) We don't fully understand the baryonic physics- simple changes to how we model the baryons can change your predictions drastically!

Big question #2: What challenges remain to be solved? *Can CDM+Baryons solve all the things?*

There is no reason to favor CDM once you consider baryons (in small galaxies)

Can we use galaxy formation simulations to predict an observable that favors a particular dark matter model?

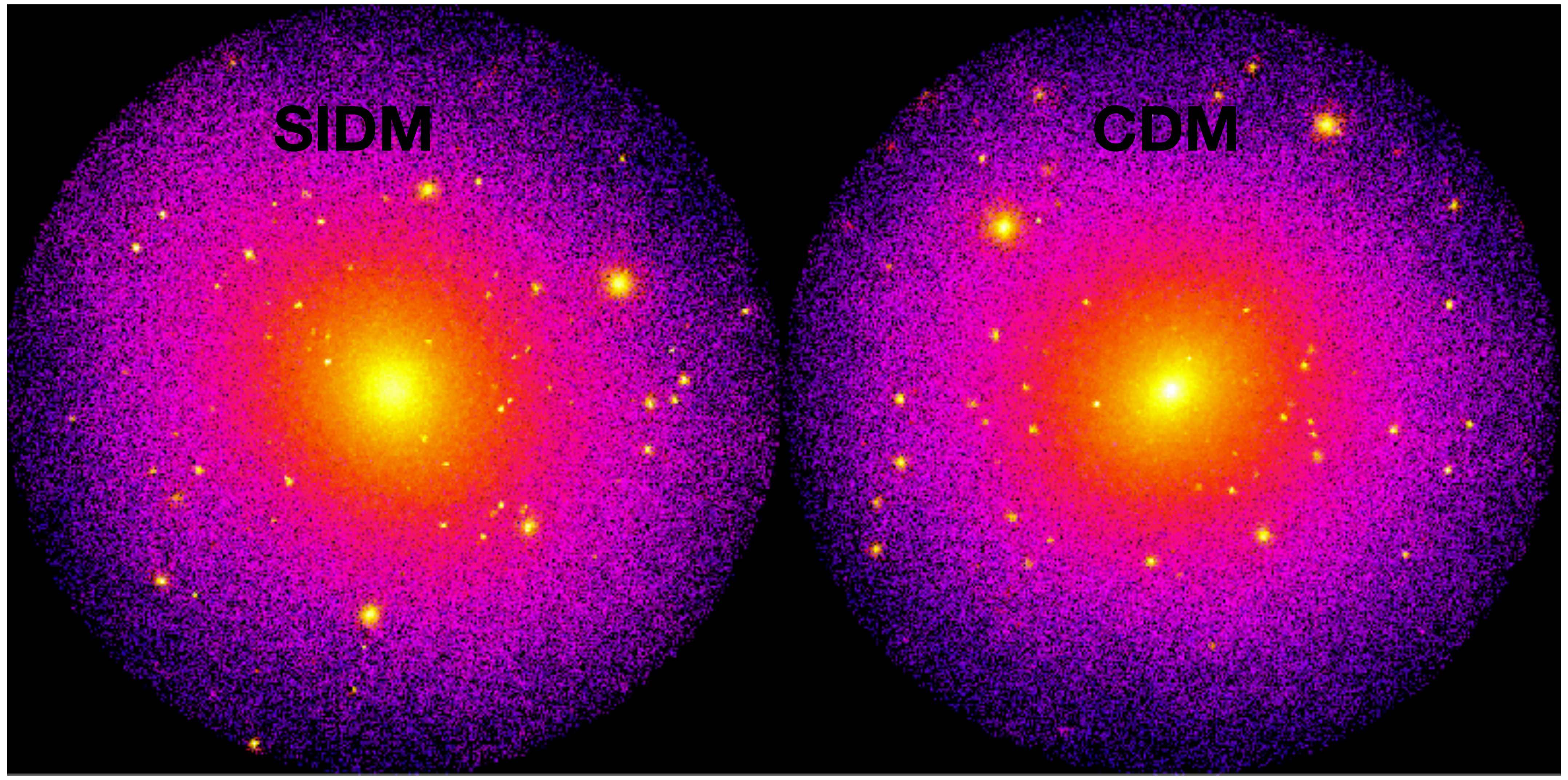
"challenge"	**CDM+Baryons**	WDM+Baryons	**SIDM+Baryons**
Bulge-less disk galaxies	✓	✓	✓
The Cusp/Core Problem	✓	✓	✓
Too Big to Fail	✓	✓	✓
Missing Satellites	✓	✓	✓
Missing Dwarfs	✓	✓	✓
Diversity	?	?	✓?

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

Observables we will be looking into:

1. Shapes of dwarf galaxies
2. The edge of galaxy formation- which halos host a galaxy?
3. Diversity of dwarf galaxies

All of predictions will be testable in the next 10 years with Roman Space Telescope, Vera Rubin Observatory and JWST



How do feedback and star formation affect the dark matter in dwarf galaxies?

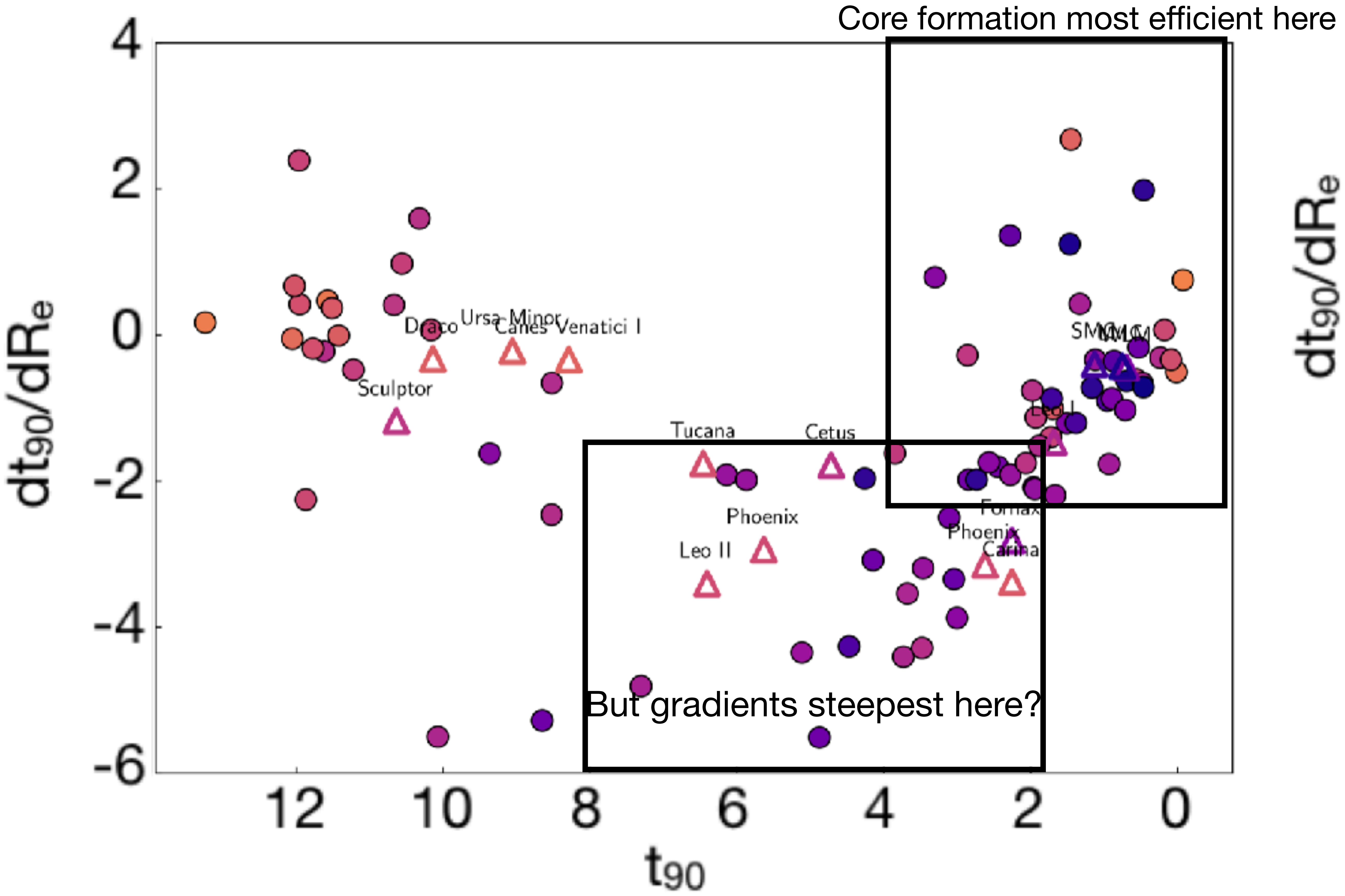
Feedback can alter the dark matter in dwarf galaxies. If we want to place constraints on dark matter using dwarf galaxies, we need to better understand baryonic processes.

