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nbody.shop

# 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:** Claire Riggs (OU—>Rutgers), Elaad Applebaum (Rutgers—>data science), Jordan Van Nest (OU), Alexi Musick (OU), Bianca Azartash-Namin (OU), Anna Engelhardt (OU REU, Grinnell College)

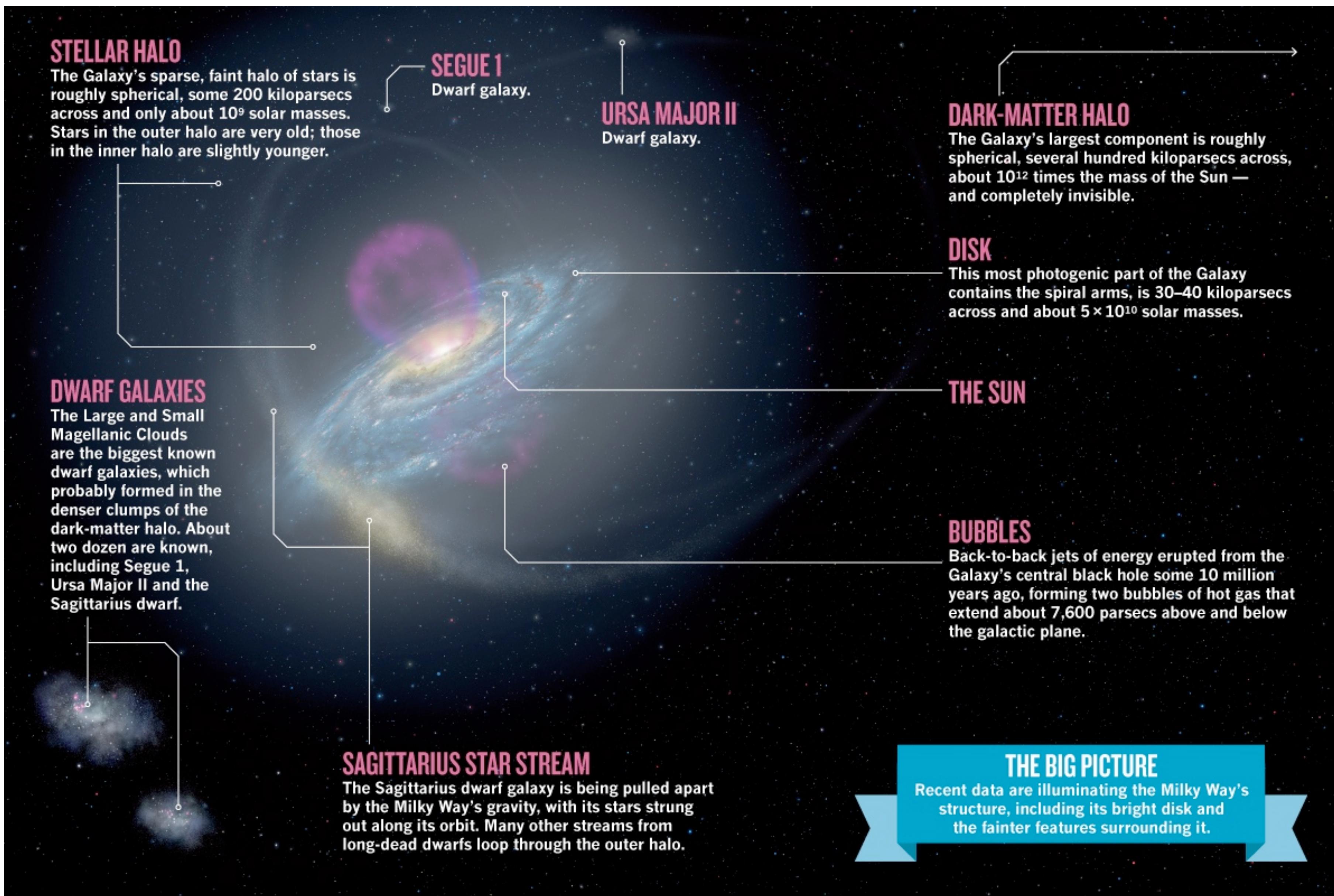
Hot gas explodes out of young dwarf galaxies

Simulation by **Andrew Pontzen, Fabio Governato** and **Alyson Brooks** on the **Darwin Supercomputer**, Cambridge UK.

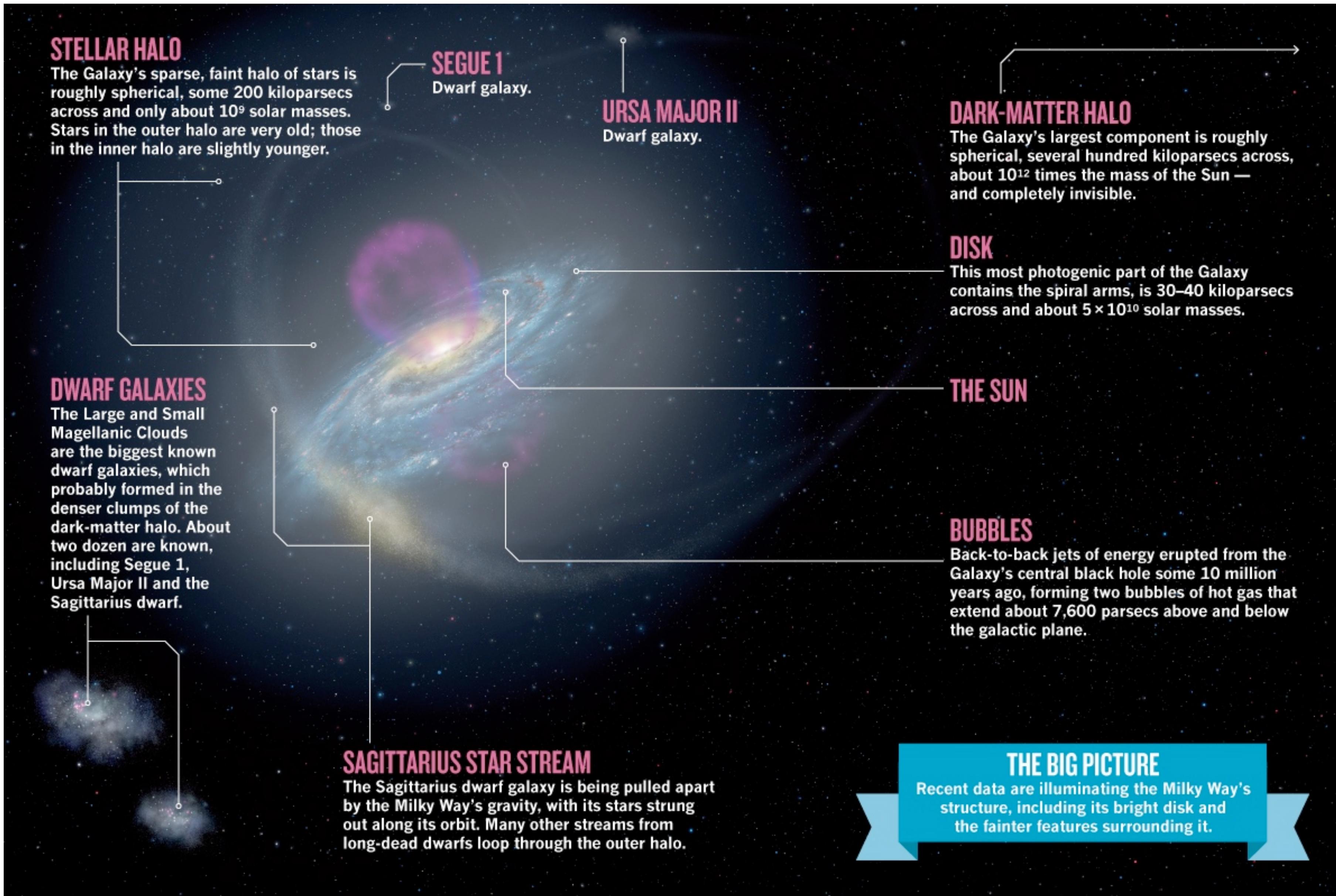
Simulation code **Gasoline** by **James Wadsley** and **Tom Quinn** with metal cooling by **Sijing Sheng**.

Visualization by **Andrew Pontzen**.

# Galaxies are collections of stars, gas (“baryons”) and dark matter



# Dwarf galaxies are galaxies smaller than the Milky Way

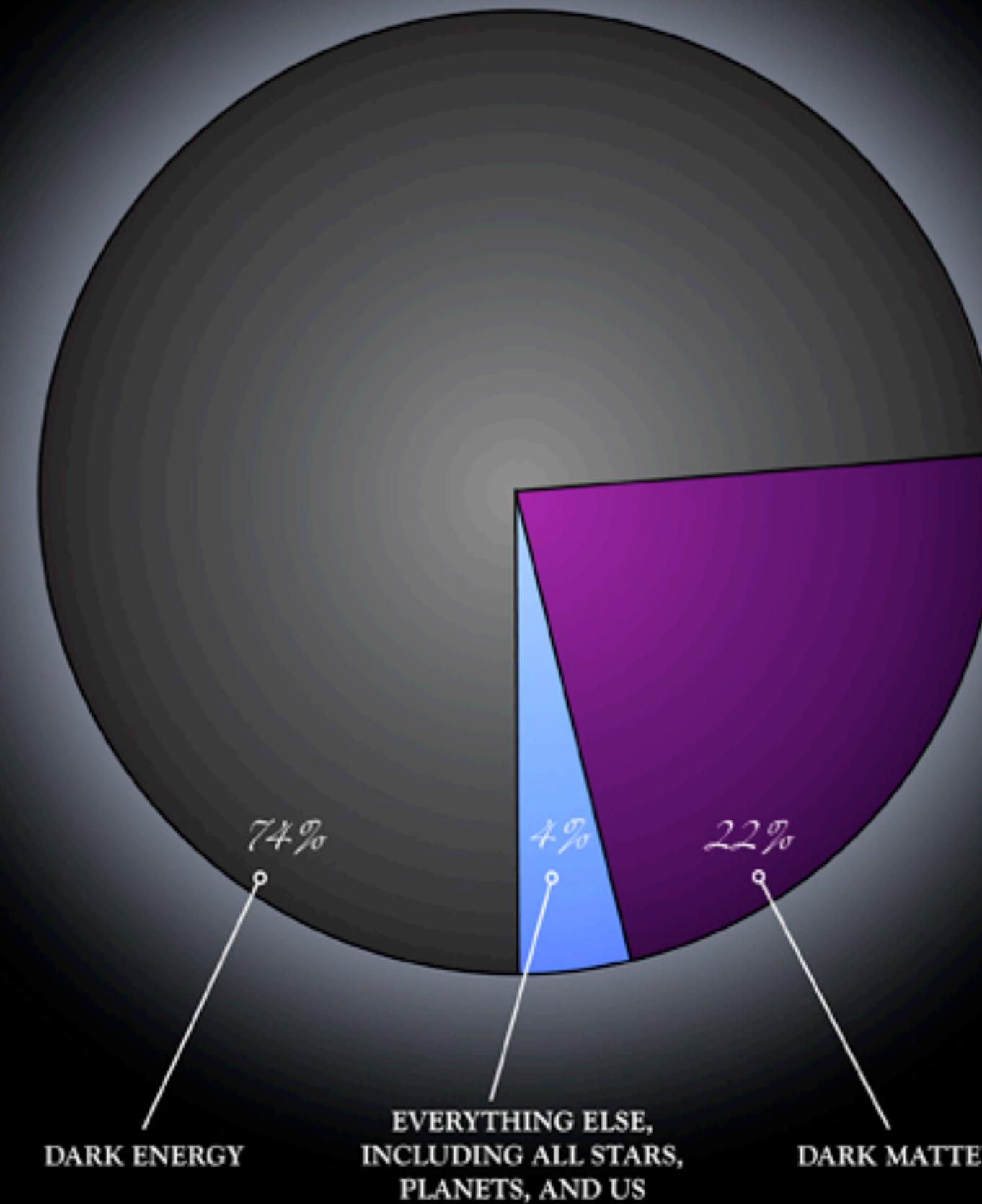


I use galaxy simulations  
to figure out how  
(dwarf) galaxies form  
and evolve- i.e., how  
they come to look as  
they do today.

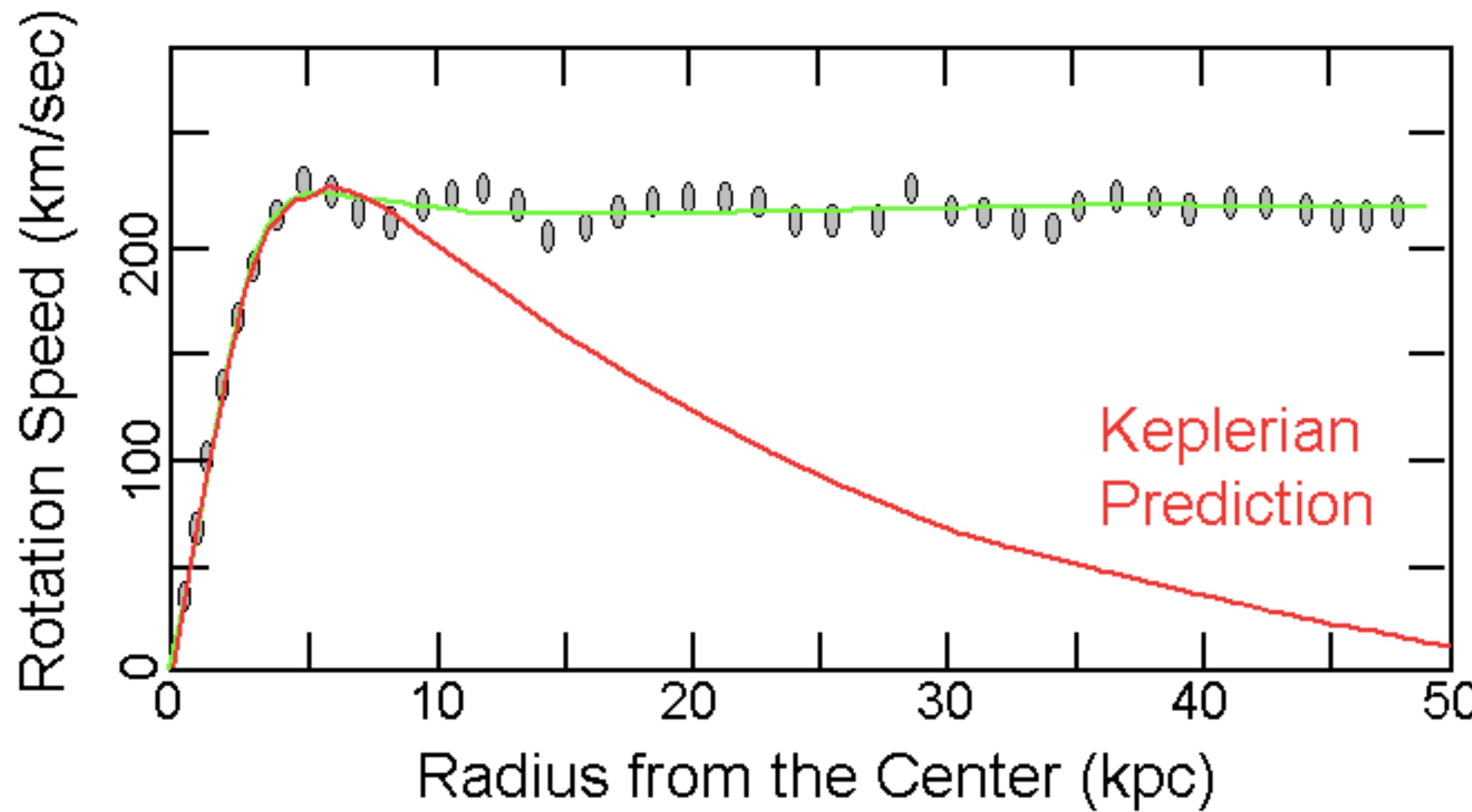
This includes  
understanding the **dark**  
**matter** halos in which  
they form.

# Components of the Universe

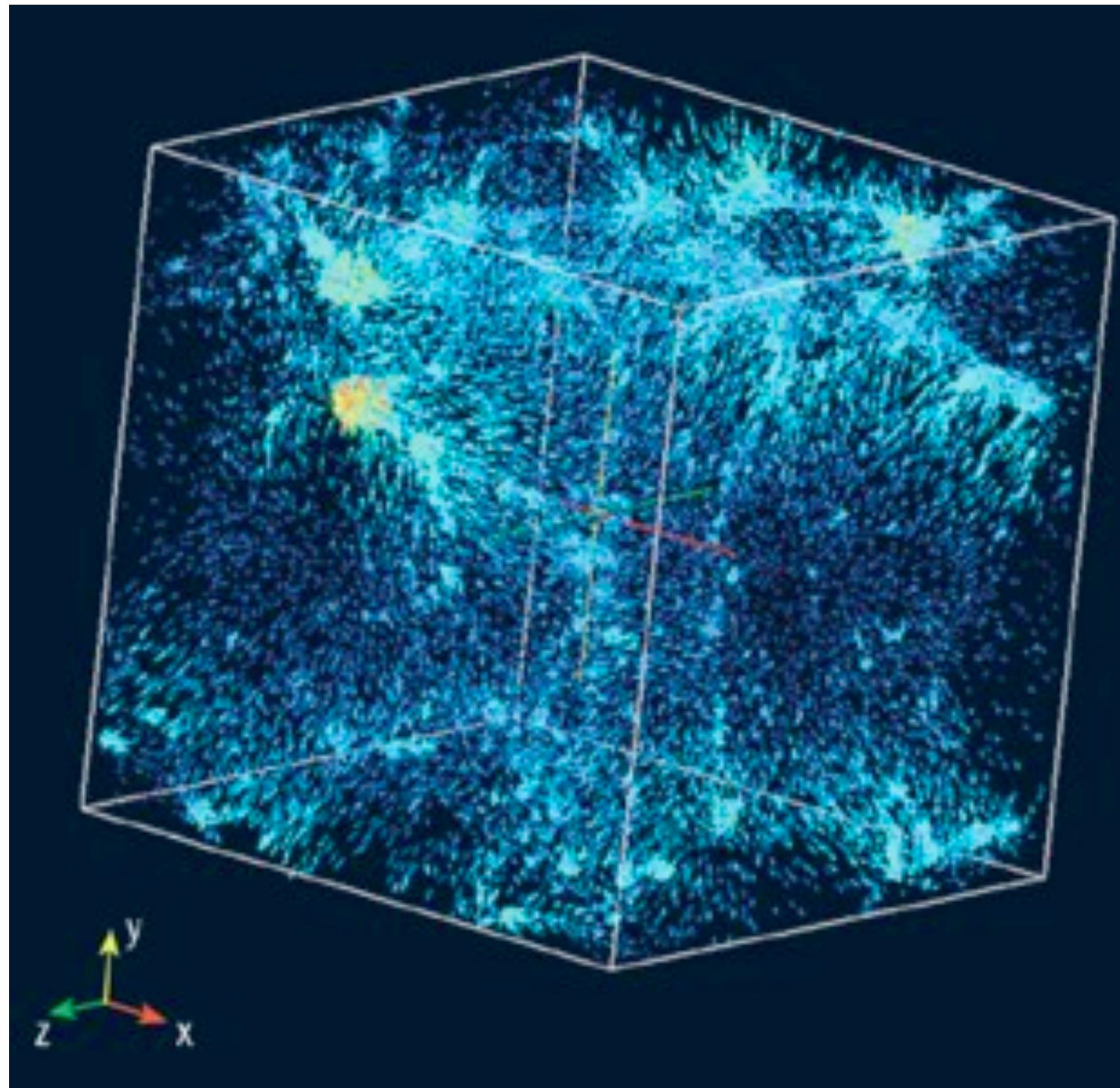
- **Radiation:** light (photons)
- **Baryonic matter (BM):** "ordinary matter" like you and me and stars and galaxies
- **Dark matter (DM):** "Exotic" non-baryonic matter (we have no idea).
- **Dark energy:** bizarre form of matter that causes the expansion of the universe to accelerate



# Observed vs. Predicted Keplerian



# What is a (N-body) Simulation?

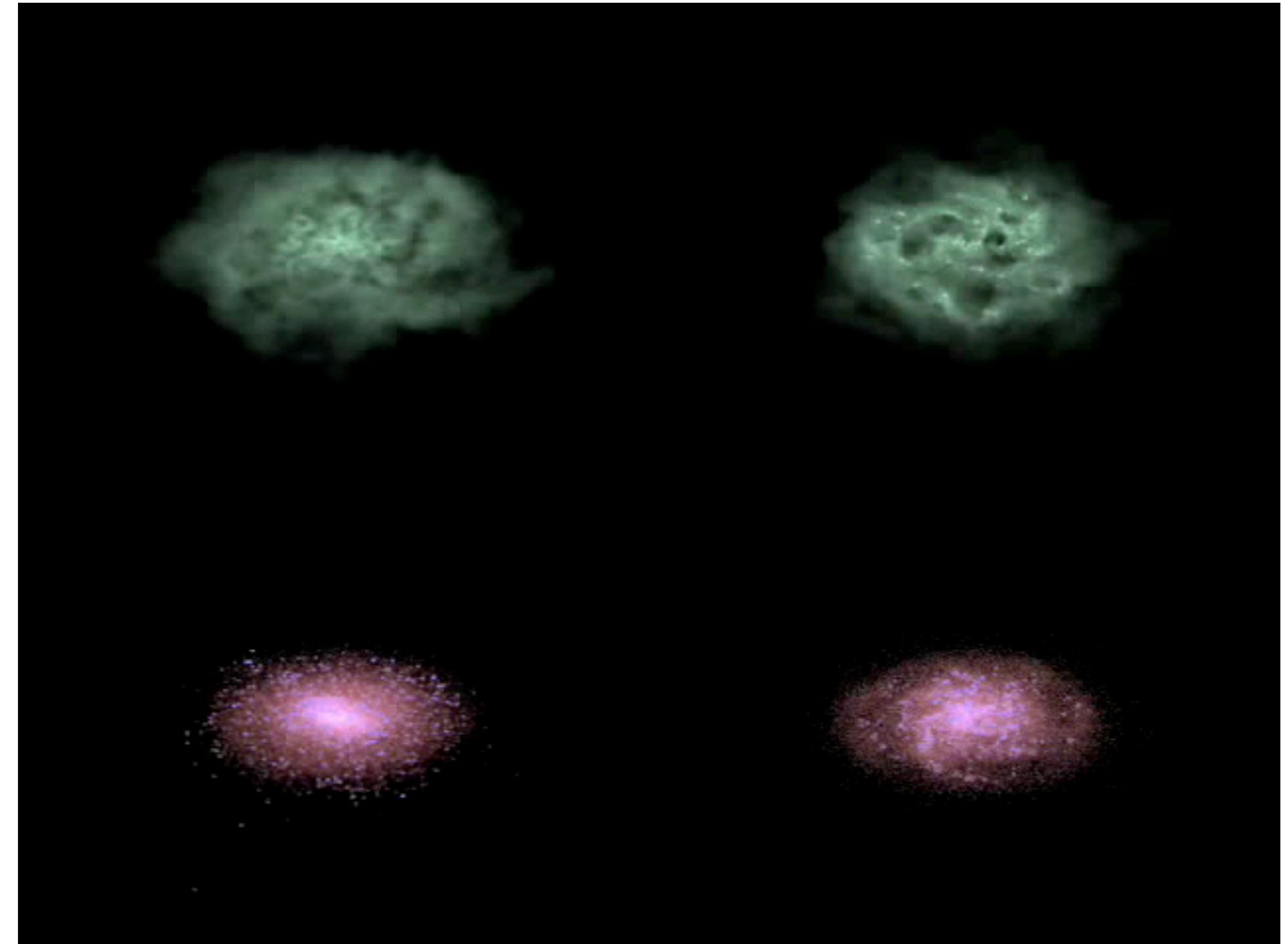


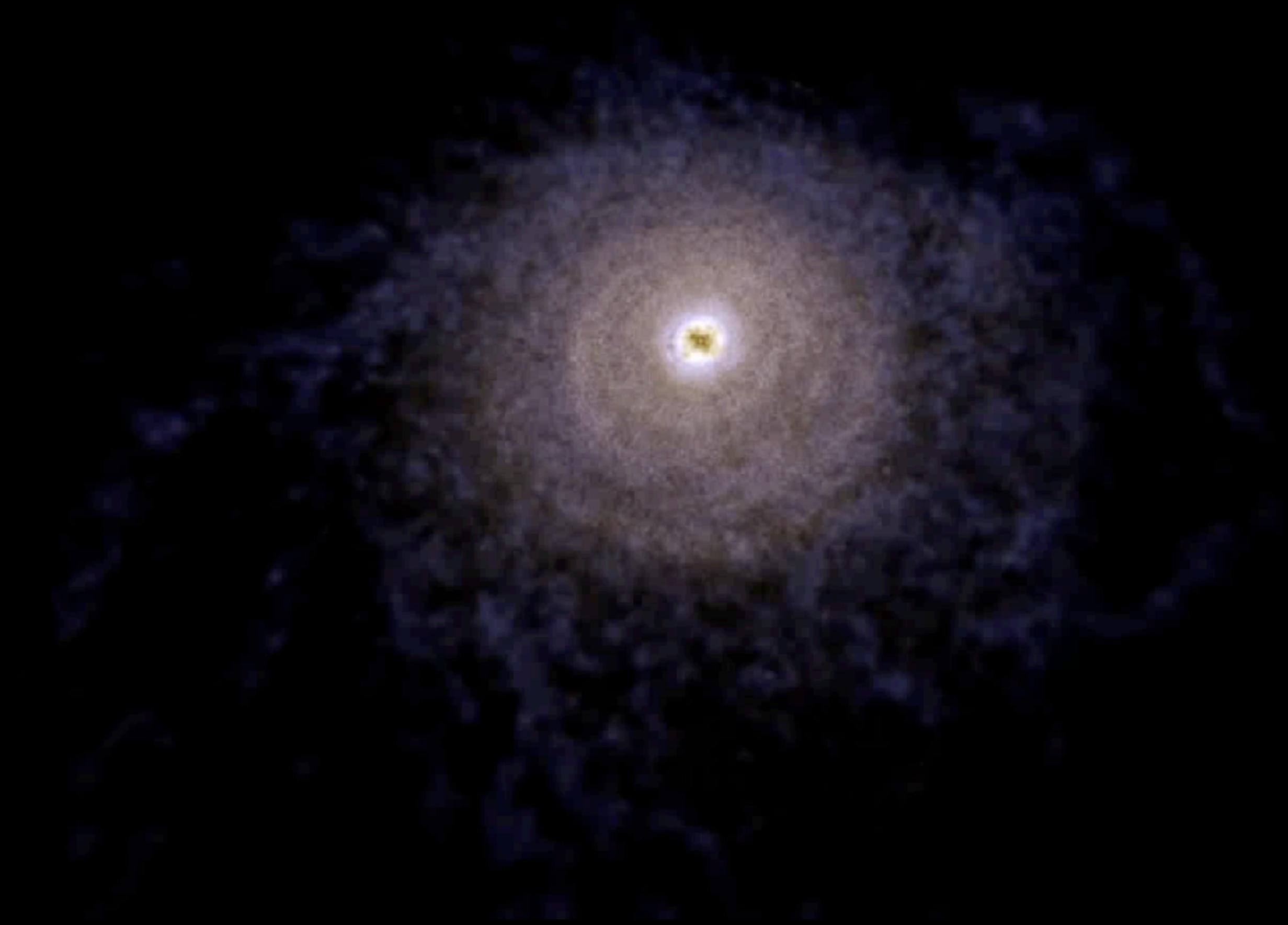
Modeling a dynamical system of particles, usually under the influence of physical forces, in this case: **gravity**

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

# What is an N-body + SPH Simulation?

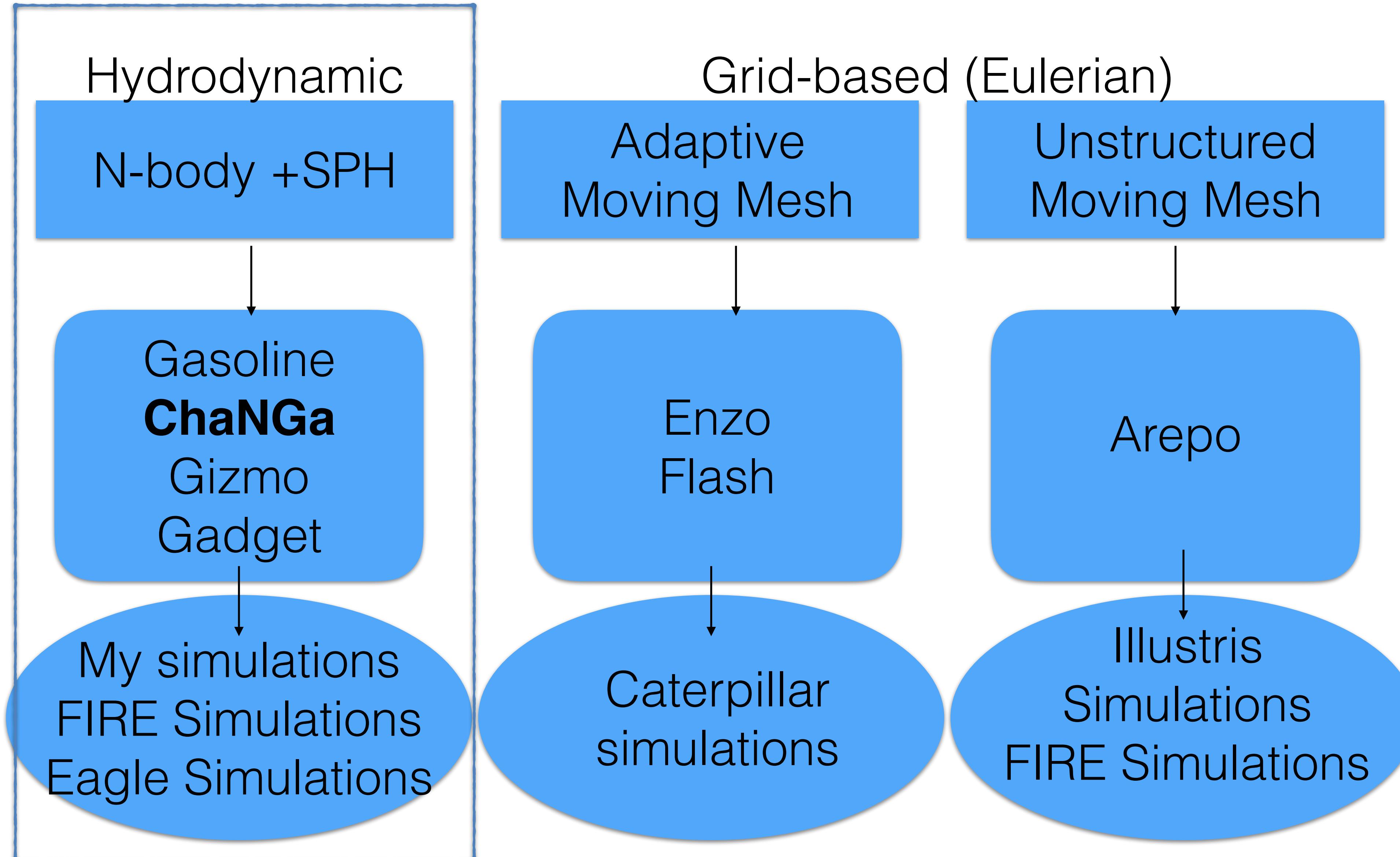
- SPH= “smoothed particle hydrodynamics”
- computational method used for simulating fluid flows- ie, **gas**
- Gas is divided into a set of discrete elements, referred to as “particles”
- “cosmological”= from early times all the way to present day





Video courtesy of A. Pontzen

# Types of galaxy simulations



# Pros & Cons of different simulation suites

	My Sims	Illustris	FIRE	Eagle	
<b>Can resolve detailed internal processes</b>	✓			✓	“zoom-in simulations”
<b>Can create large volume runs</b>	✓	✓		✓	“large volume simulations”
<b>Can simulate hi-res galaxy clusters</b>	✓	✓			Large dynamic range

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 (baryonic physics) can imprint its affects on all three components

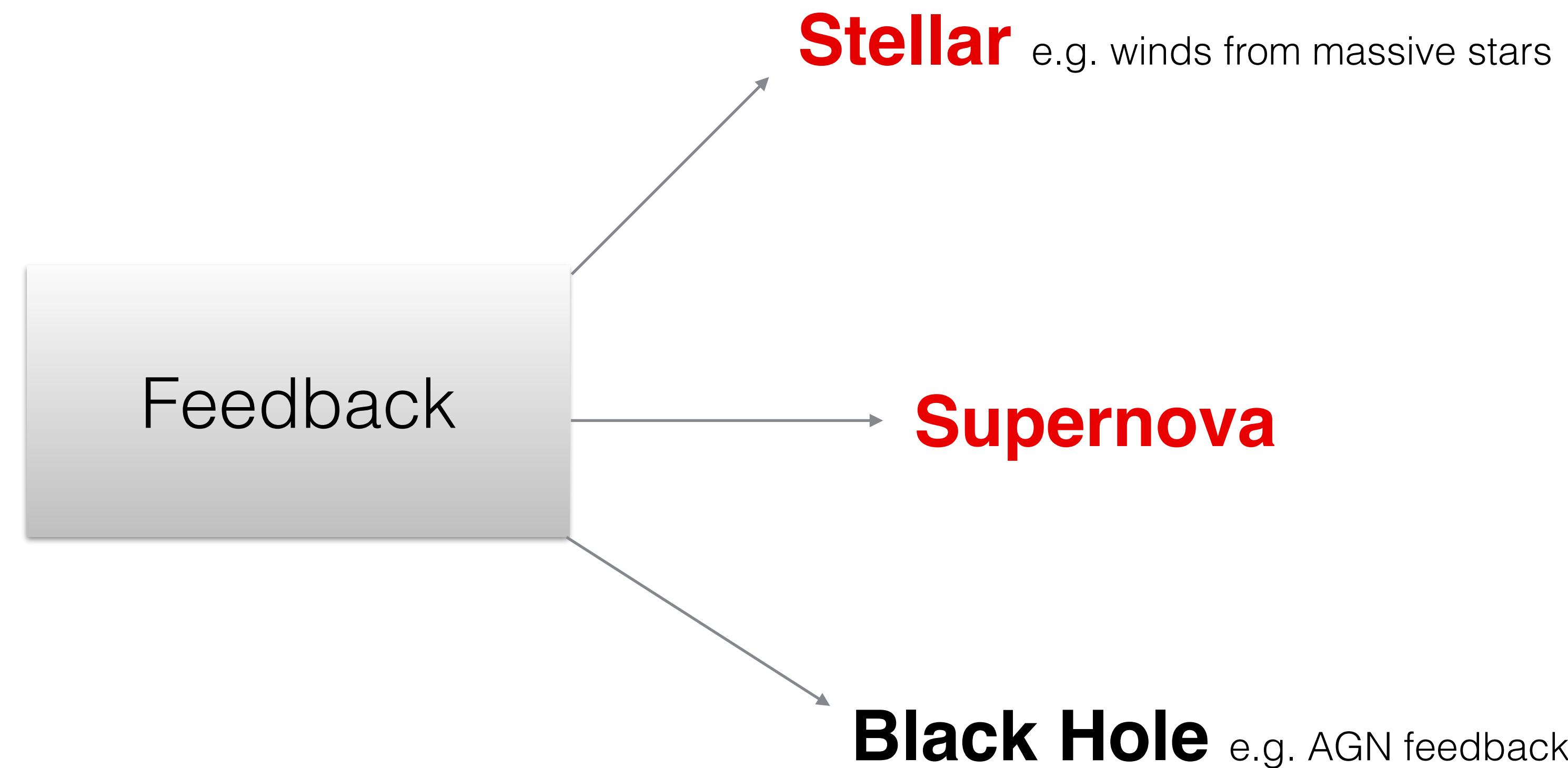
All feedback mechanisms have  
this in common:

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

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

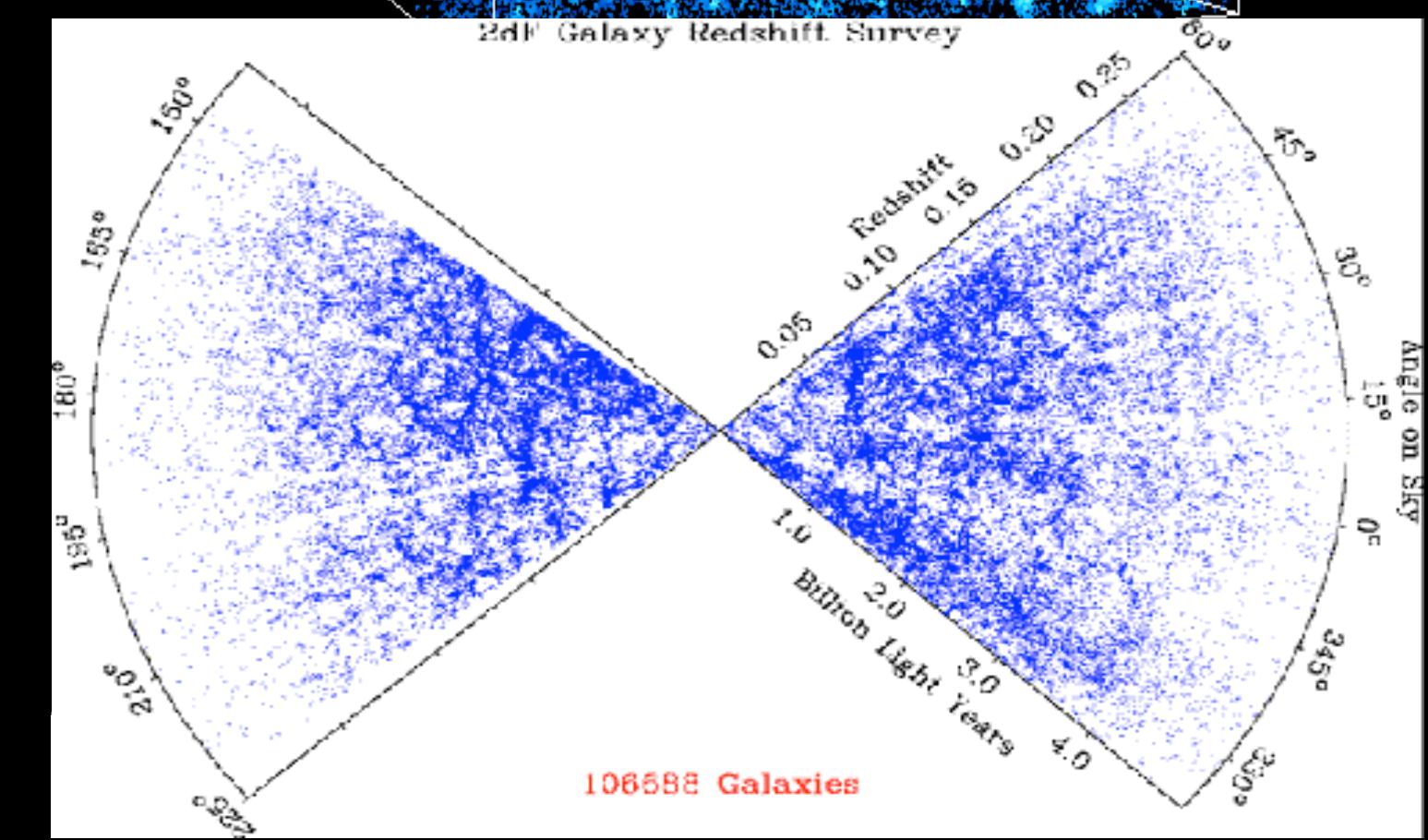
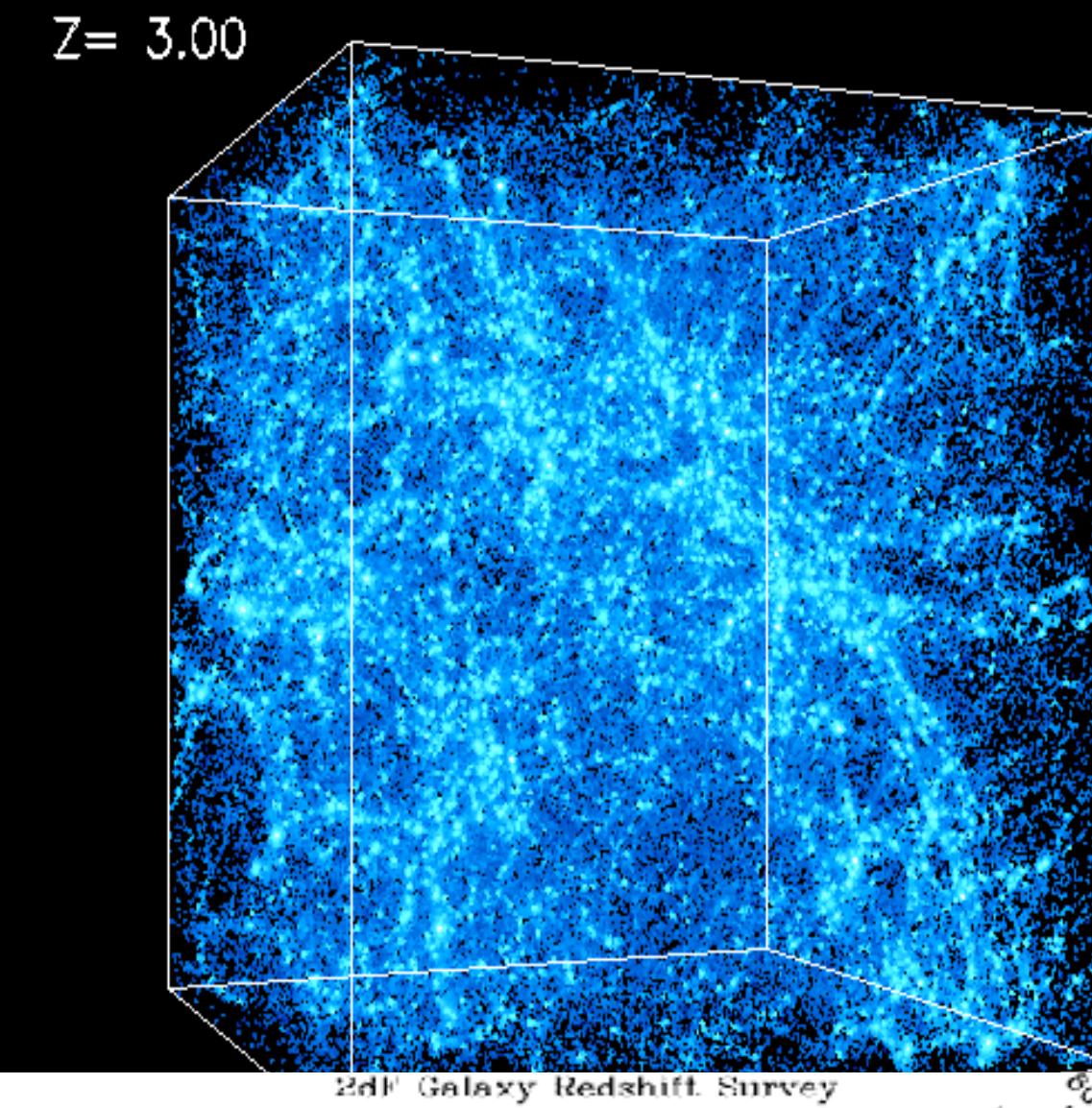
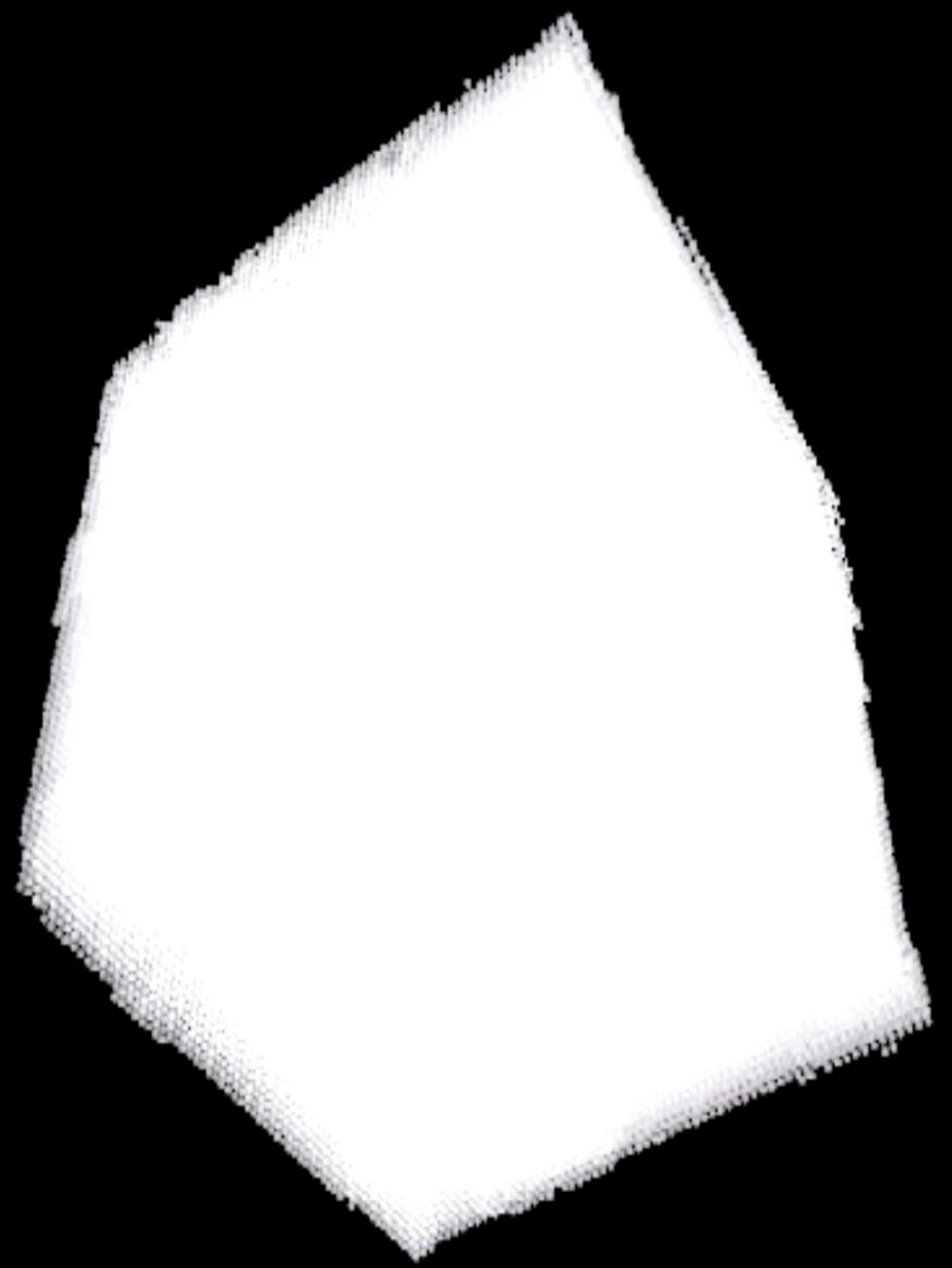
# Feedback is necessary to form realistic\* galaxies.

\*realistic= look like observed galaxies in basic properties



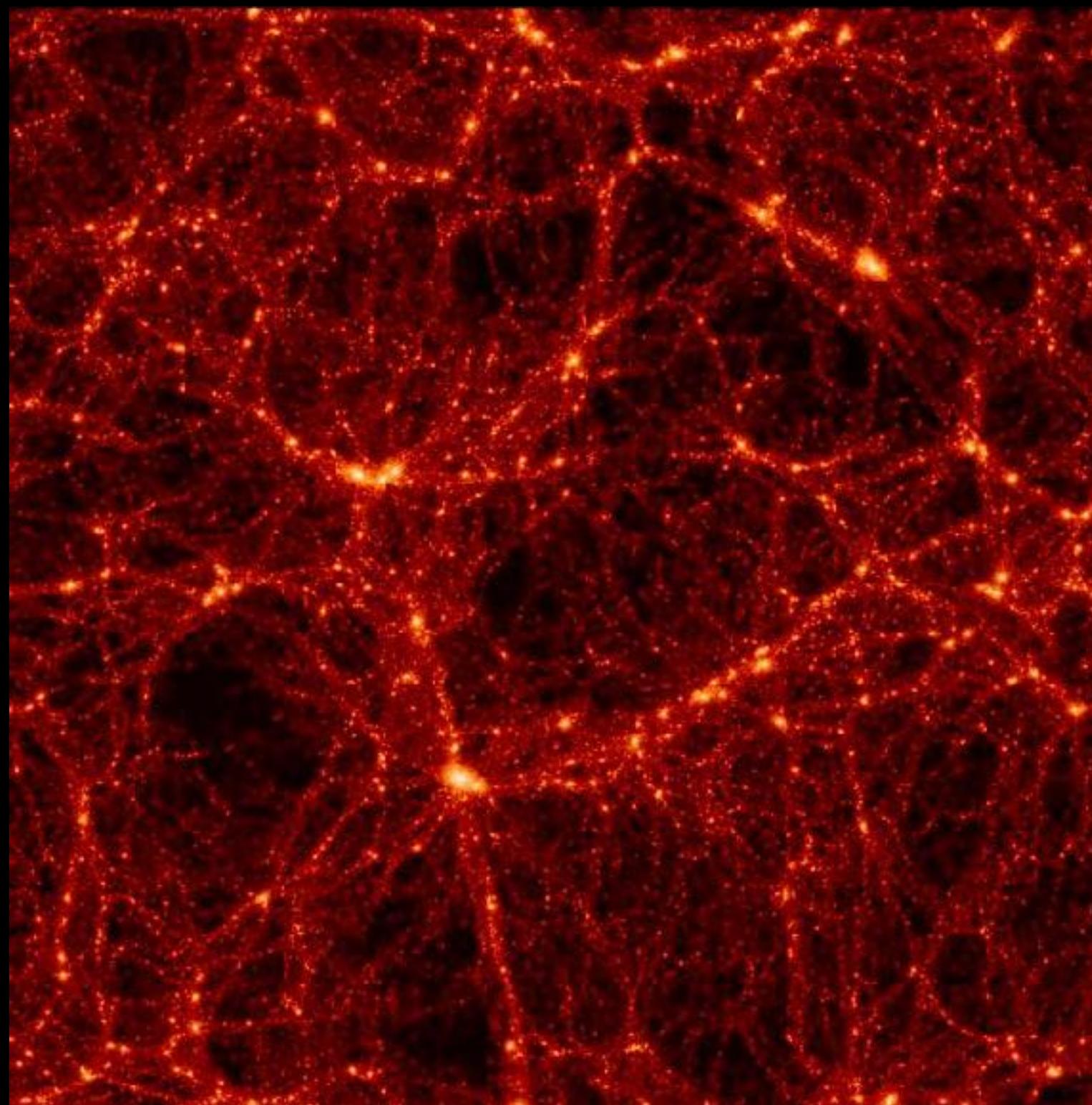
Depending on mass of galaxy, different sources have varying importance

# Dark Matter sets the structure



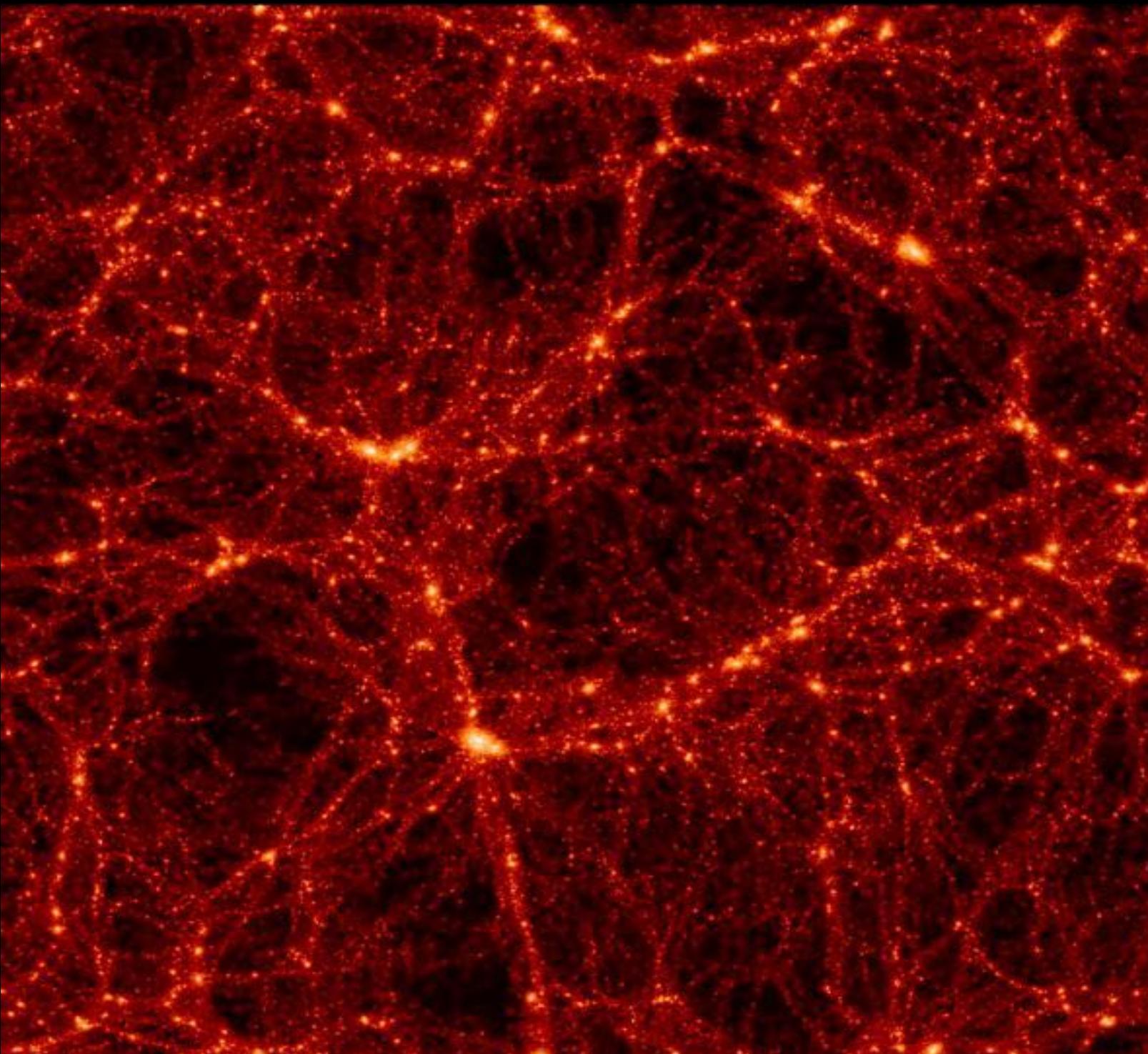
# Where do galaxies fit in?