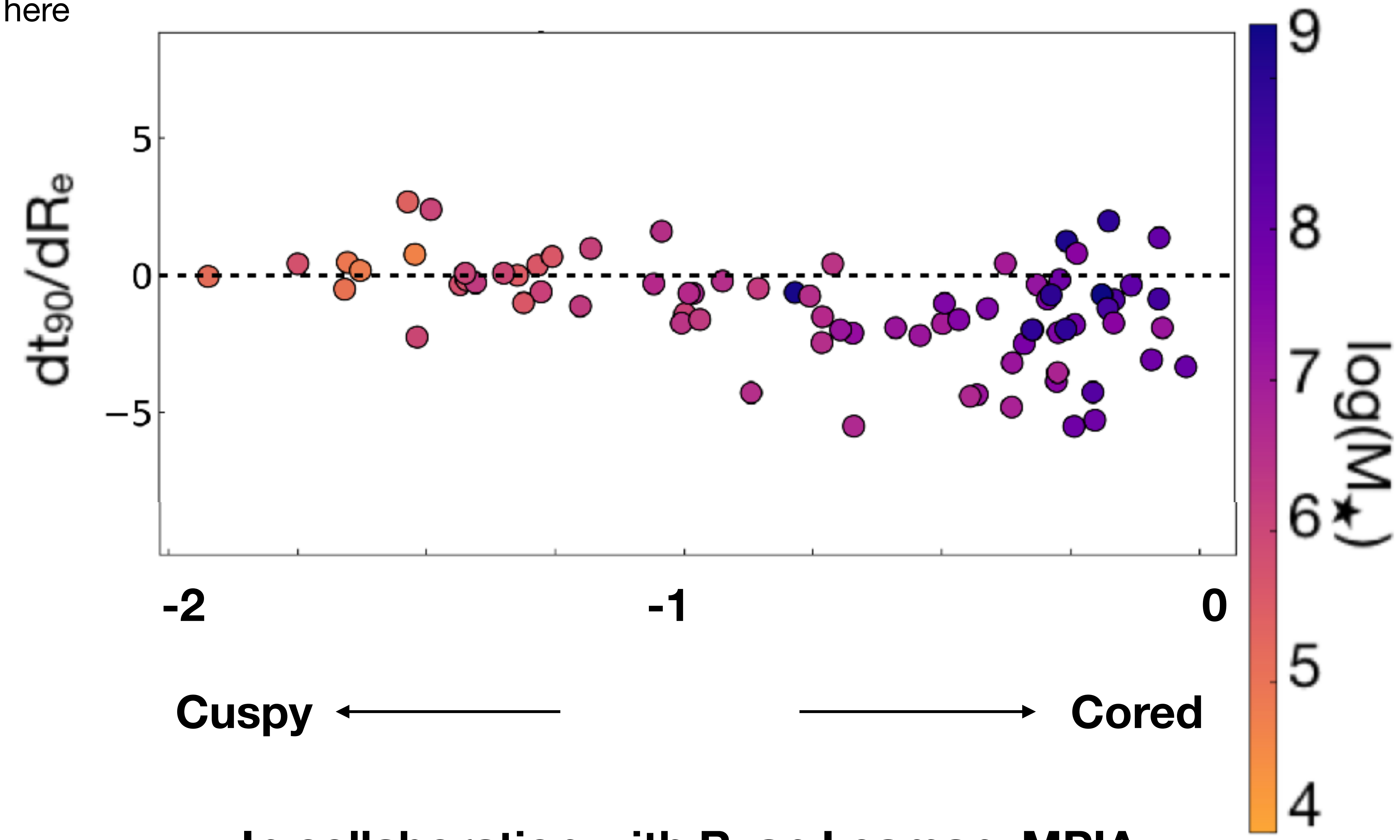
What challenges remain to be solved?

With baryons (i.e. feedback), we can make a lot of alternative DM scenarios work. We need to think about how we can use future data to differentiate between them all!

Where can students get involved?

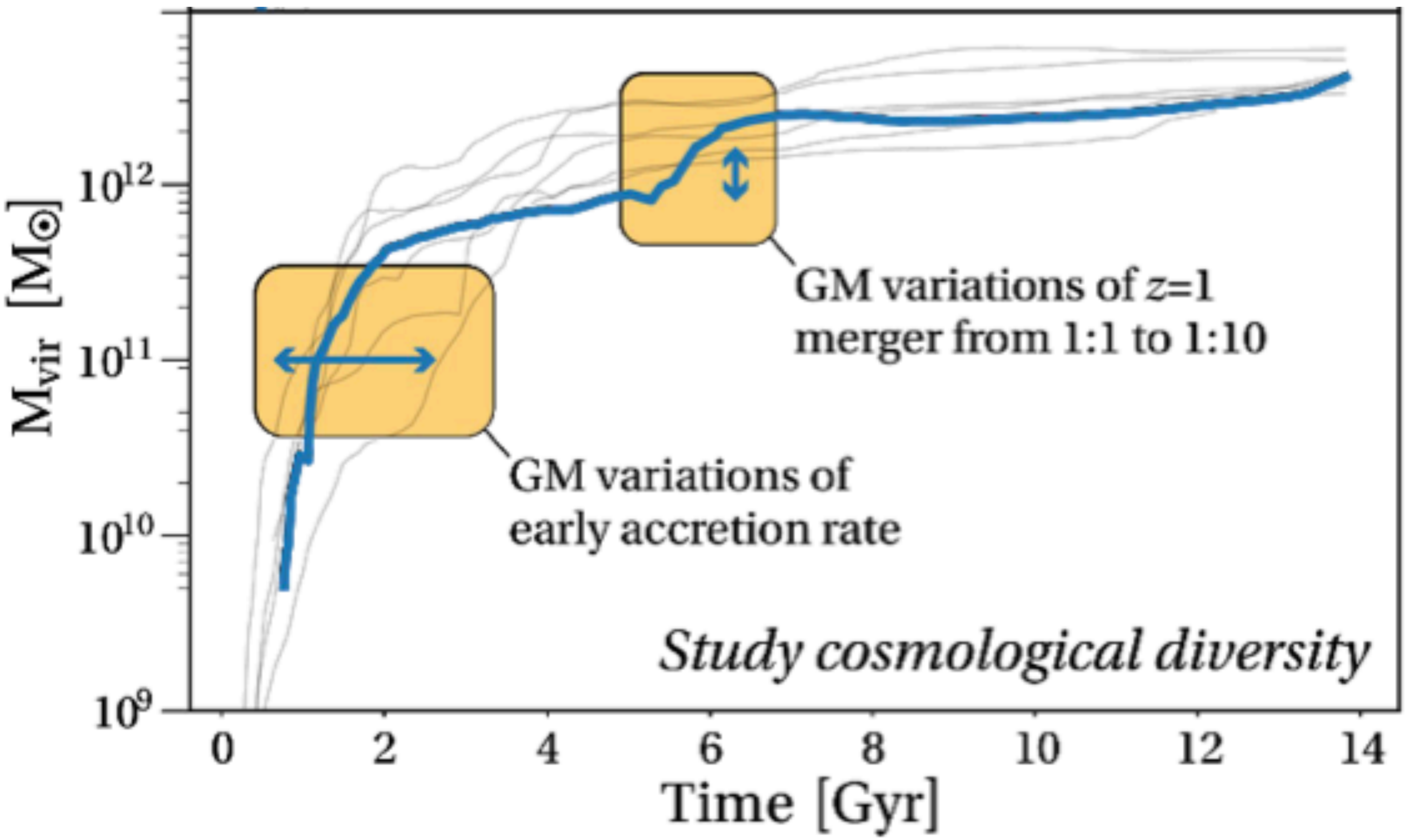
Radial Gradients in Dwarf galaxies- a consequence of core formation?