1. Tidal torqueing spins up both DM and BM into solid body rotation



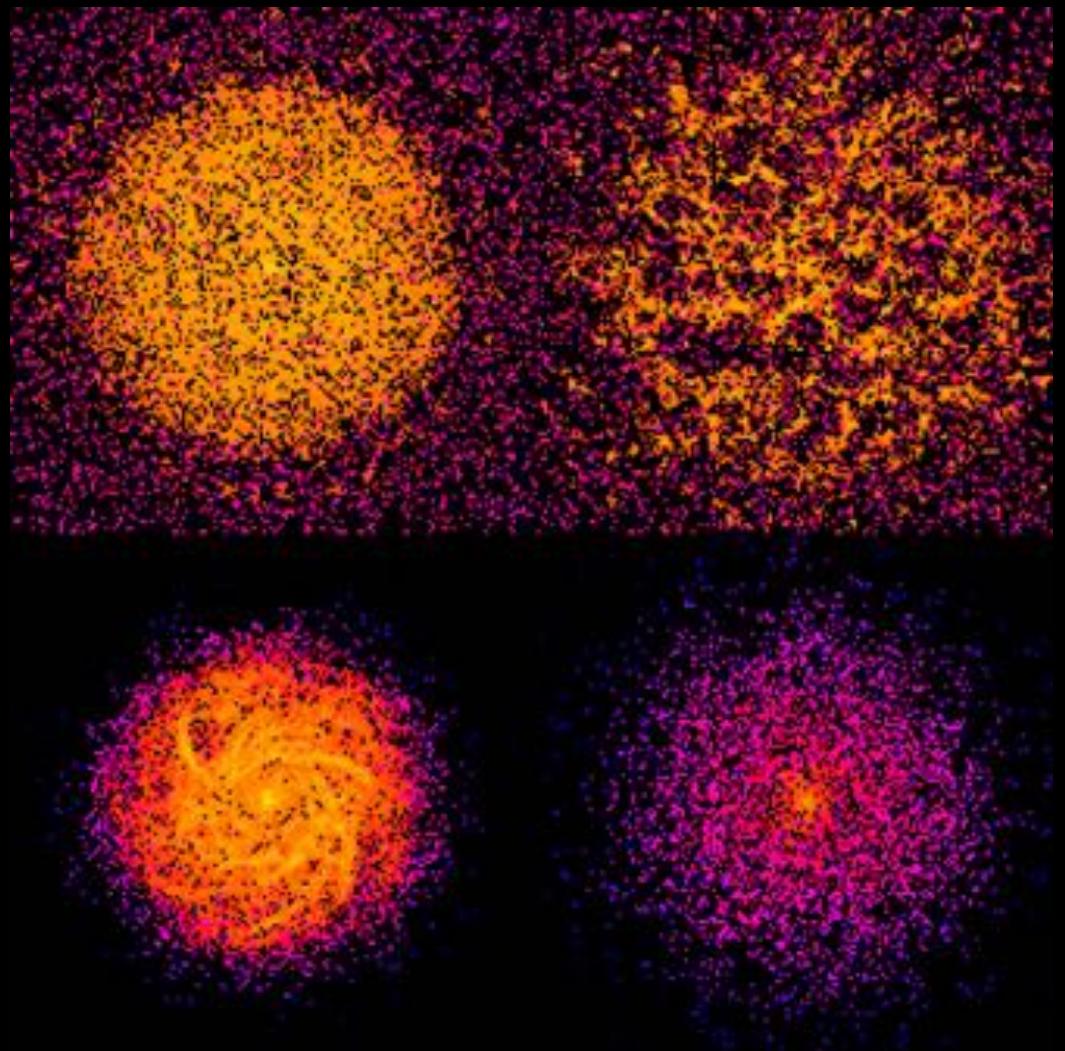
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2. DM and BM collapse in an overdense region



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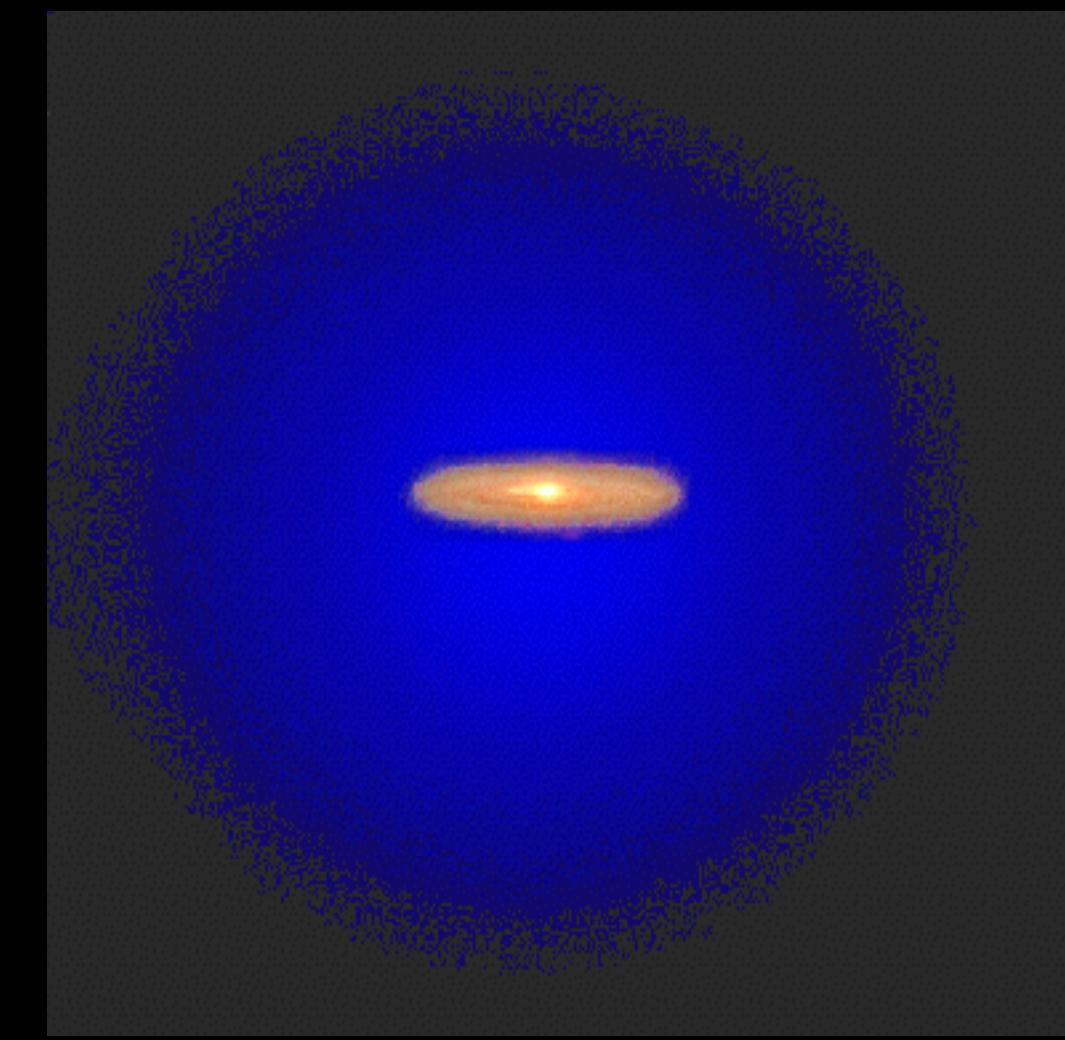
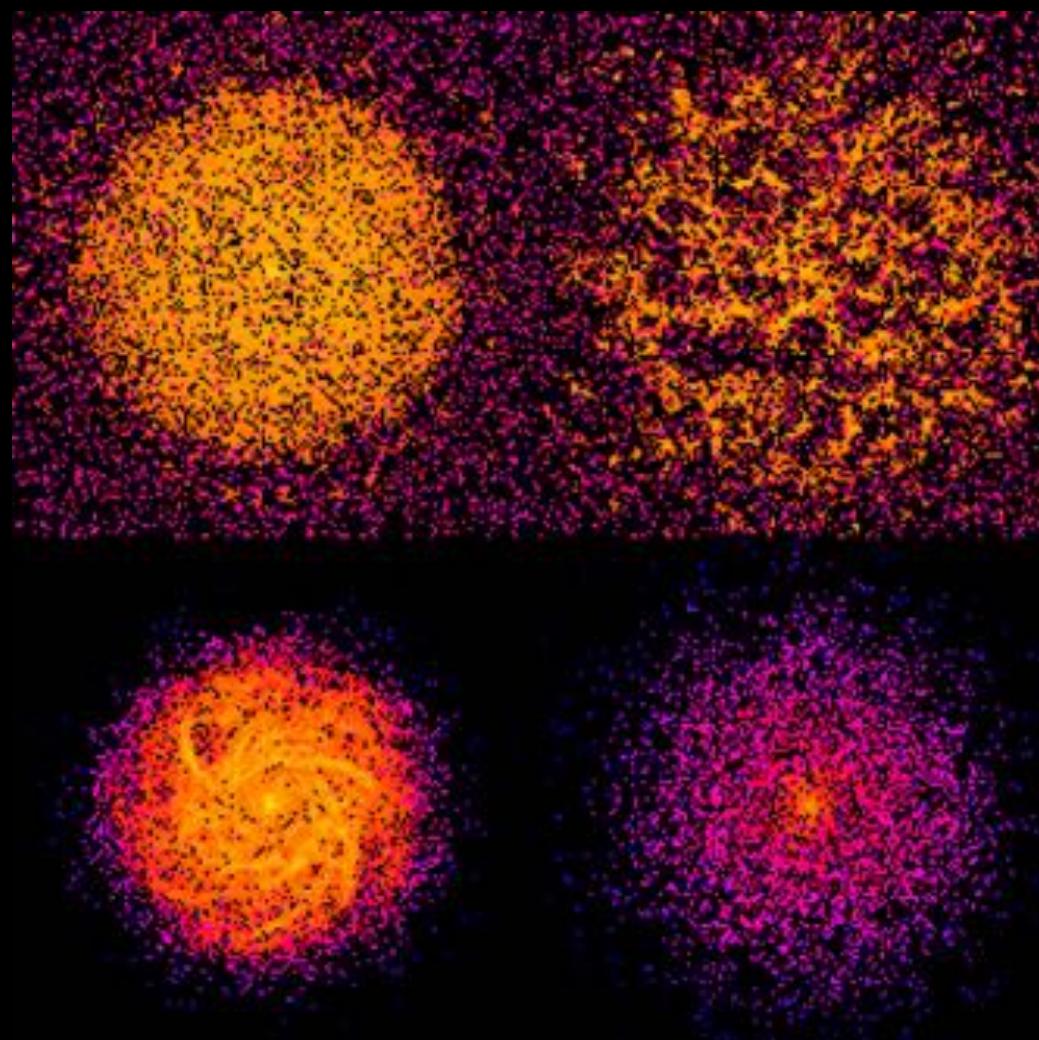
1. Tidal torqueing spins up both DM and BM into solid body rotation
2. DM and BM collapse in an overdense region
3. DM = collapse halts when system virializes



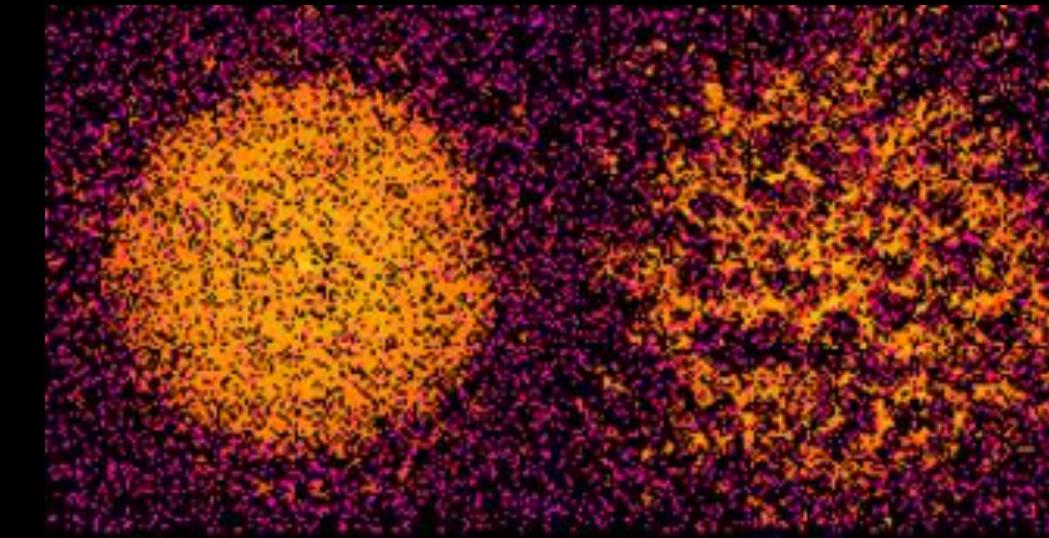
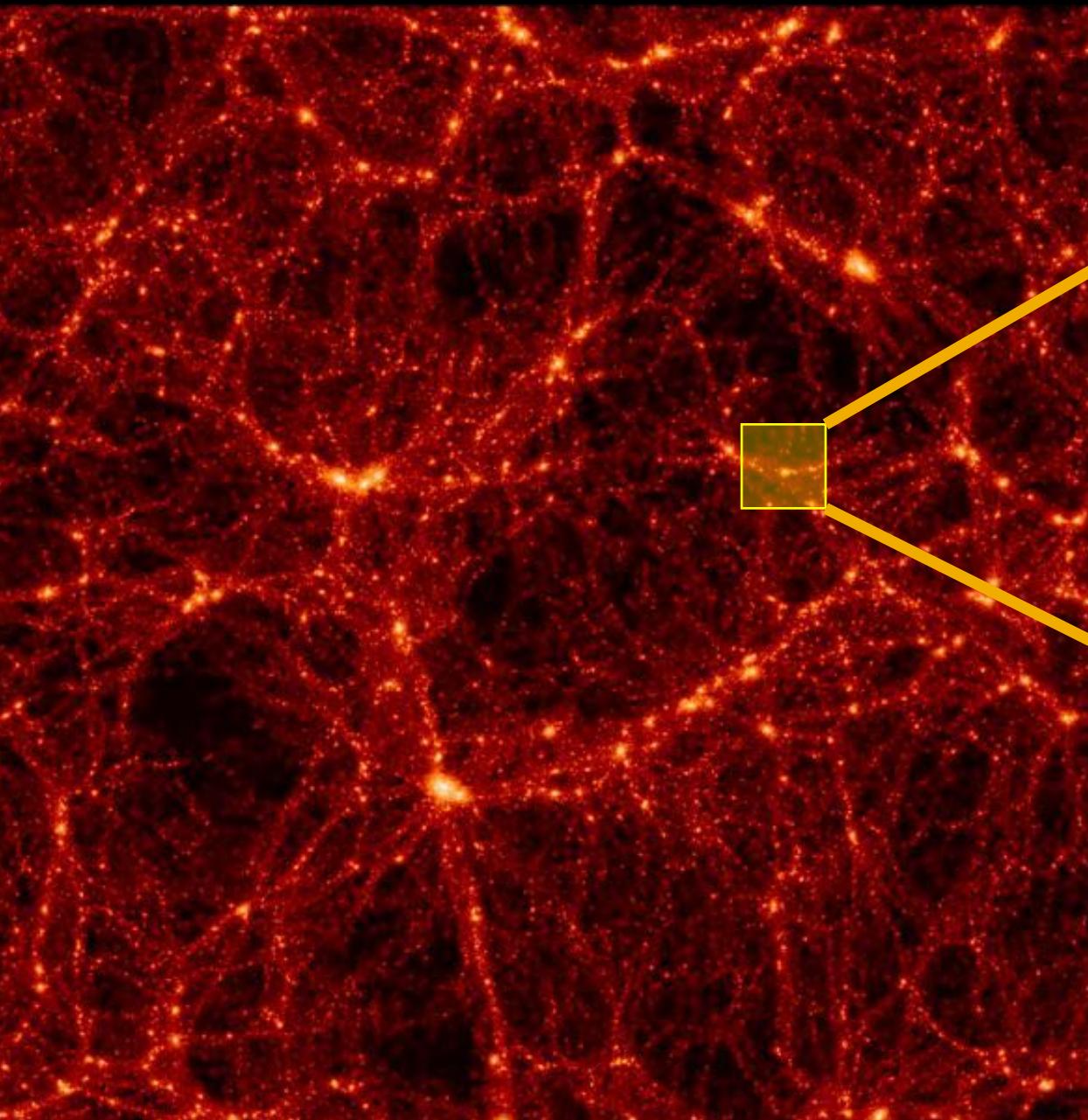
# Where do galaxies fit in?

1. Tidal torqueing spins up both DM and BM into solid body rotation
2. DM and BM collapse in an overdense region
3. DM = dissipationless => collapse halts when system virializes
4. BM cools, decouples from DM; settles into rotating disk

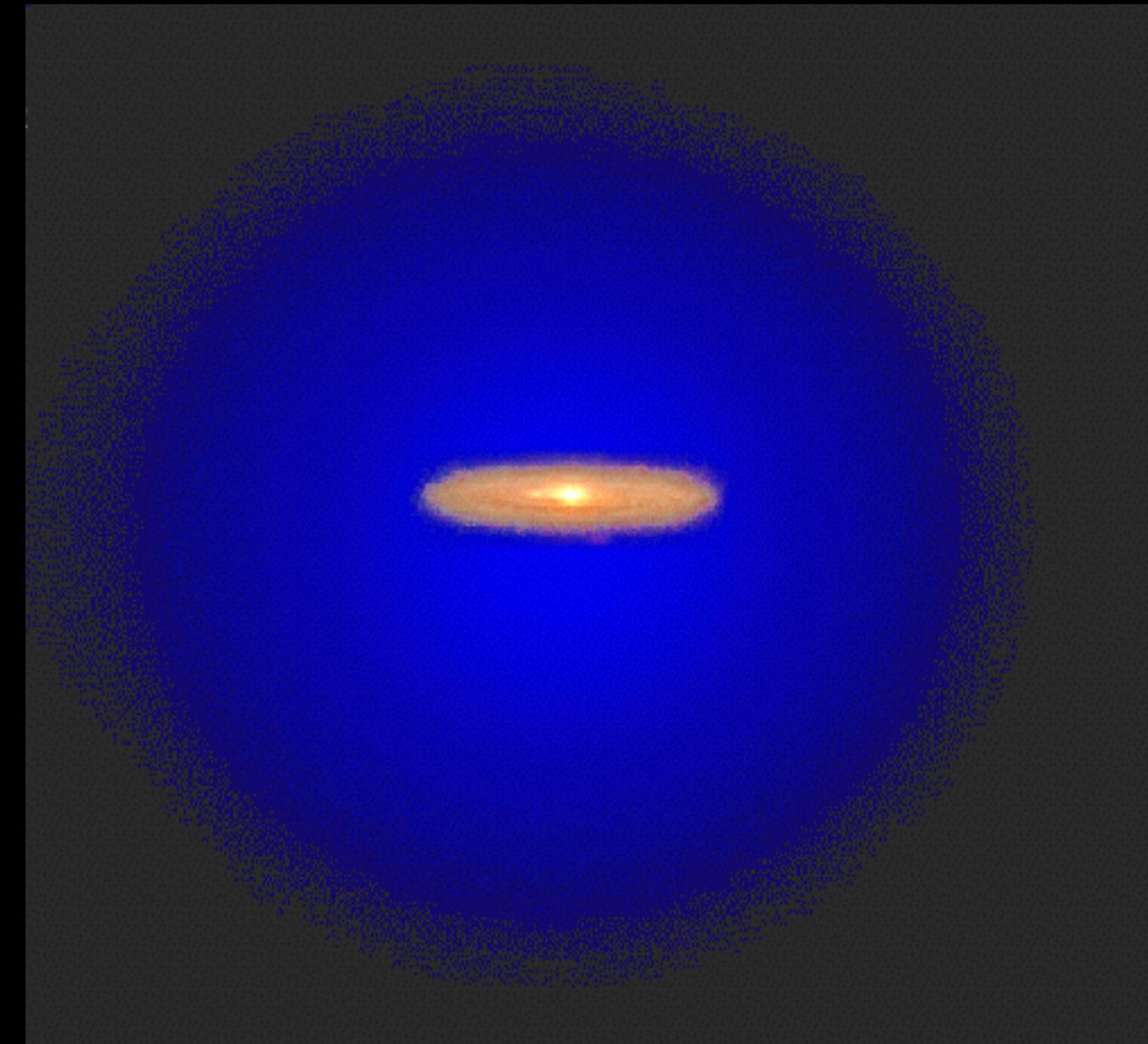
LCDM model



We've now learned that **dark matter** sets the large scale structure, and that gas cooling and collapse has something to do with **star formation** and the formation of galaxies