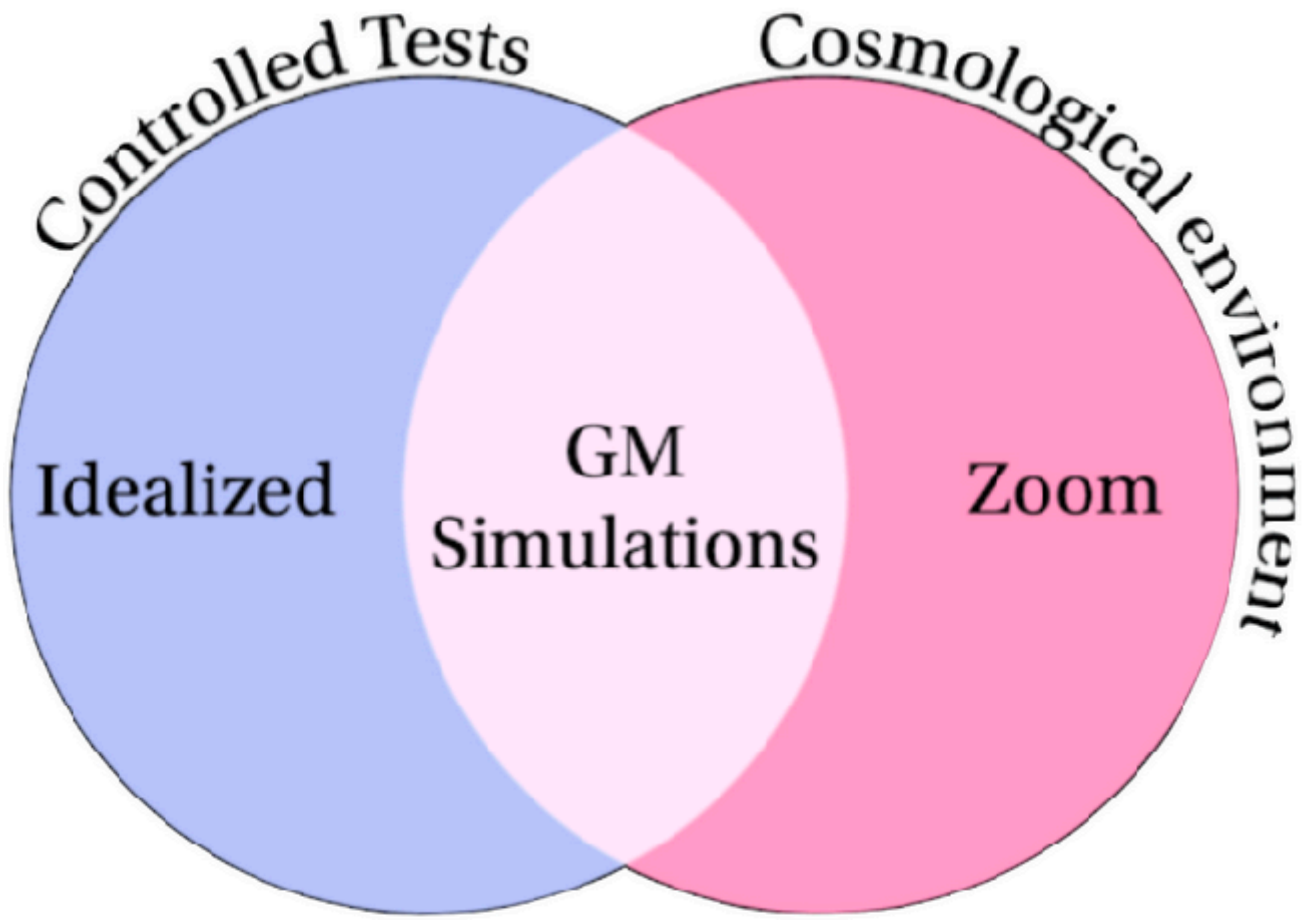




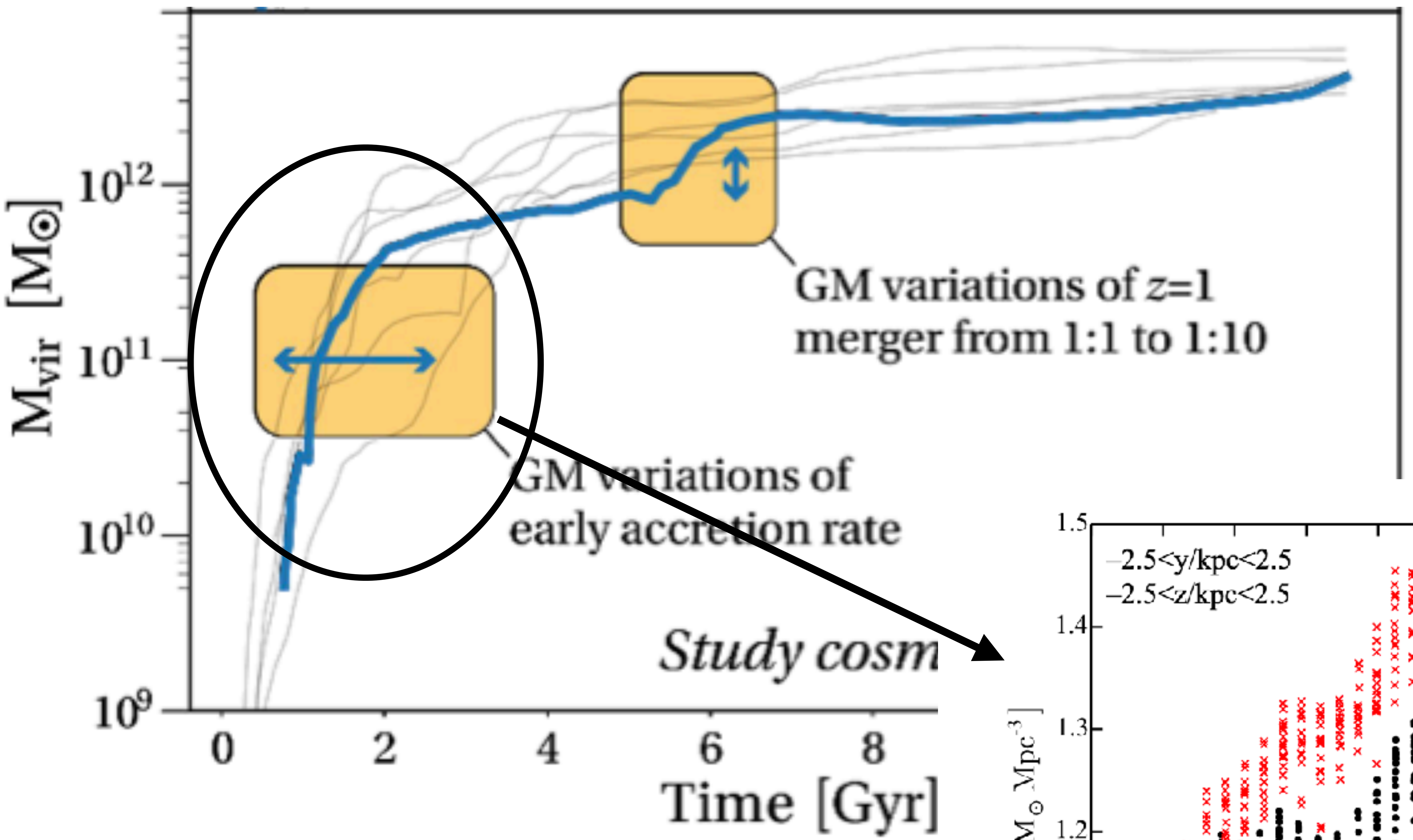
In collaboration with Ryan Leaman, MPIA

Work started at OU by my former UG Claire Riggs- now 1st year grad at Rutgers

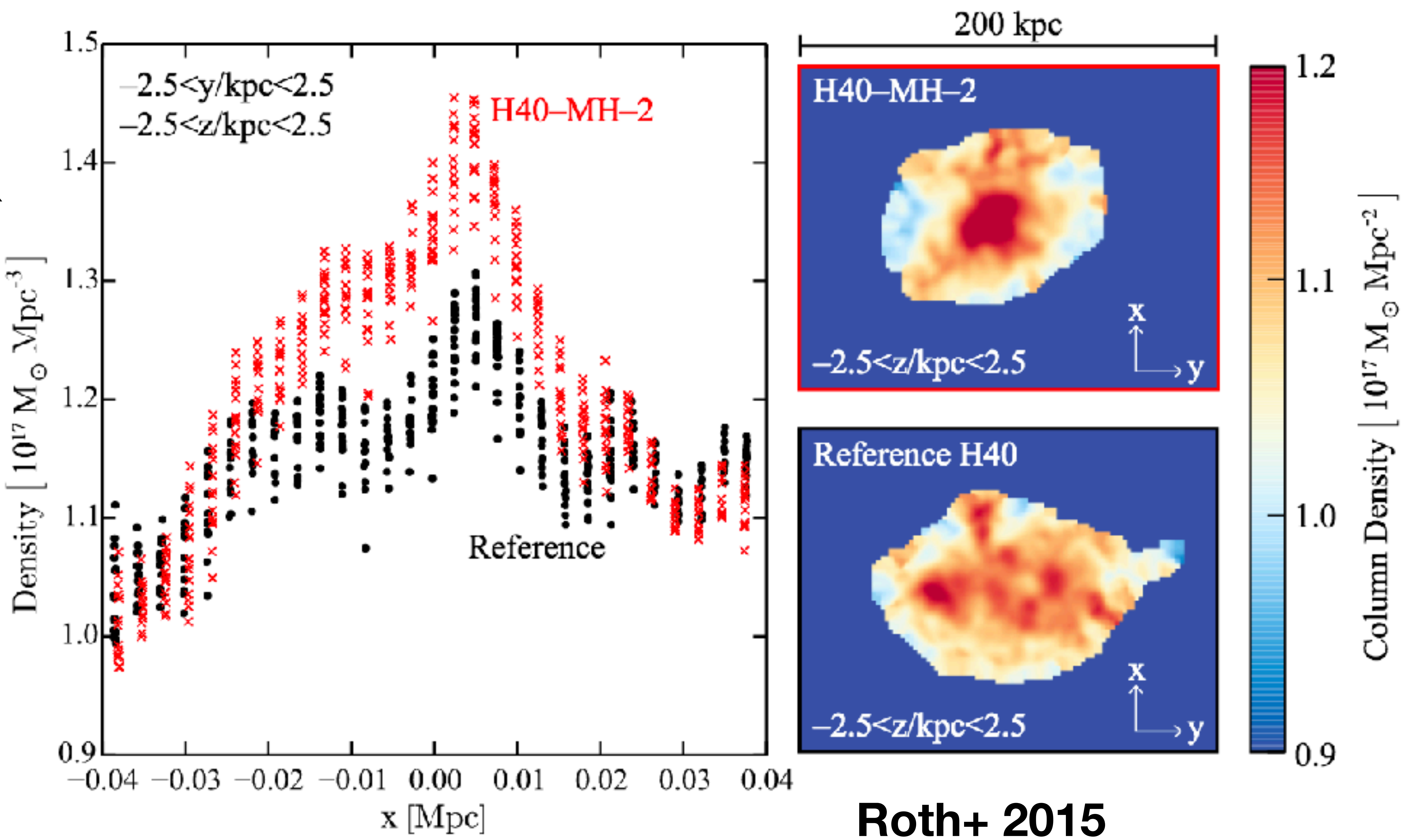




Genetic Modification (GM): Performing controlled experiments in galaxy formation

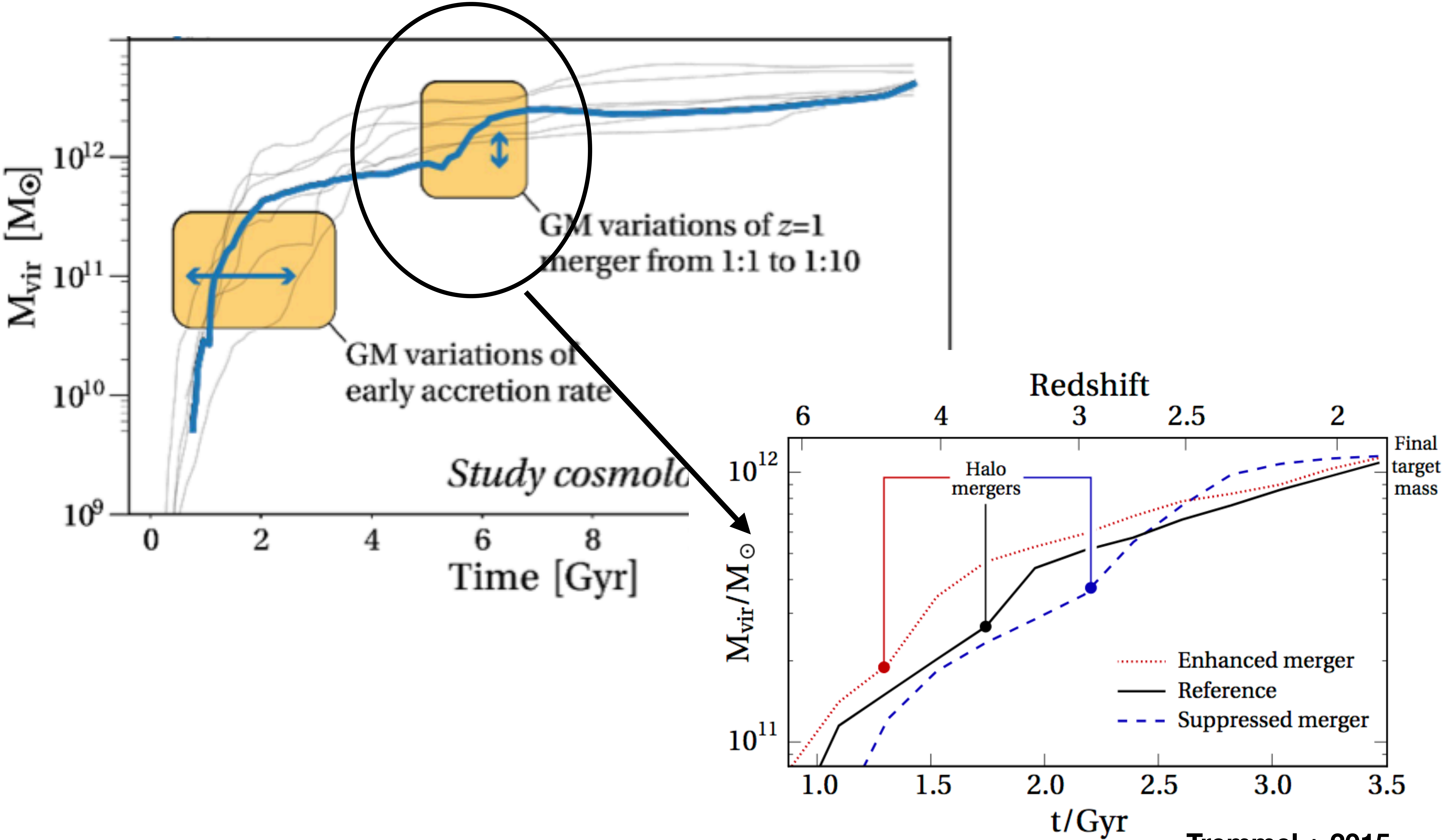


M_{vir} [$M_\odot$]
10^{12}
10^{11}
10^{10}
10^9
GM variations of z=1 merger from 1:1 to 1:10
GM variations of early accretion rate
Study cosm
0
2
4
6
8
Time [Gyr]



−2.5<y/kpc<2.5
−2.5<z/kpc<2.5
H40–MH–2
Reference
Density [10^{17} $M_\odot$ Mpc^{-3}]
x [Mpc]
200 kpc
H40–MH–2
Reference H40
−2.5<z/kpc<2.5
x
y
Column Density [10^{17} $M_\odot$ Mpc^{-2}]
1.2
1.1
1.0
0.9

Roth+ 2015



Tremmel + 2015

Leveraging “Big Data” techinques

Two different database methodologies have been developed-

1. **Web browser based service to flexibly calculate and visualize galactic merger trees found in large-scale astrophysical simulations:** service uses a new, parallel data management system called Myria as back-end and the state-of-the-art data visualization library D3 within its graphical front-end. **This service was demonstrated live at the workshop for Data Analytics in the Cloud in June 2014 on a 5 TB dataset.**

Leveraging "Big Data" techniques

Two different database methodologies have been developed-

2. TANGOS **Halo Database:** ingests, runs and calculates various basic properties of all halos in a simulation (including profiles, images etc) then exposes them through a python interface and webserver.

These techniques are unique and one-of-a-kind in the simulation community.
Undergraduate students will get extremely **valuable, hands-on experience with database manipulation & management and usage with very large data samples.**

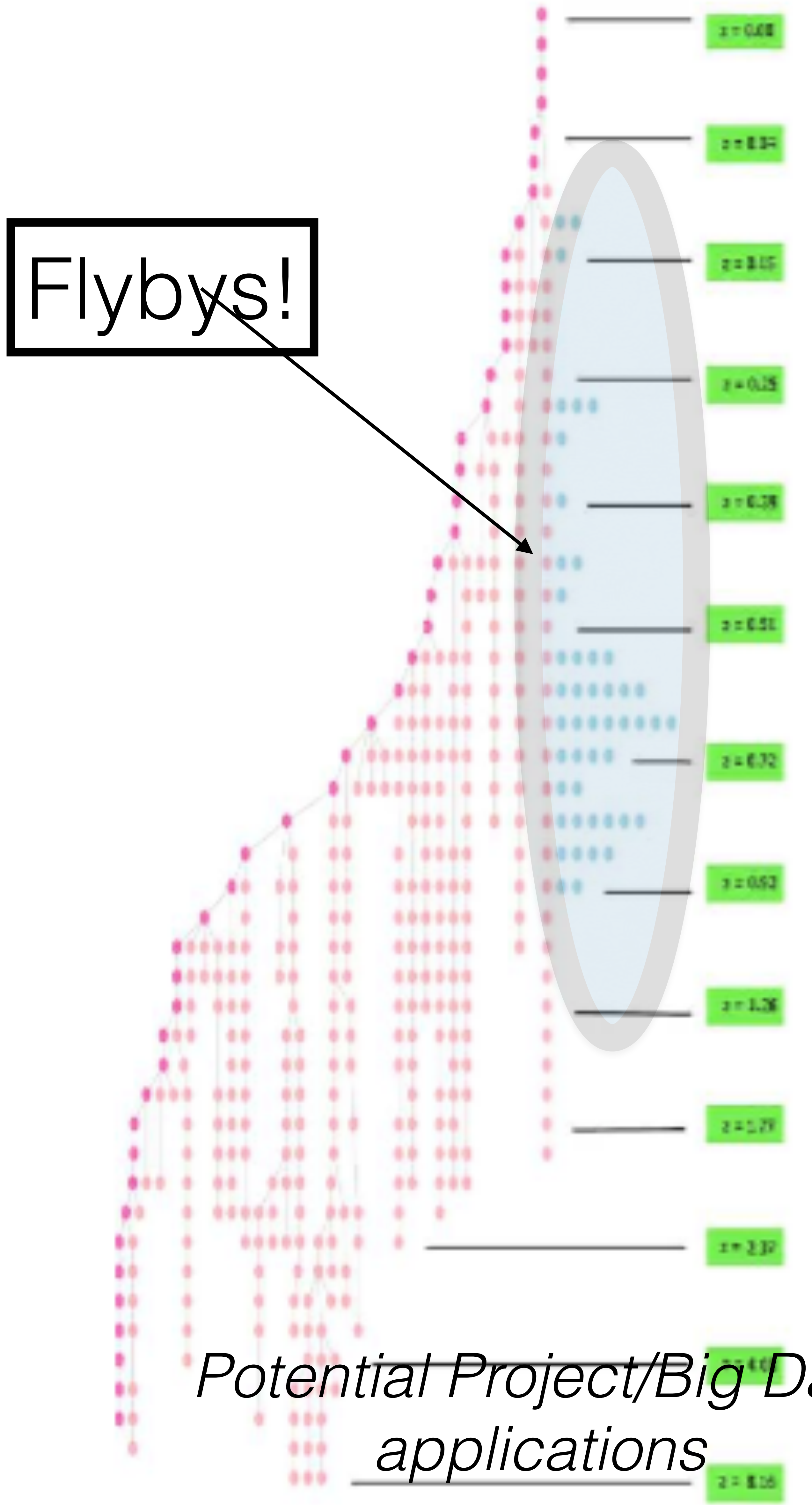
Pontzen+ 2018

The Low Surface Brightness Universe

Machine Learning on Simulation Outputs-

Decision Tree **Machine Learning:** Romulus25 studies can leverage machine learning techniques since the sample of galaxies is enormous.