<http://ned.ipac.caltech.edu/level5/March08/Mayer/Mayer4.html>



This implies a “galaxy-halo” connection

# Starting Assumption:

## There is No Small Scale “Crisis”

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

“challenge”	CDM+ baryons	WDM	SIDM
Bulge-less disk galaxies	✓		
The Cusp/Core Problem	✓		✓
Too Big to Fail	✓	✓	✓
Missing Satellites	✓	✓	
Missing Dwarfs	✓	✓	✓
Diversity	✓?		✓
Planes of Satellites		Still to be explored	

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# Dwarf Galaxies

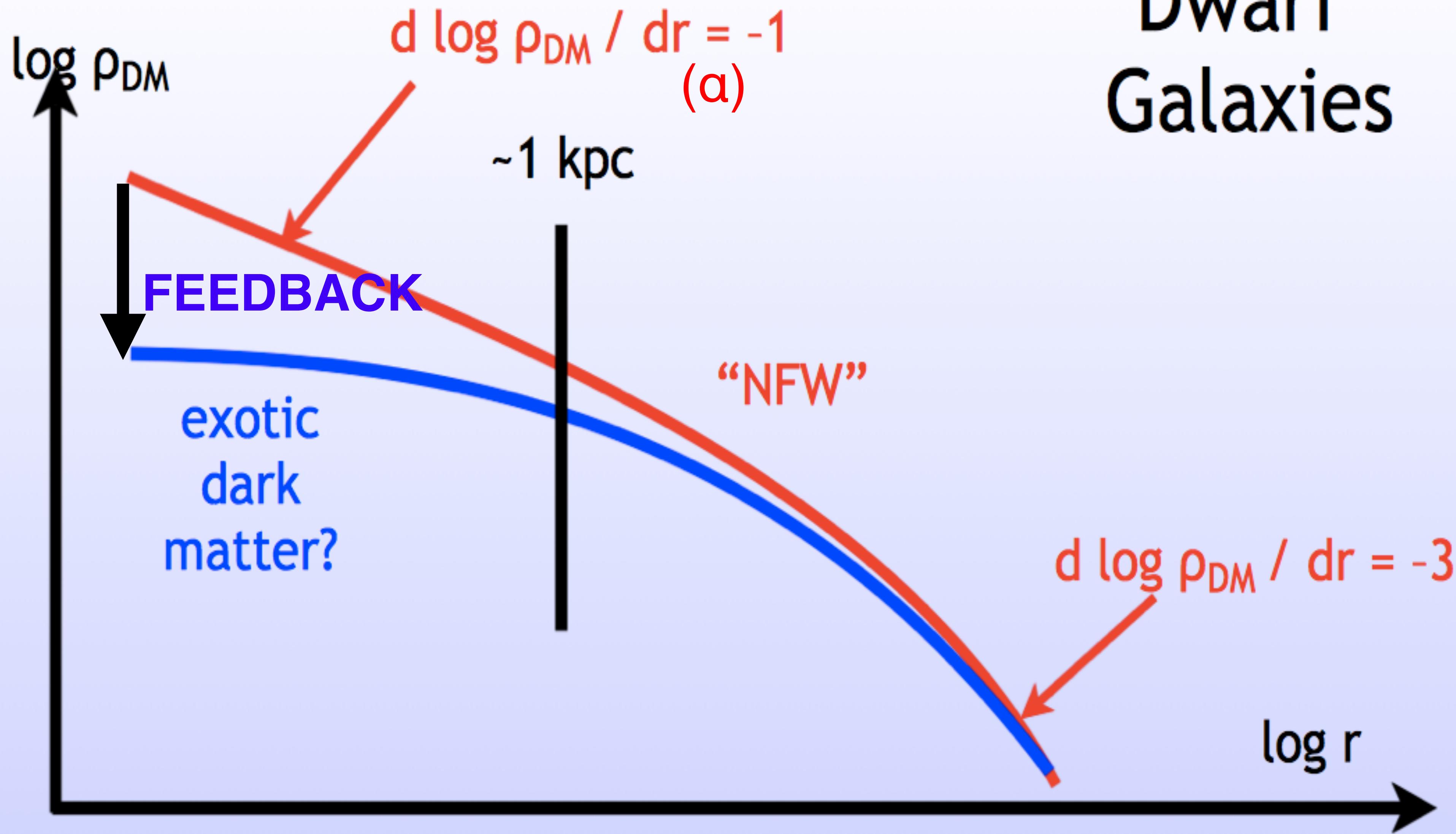
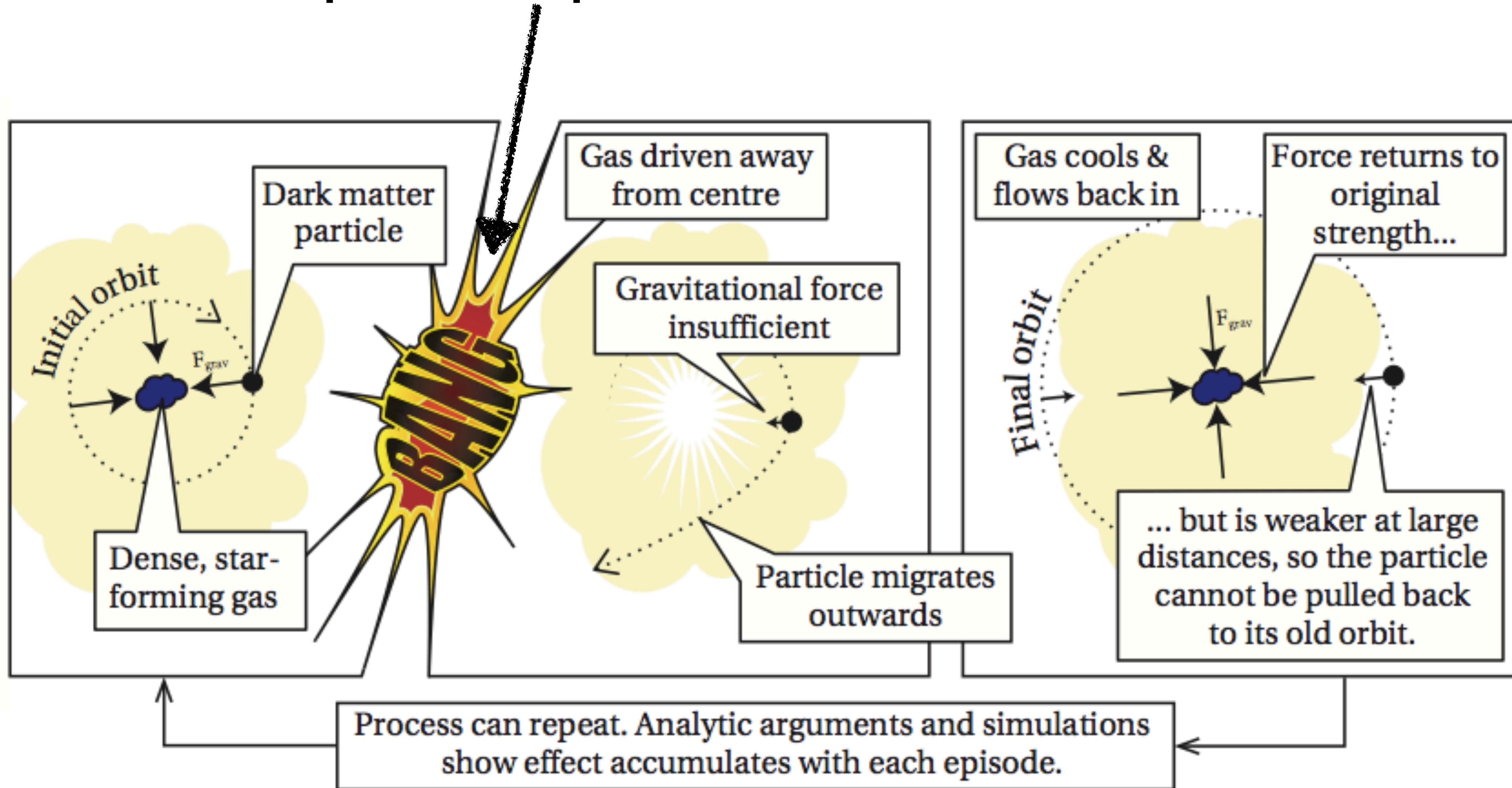
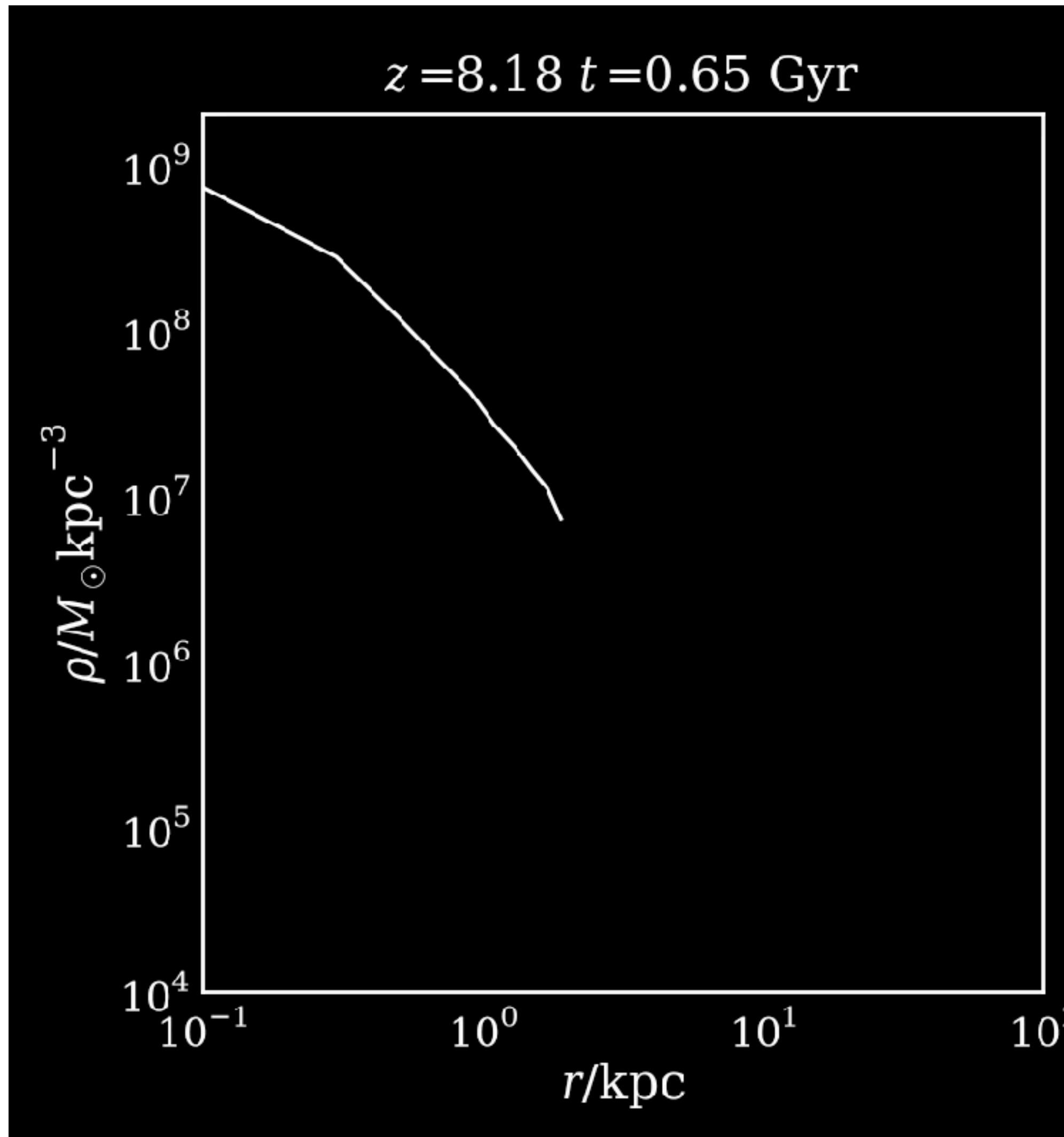


Figure courtesy of F. Governato

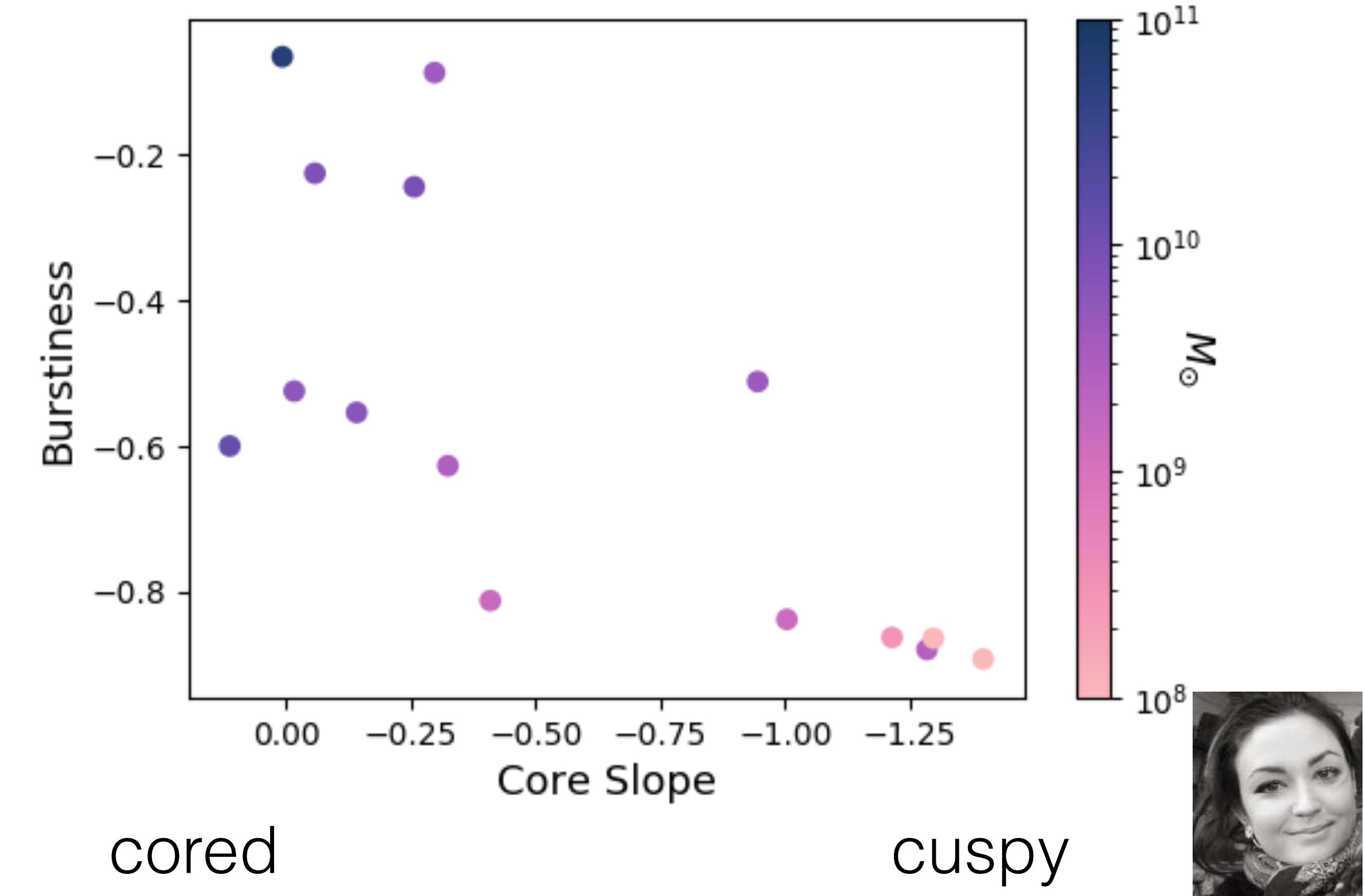
# Supernova explosion/feedback



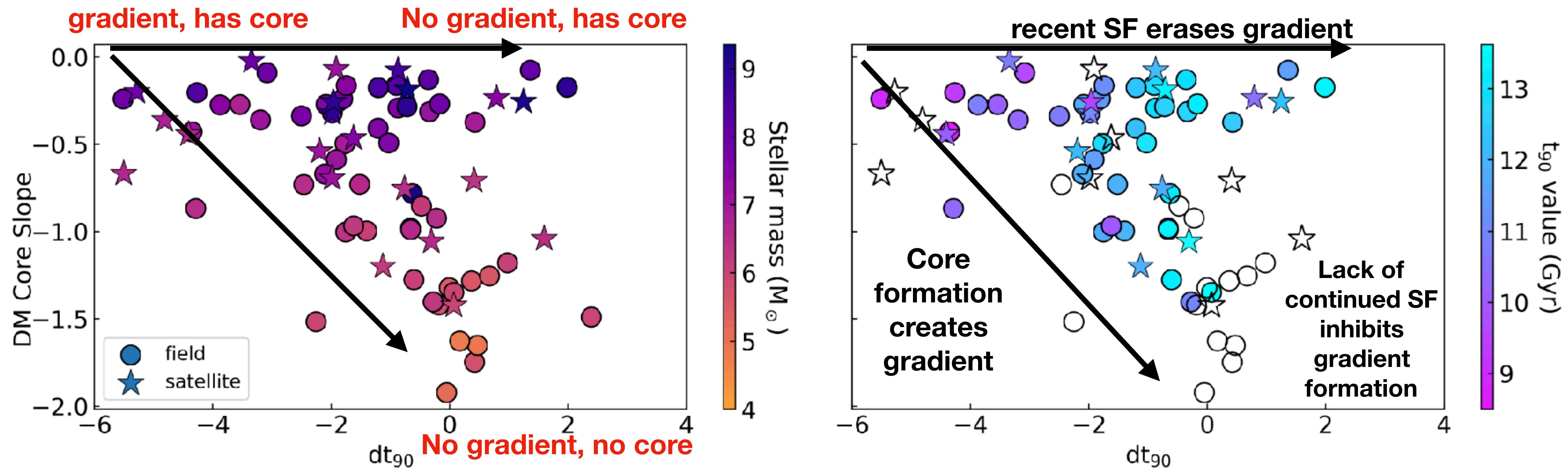
Repeated feedback events => flattening of DM core