Example: Galaxies can not only be perturbed by mergers, but also by *flybys.* *Decision Tree ML* can identify flybys and we can study whether flybys are responsible for massive low surface brightness galaxies (or aligned mergers?) e.g. DiCintio+ 2019



Potential Project/Big Data applications

EPO & DEI

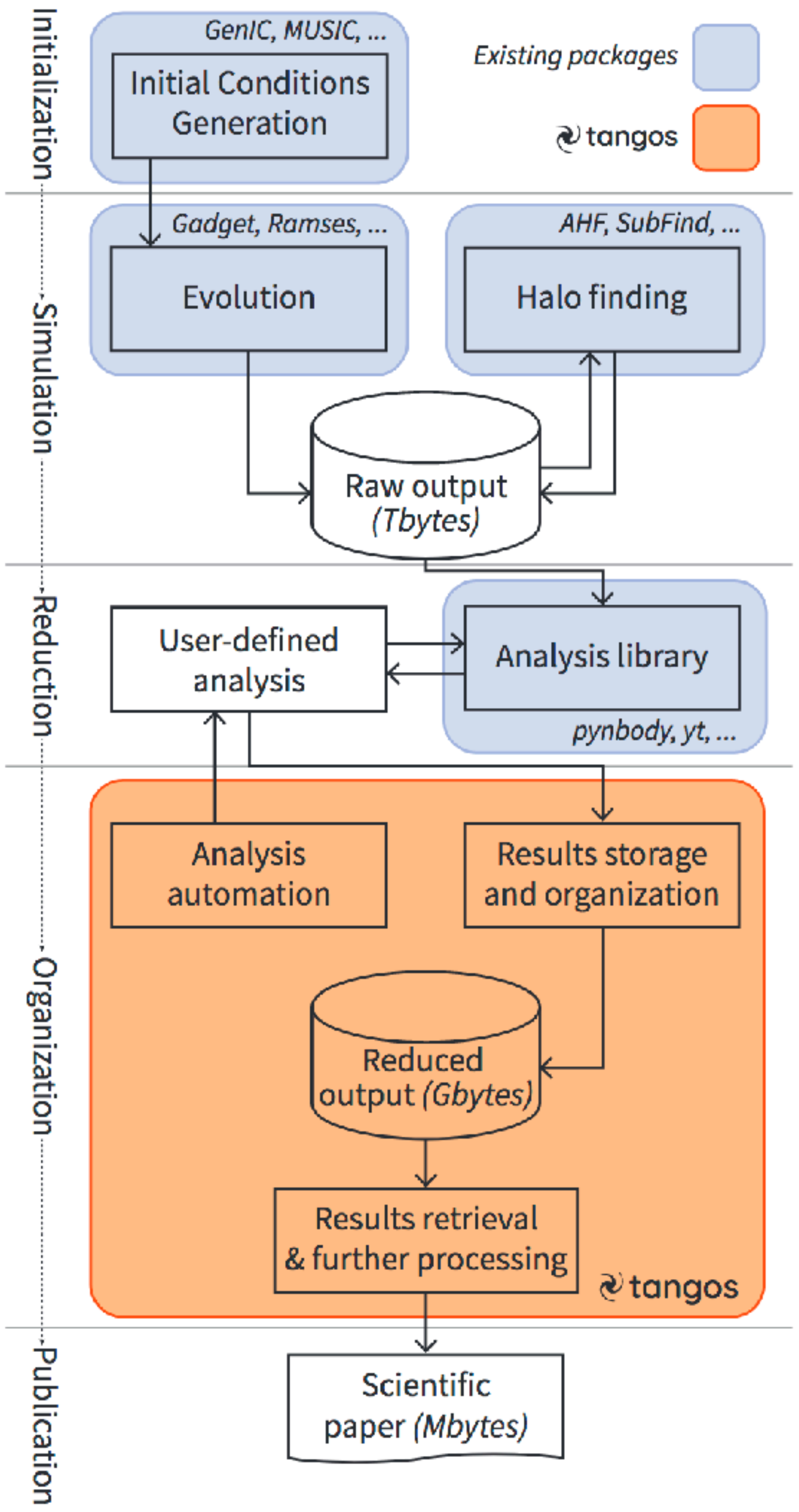
Mobile Planetarium for local community engagement: Relatively inexpensive method of bringing astronomy directly to schools, and can be adapted for a variety of age groups to address learning goals. Has been funded previously by HST EPO.

Outreach with VR: use 3D images and inexpensive VR technology to bring astronomy to classrooms in the area. Connects with the DTI, connects with the community.

Seek funding to increase diversity in physics major: S-STEM funding as a tool to make physics curriculum more inclusive

Connection to data science at Wellesley

TANGOS **Halo Database:** ingests, runs and calculates various basic properties of all halos in a simulation (including profiles, images etc) then exposes them through a python interface and webserver.



Pontzen+ 2018

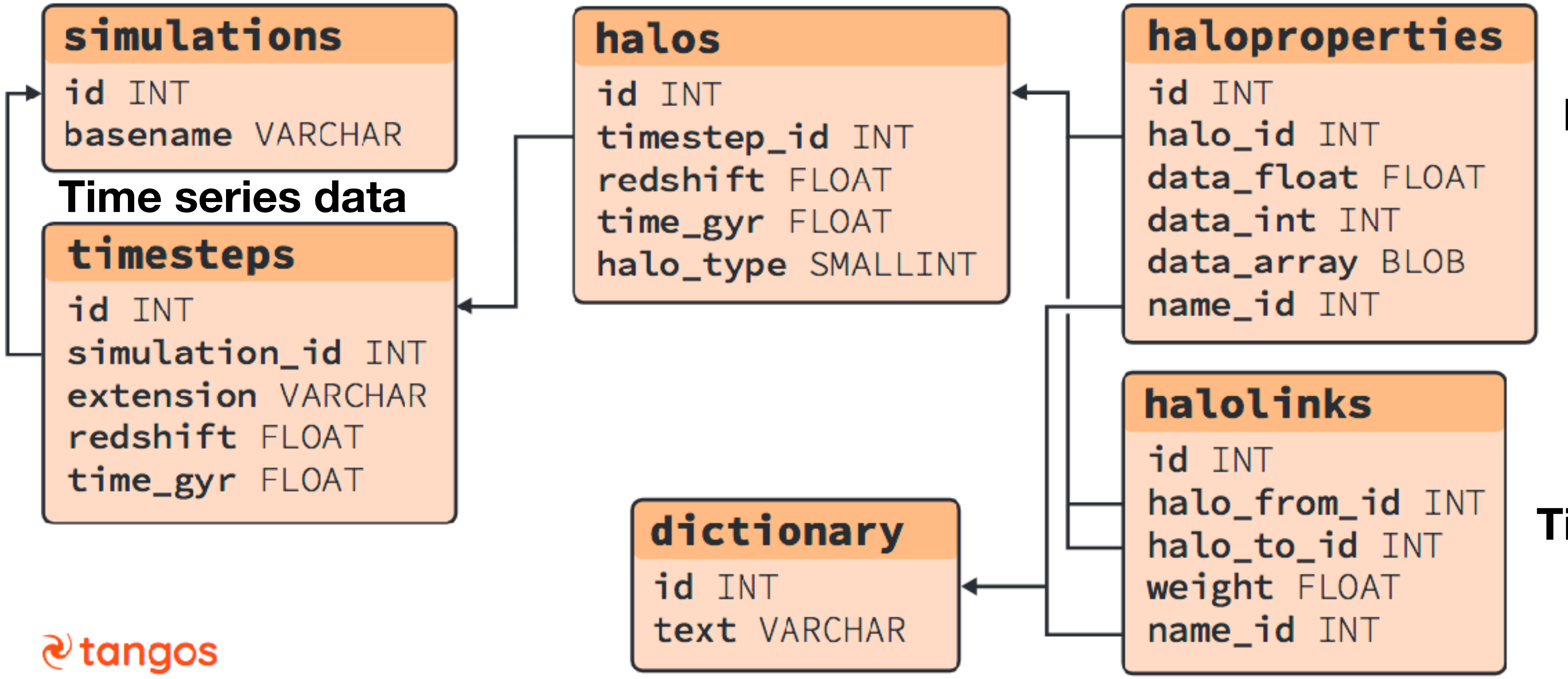
https://www.youtube.com/watch?v=xHyzJmNsVM