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



# 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.

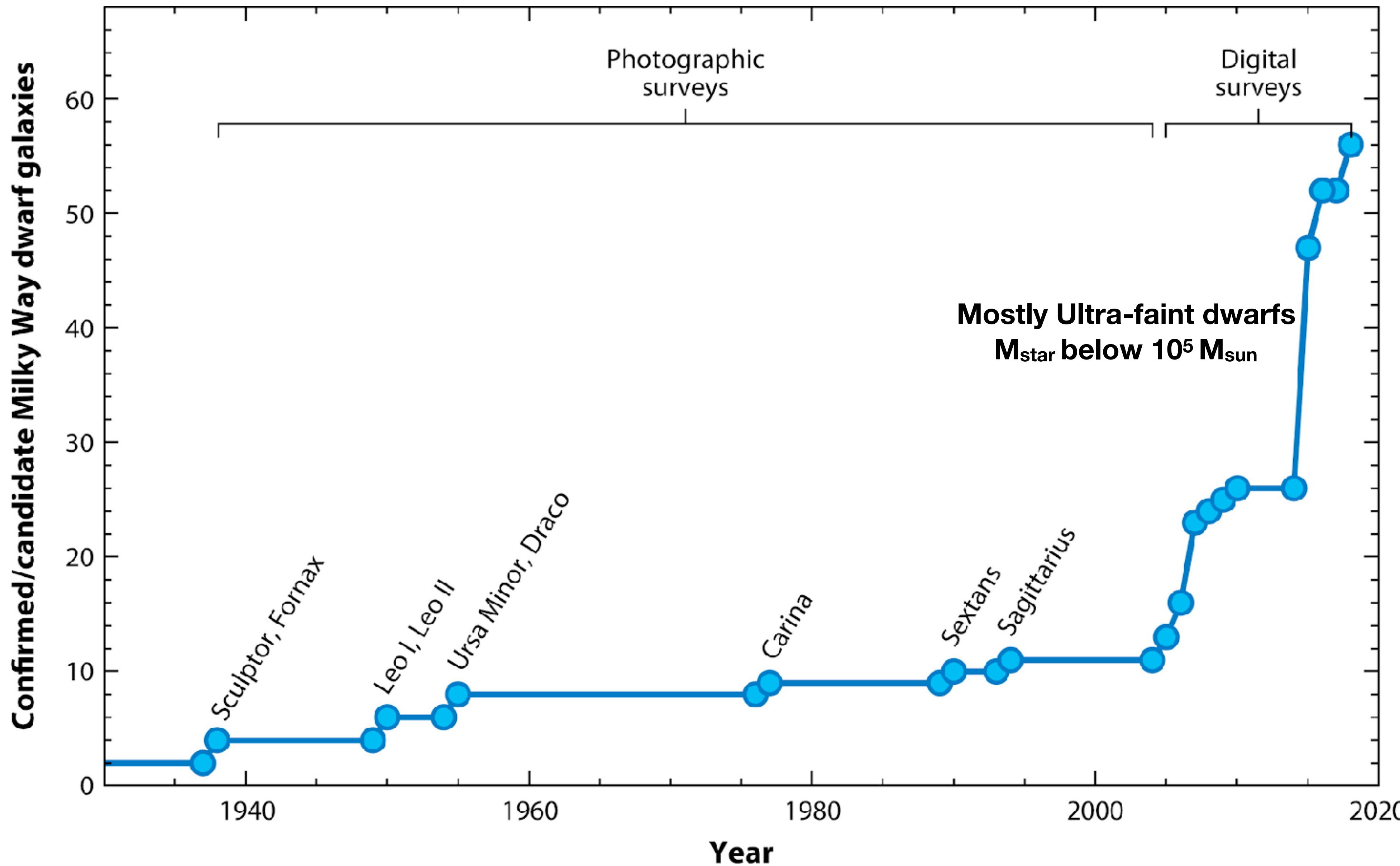
Lack of age gradient does not mean the galaxy does not have a core!

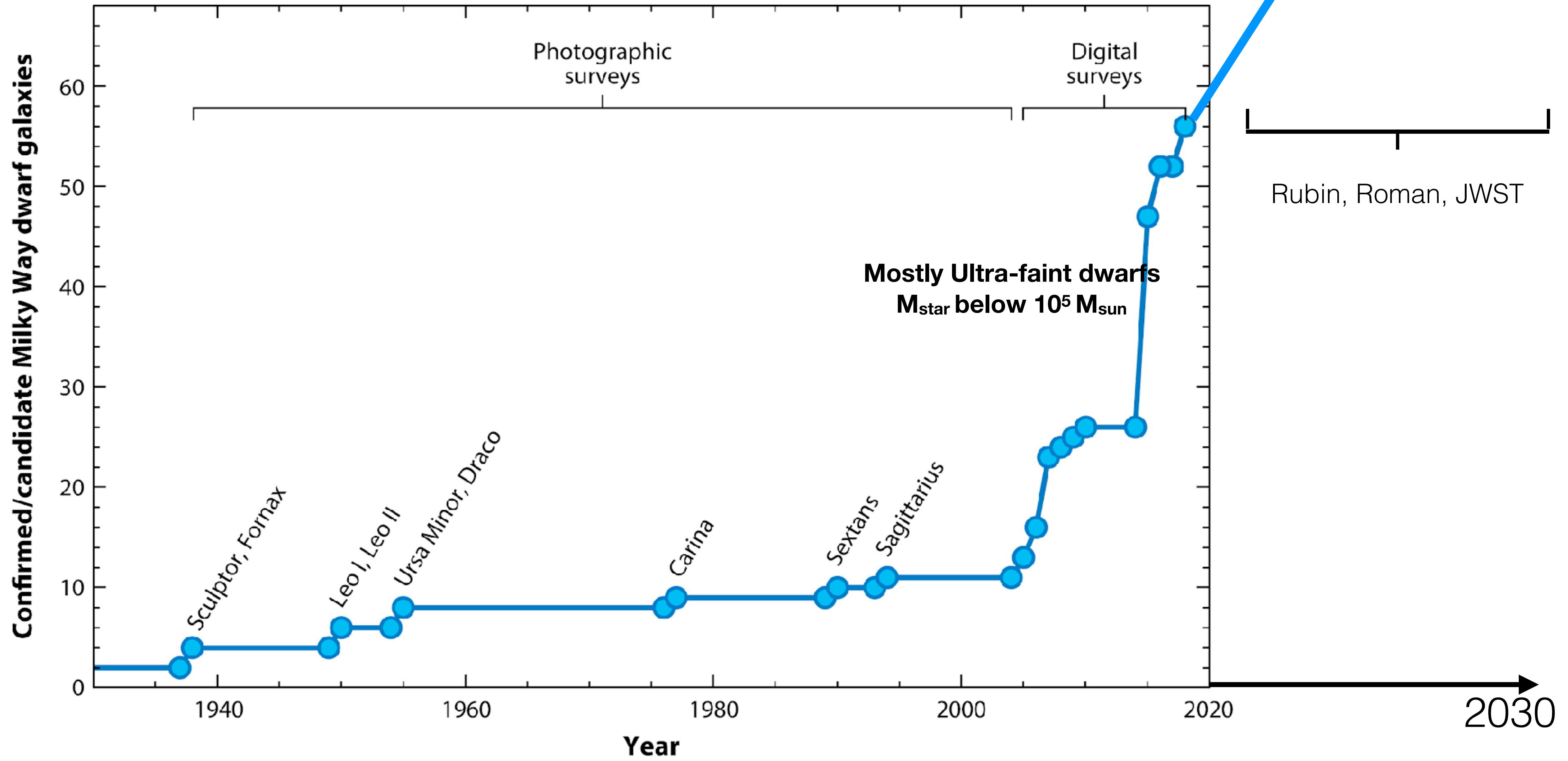
# Key Problems

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

We still need baryons in alternative dark matter models. Is there a smoking gun that points to a given dark matter model?