Any data

Sub-categories of data

Properties of that data sub-category

Time series data



Time series links within sub-category

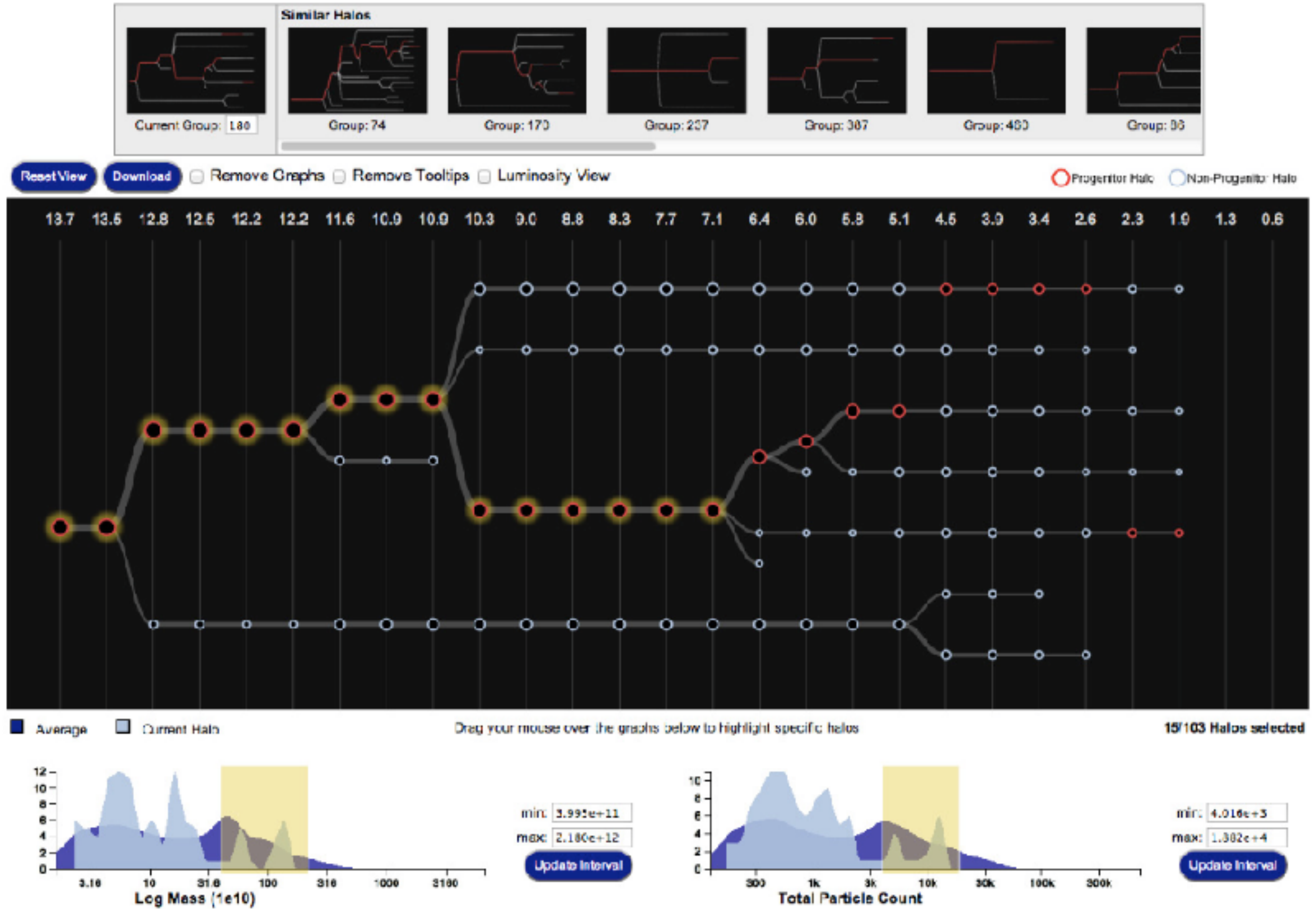
tangos

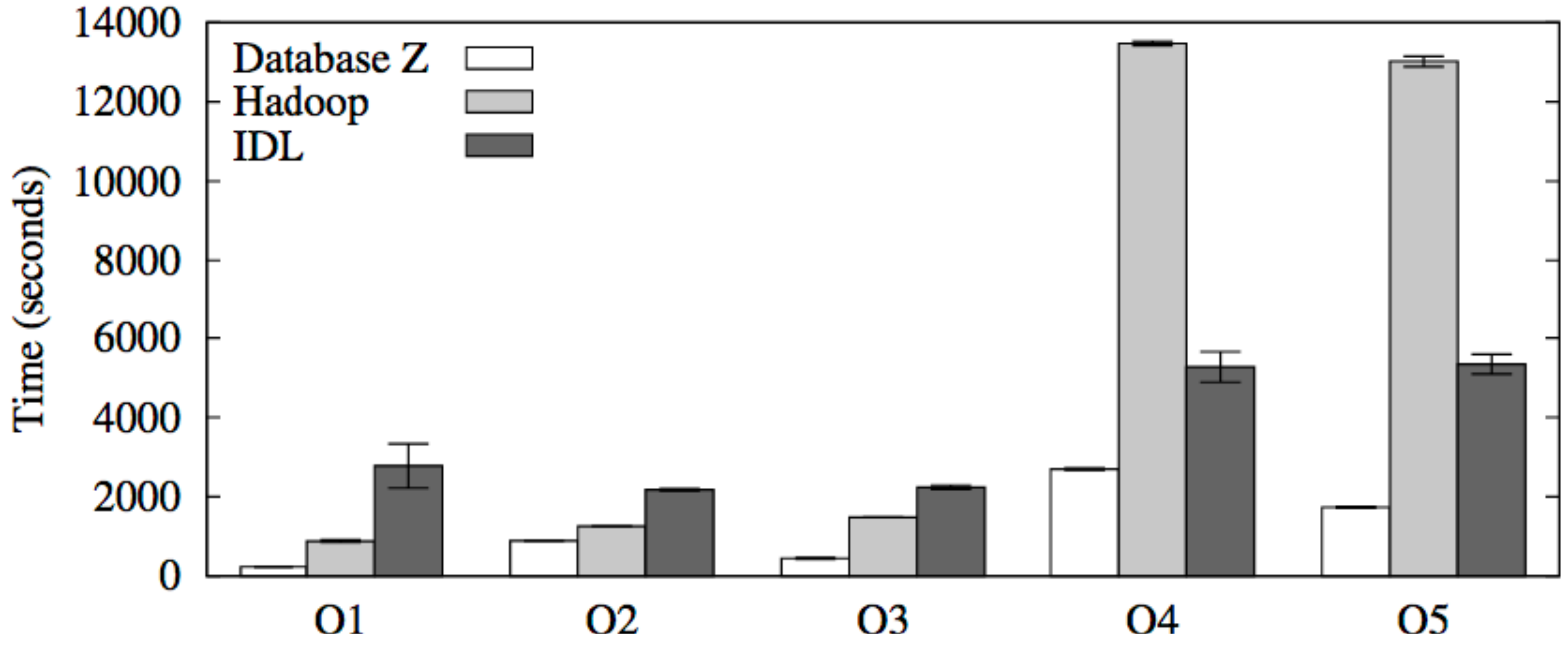
Python accessible data products

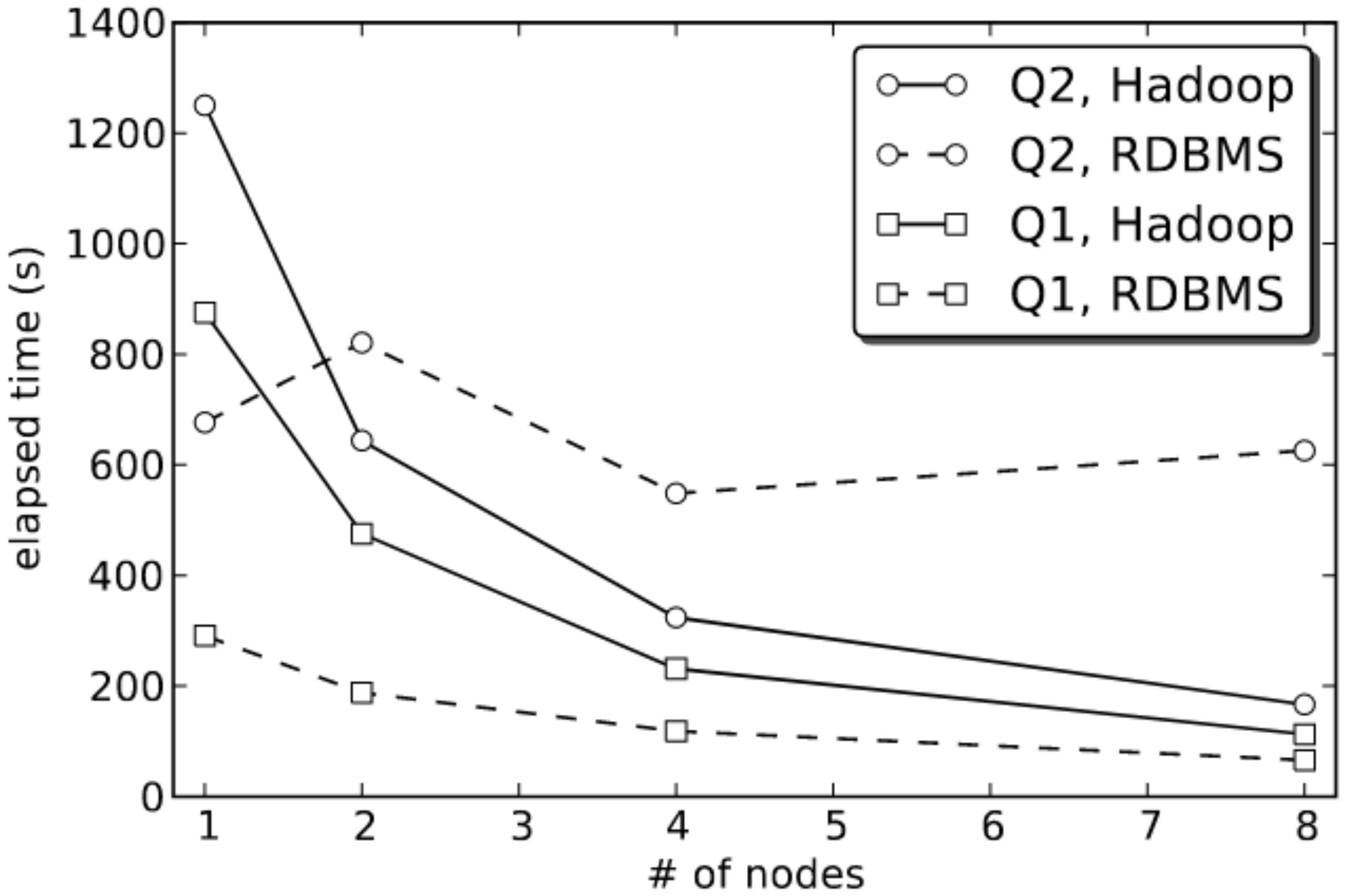
"Relational Database"

Applications in:
-Cognitive Science
-Digital Humanities
- any statistical databases (e.g. economics, social justice…)

Connection to Wellesley: exploring database methodologies





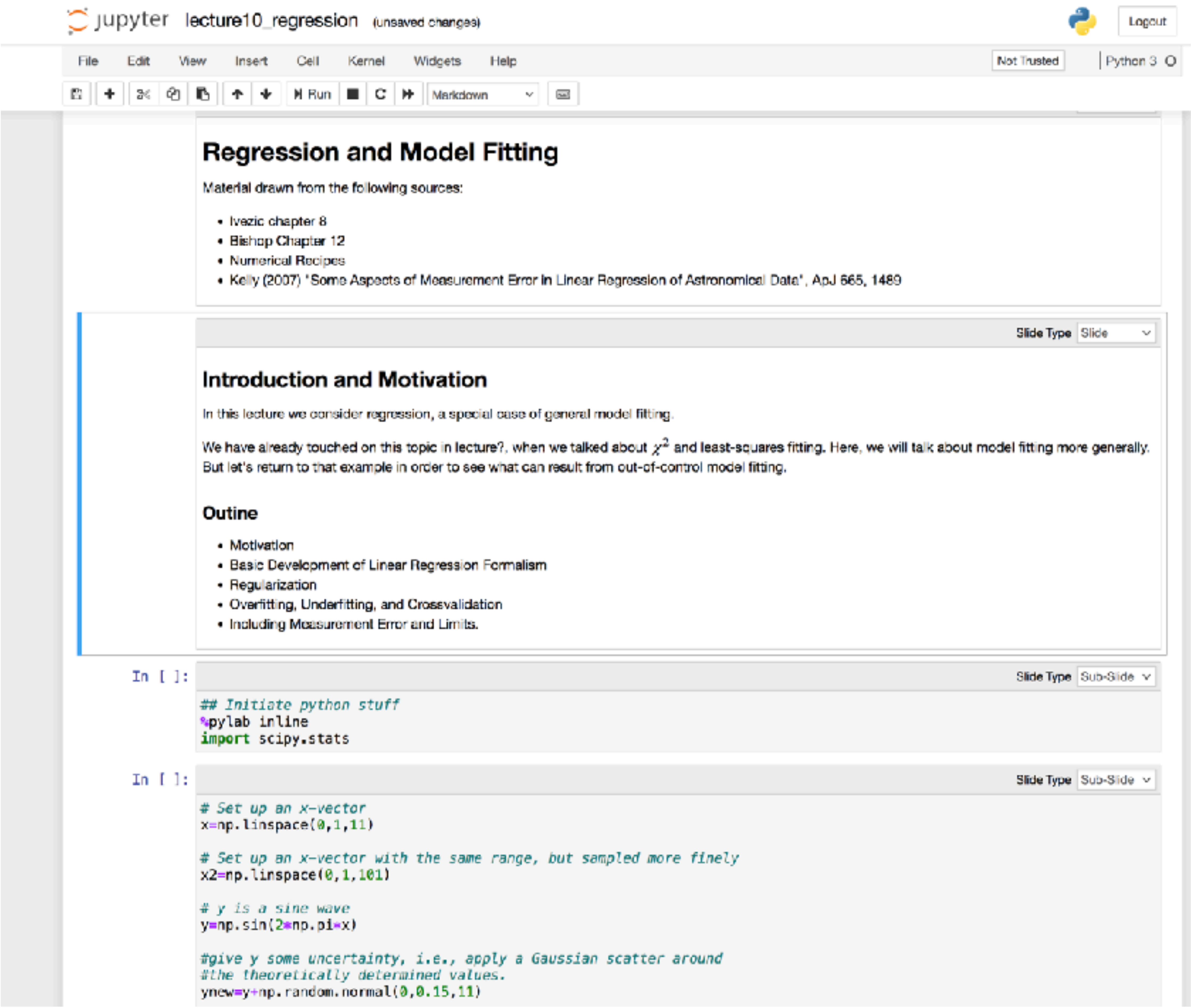


Different techniques complementary to different sets of data and computational resources- could be an interesting cross disciplinary project!

Connection to Wellesley- data science with a concentration in physics?

- Example experiential capstones: data analysis at CERN, working at the Center for Computational Astrophysics (CCA), quantum computing internships in industry…

- Course work hands-on & project-based via jupyter notebooks



github.com/ferahm/datascience_example

Take home science message: Feedback effects are imprinted on observations of galaxies. In order to understand how galaxies got to look the way they do, we must understand the (messy) role of feedback in galaxy formation. But, upcoming observations will constrain the baryons, allowing simulations to constrain dark matter!

Take home student message: Working with galaxy formation simulation data trains you for multiple career paths, from academic to industry. There are some really fun data science projects just waiting for you!

Questions?