# There has been an explosion in finding fainter and fainter dwarfs





# 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

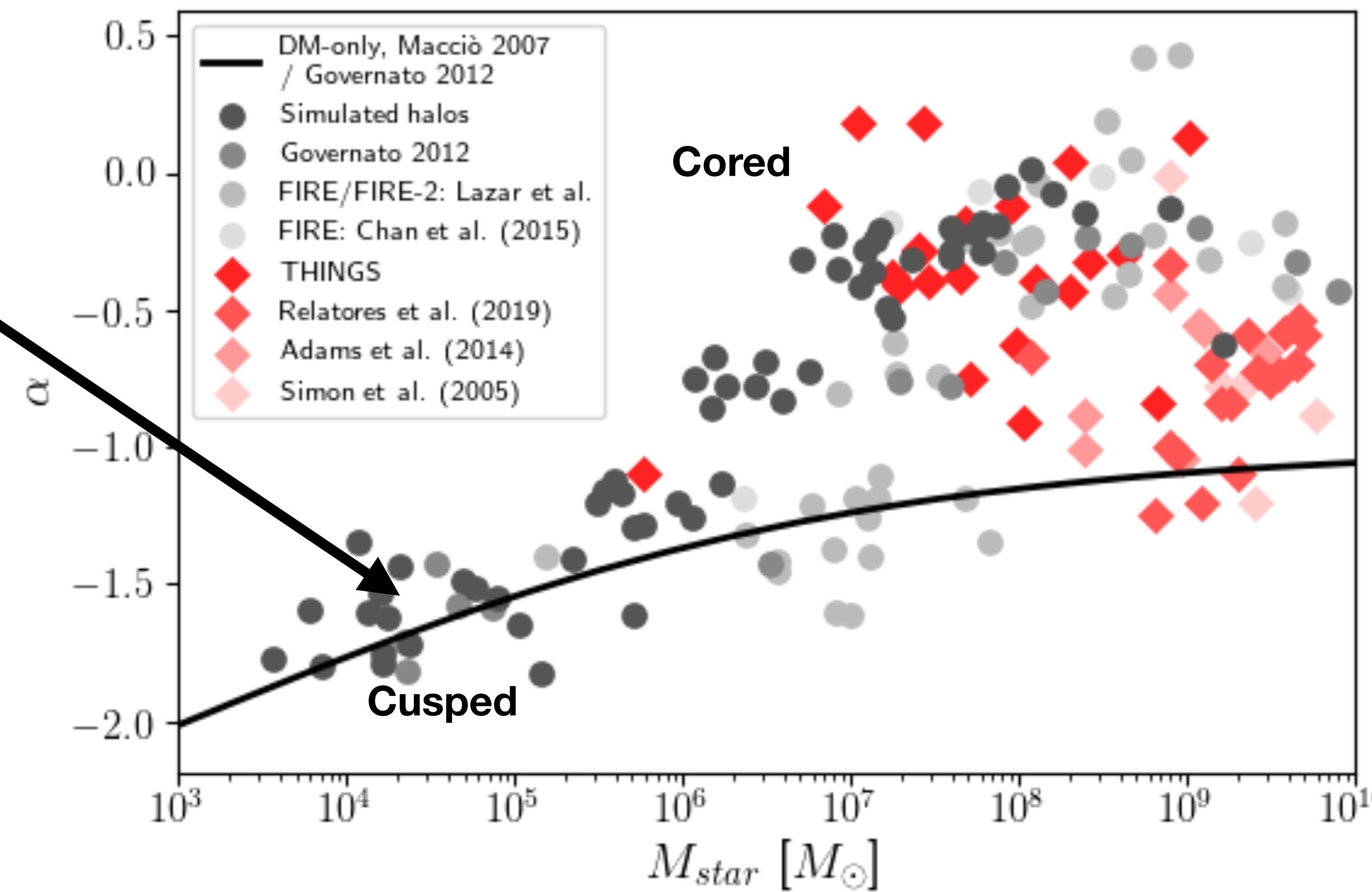


Figure from my grad student, J. Van Nest

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



MARVELous Dwarfs

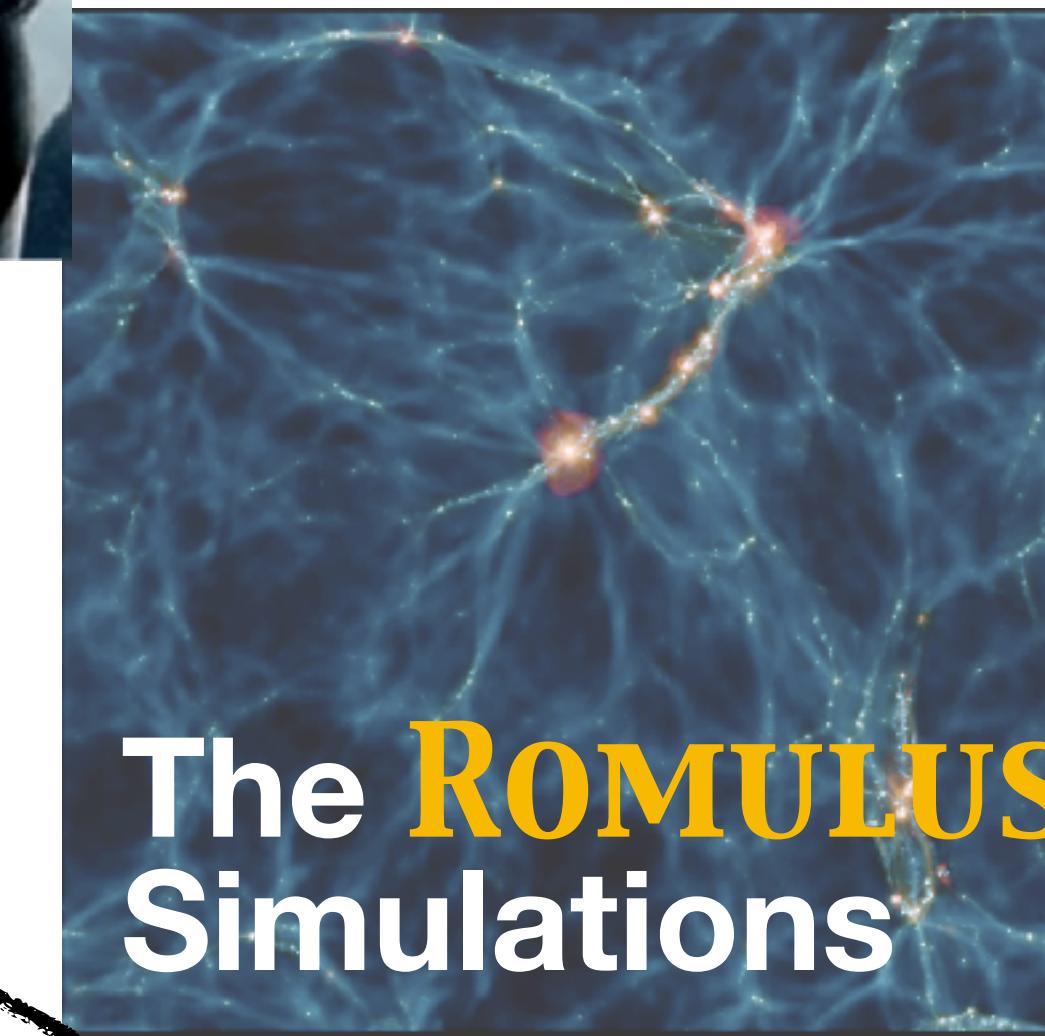
Ultra-faints in isolation



Ultra-faints in the vicinity of a MW

Dwarfs (and UDGs) across environments

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



The ROMULUS  
Simulations



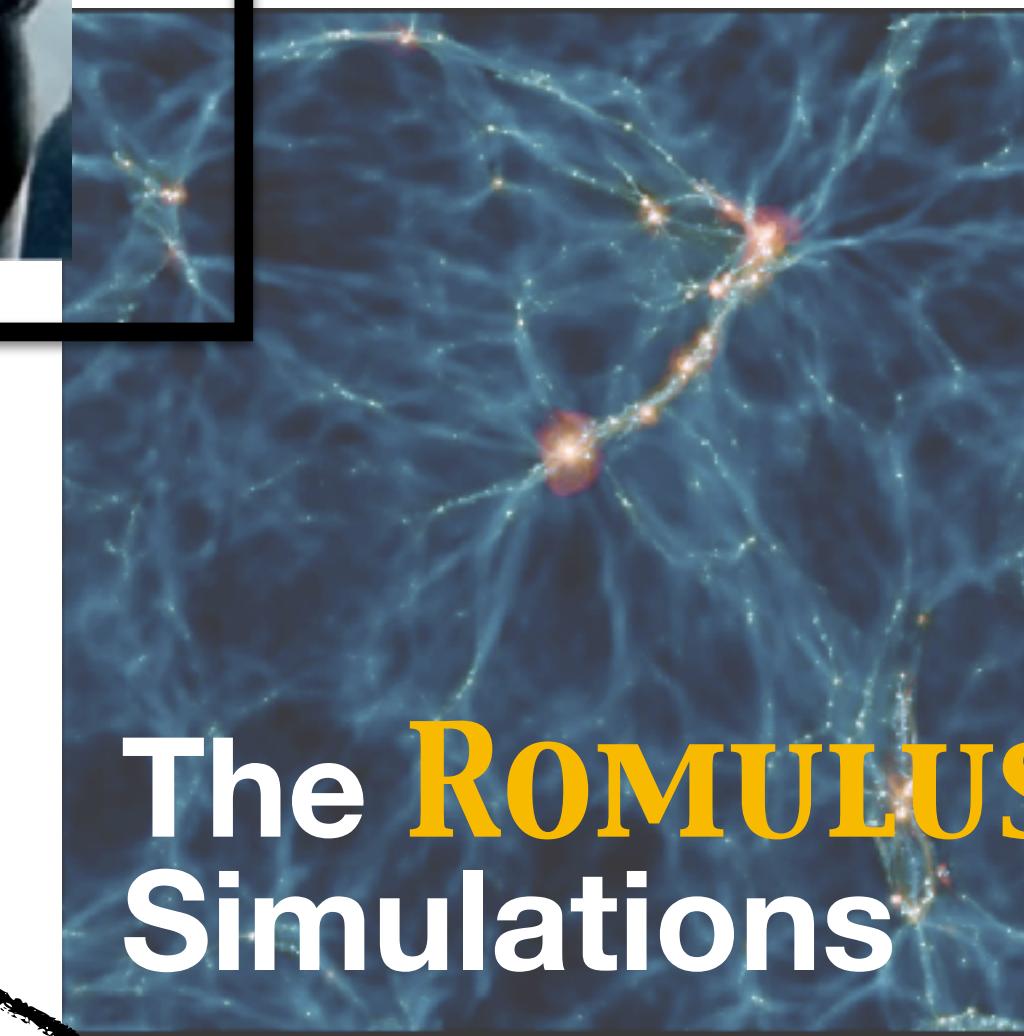
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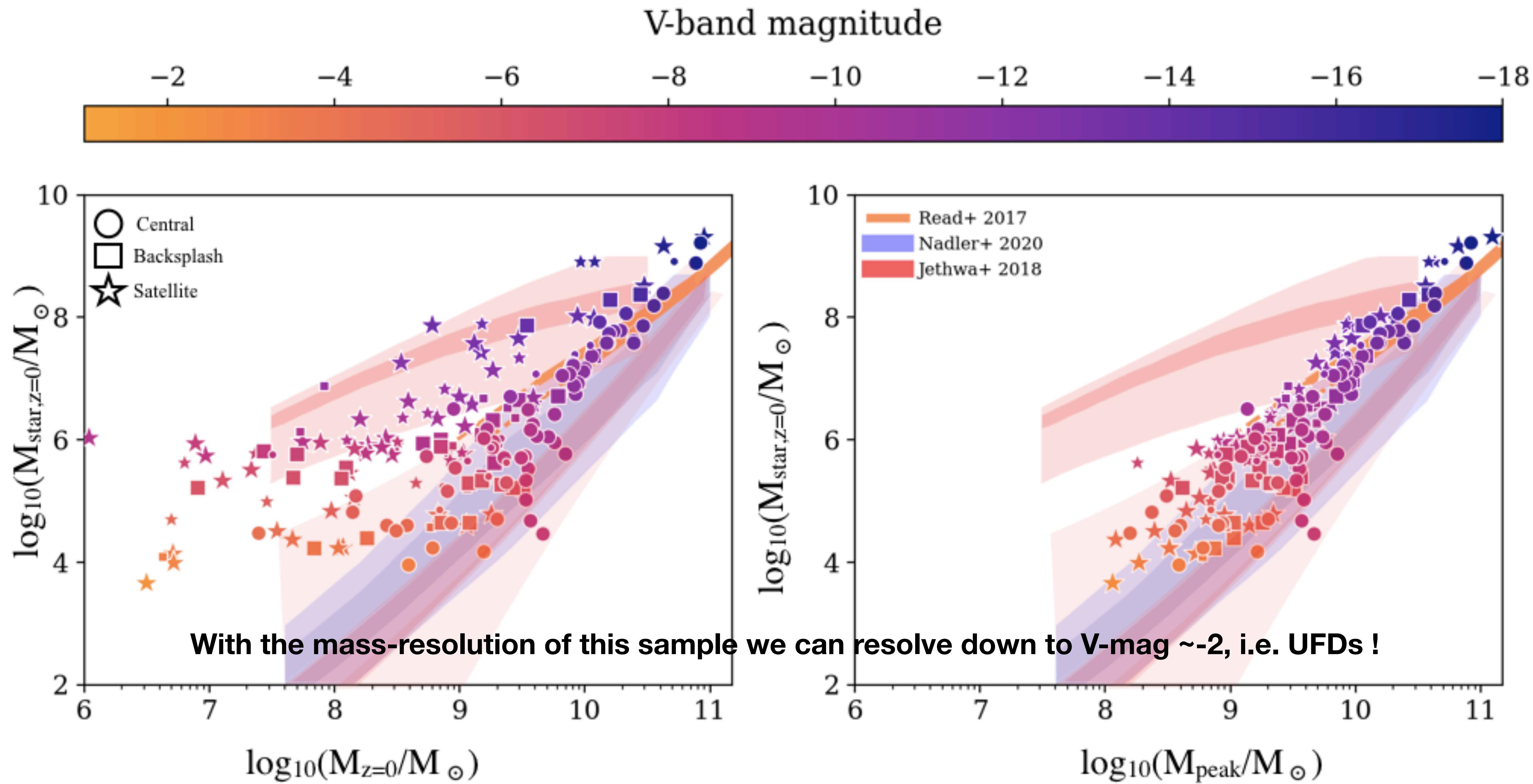
Michael's talk last week

MARVELous Dwarf Volumes + Justice

League Dwarfs = **211 High-resolution  
simulated dwarfs**



# Want simulated dwarfs? I got 'em!



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

**Dwarf Galaxy Volume: “Cpt Marvel”**

Run on NASA Supercomputer “Pleiades” made available by the NASA High-End Computing (HEC) Program through the NASA Advanced Supercomputing (NAS) Division at Ames Research Center

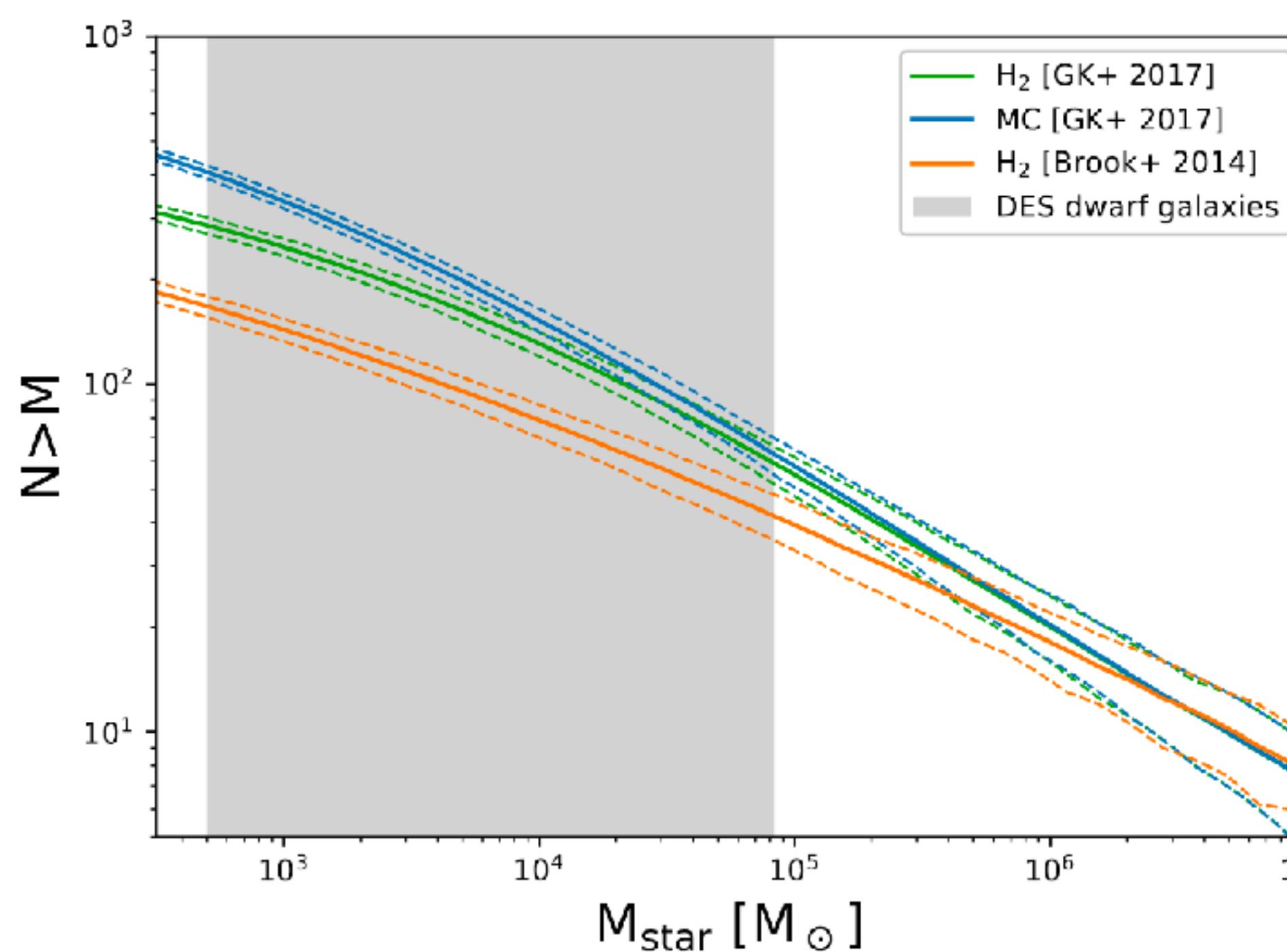
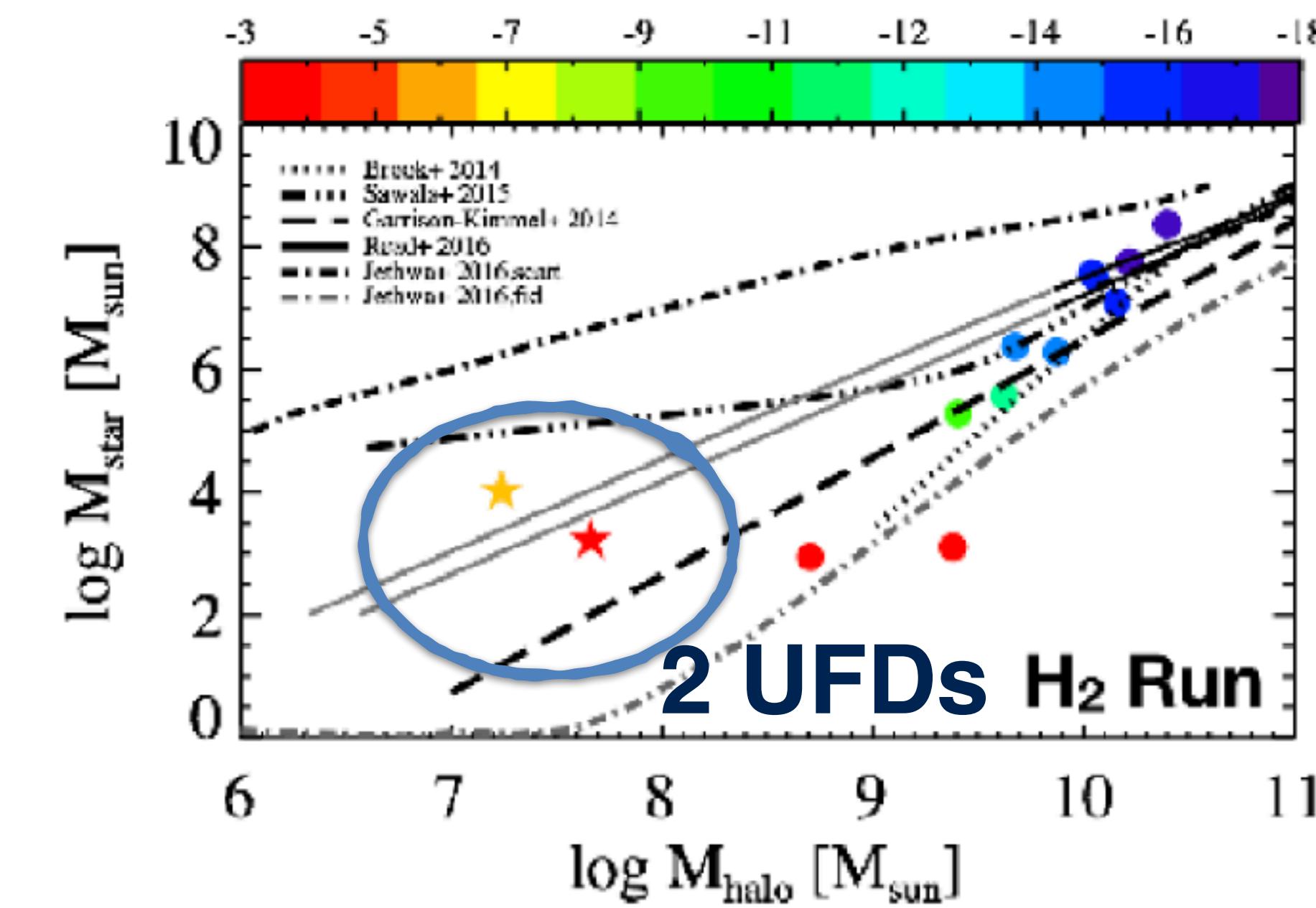
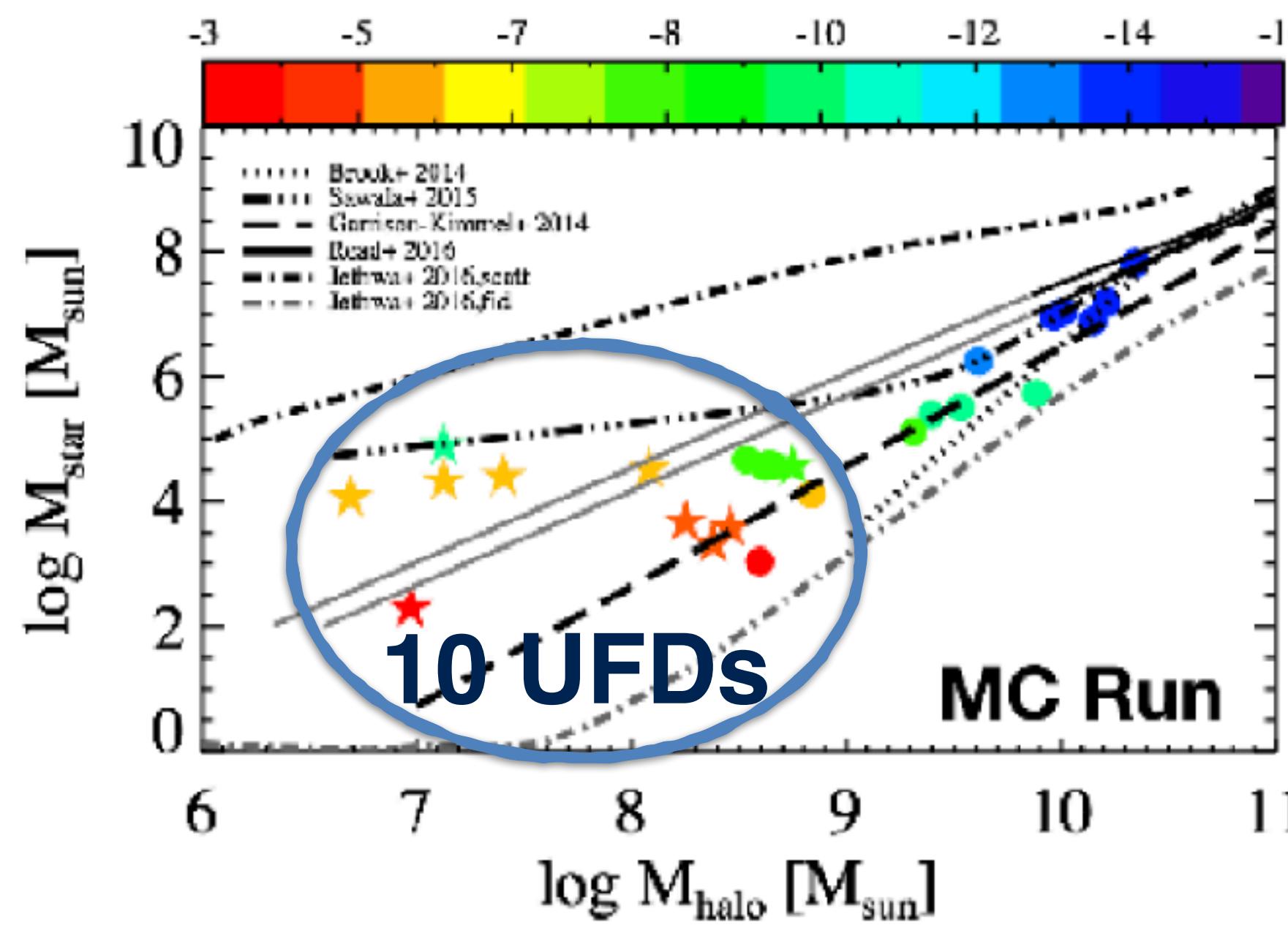
Left: dark matter  
Right: gas

Alyson Brooks (Rutgers University)  
Jillian Bellovary (Queensborough Community College)  
Charlotte Christensen (Grinnell College)  
Ferah Munshi (University of Oklahoma)



# The abundance of ultra-faint dwarf galaxies- can we use this to constrain DM?

**This is important to figure out for current/upcoming telescopes/missions like DES, JWST, Rubin's LSST, Roman**

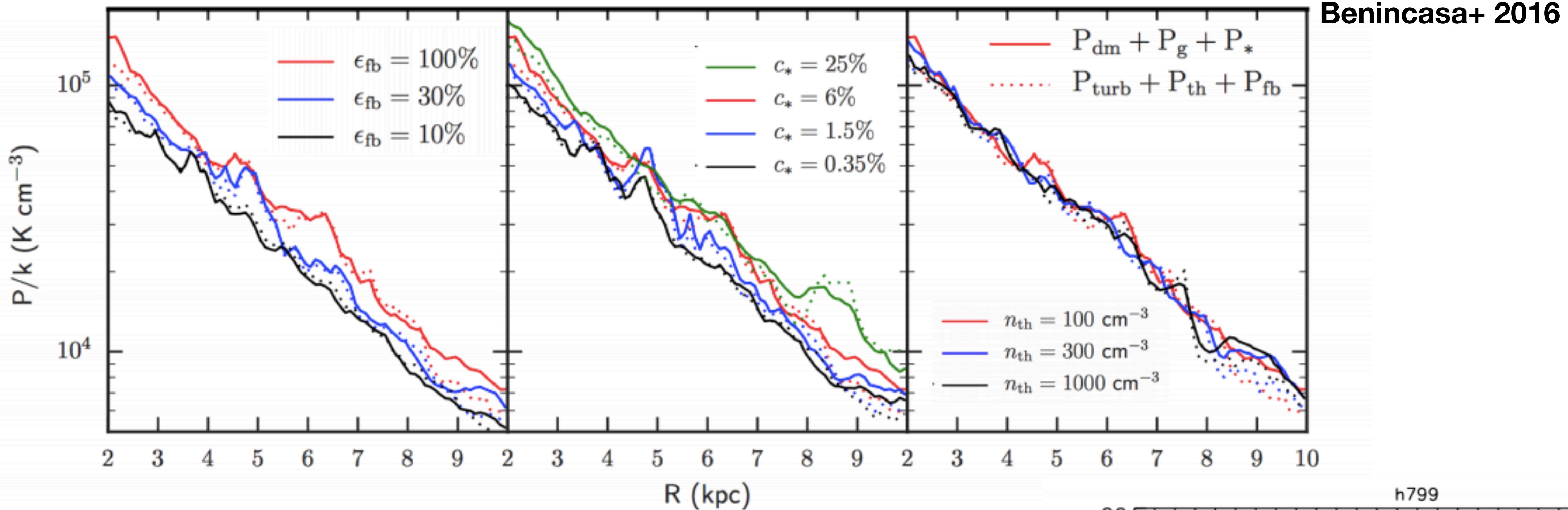


Any predictions you  
make depend on your  
star formation and  
feedback model

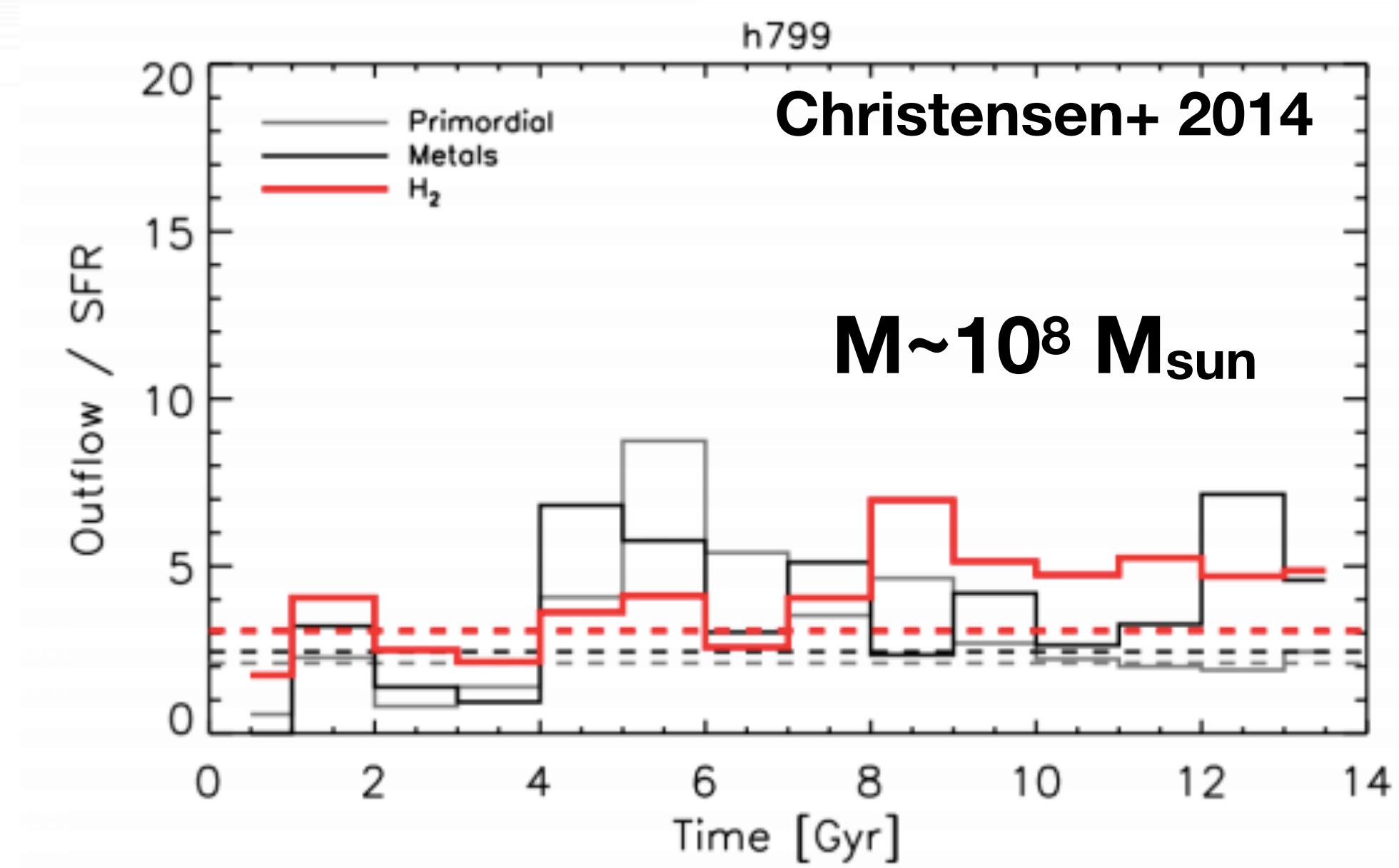


Munshi+ 2019, with former  
graduate student E. Applebaum

# Why haven't we worried before?



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



# V-band magnitude

-2

-4

-6

-8

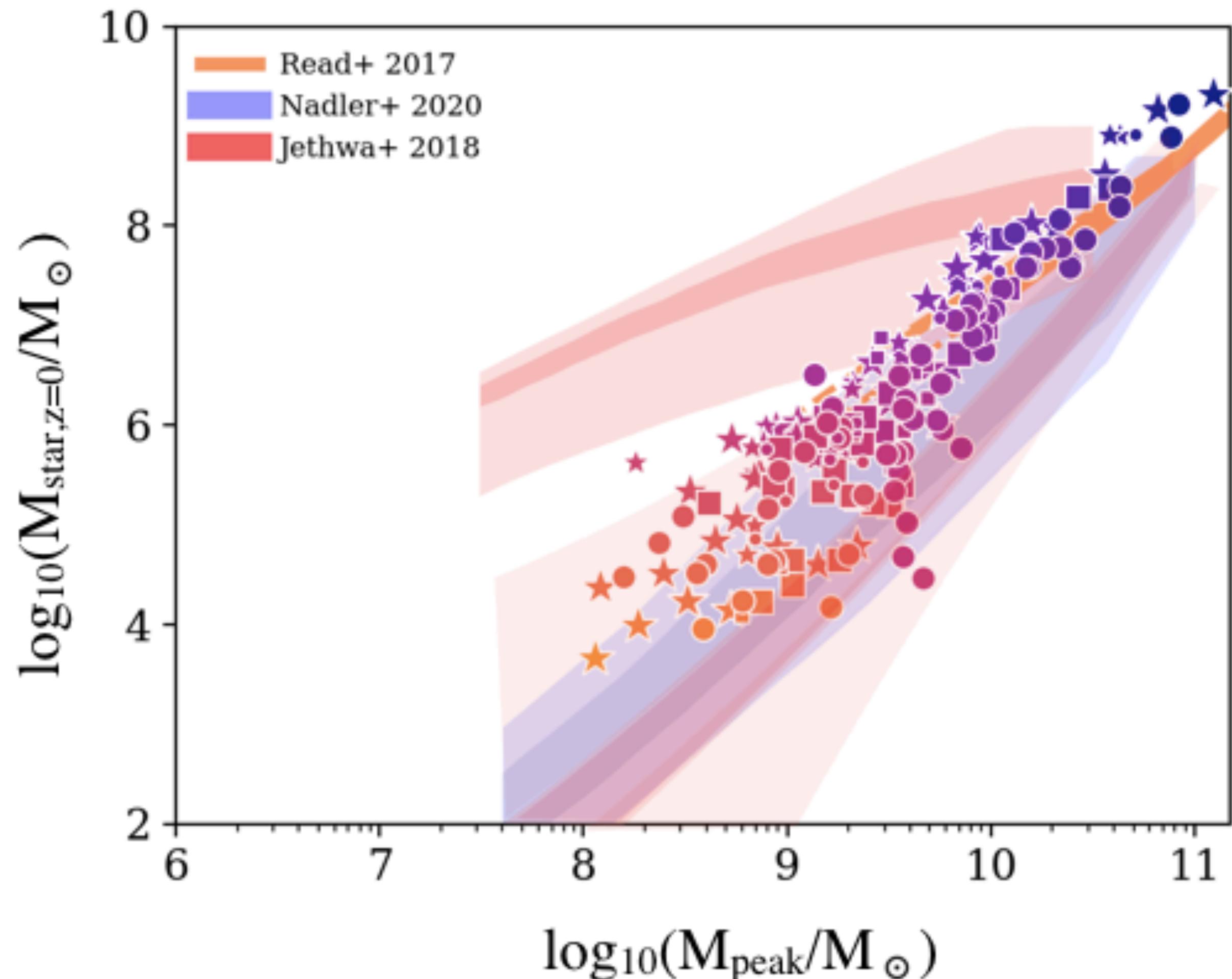
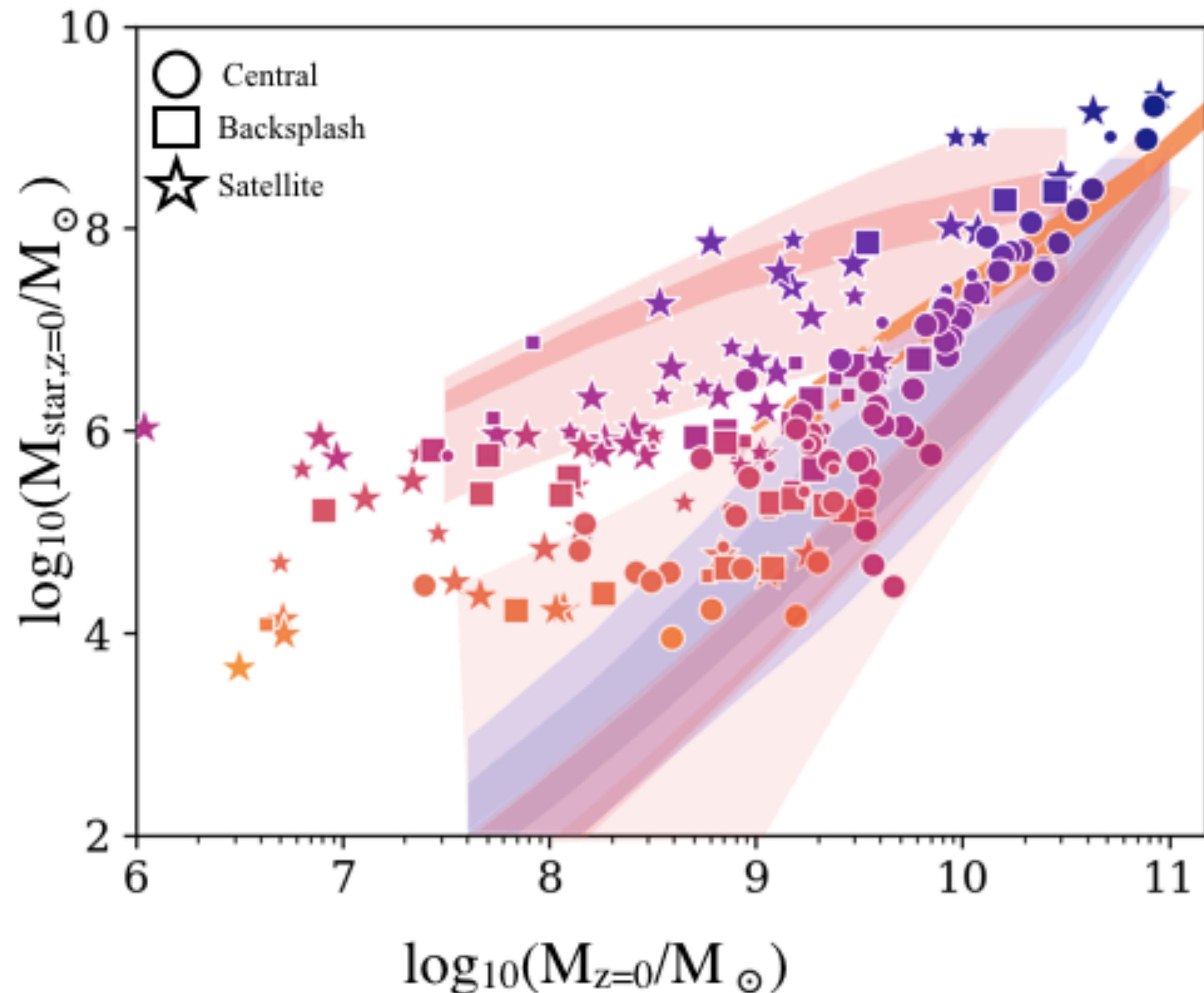
-10

-12

-14

-16

-18



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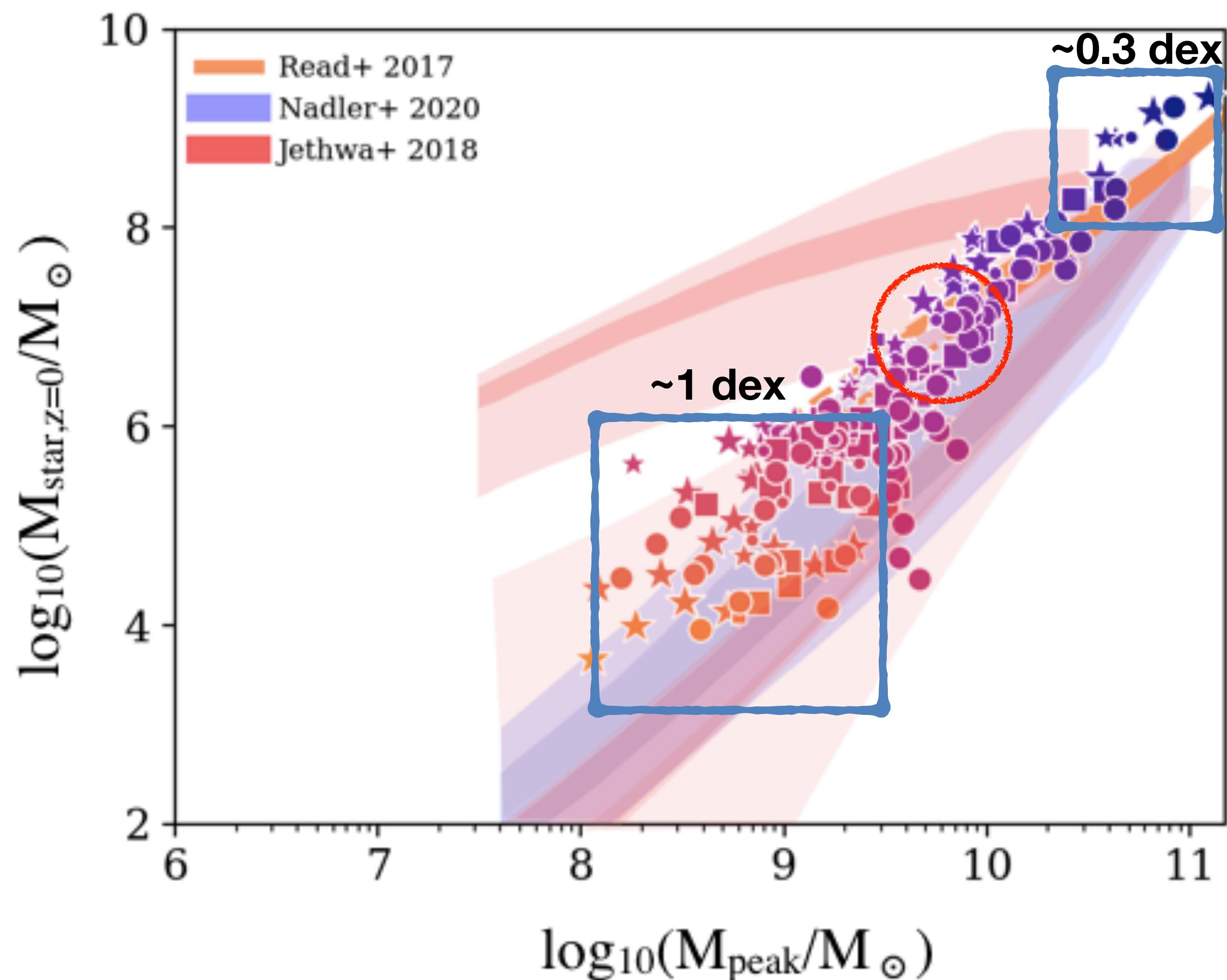
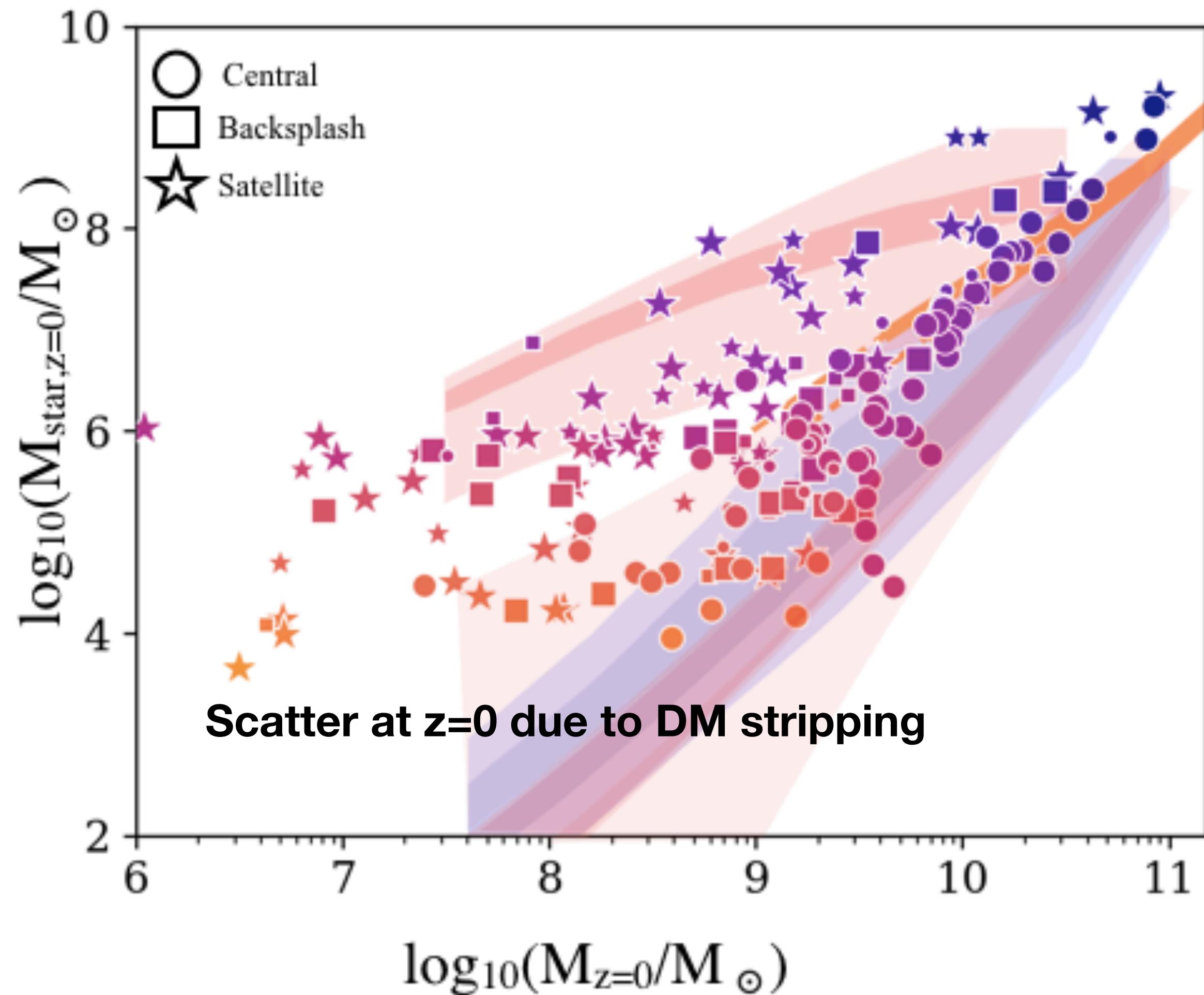
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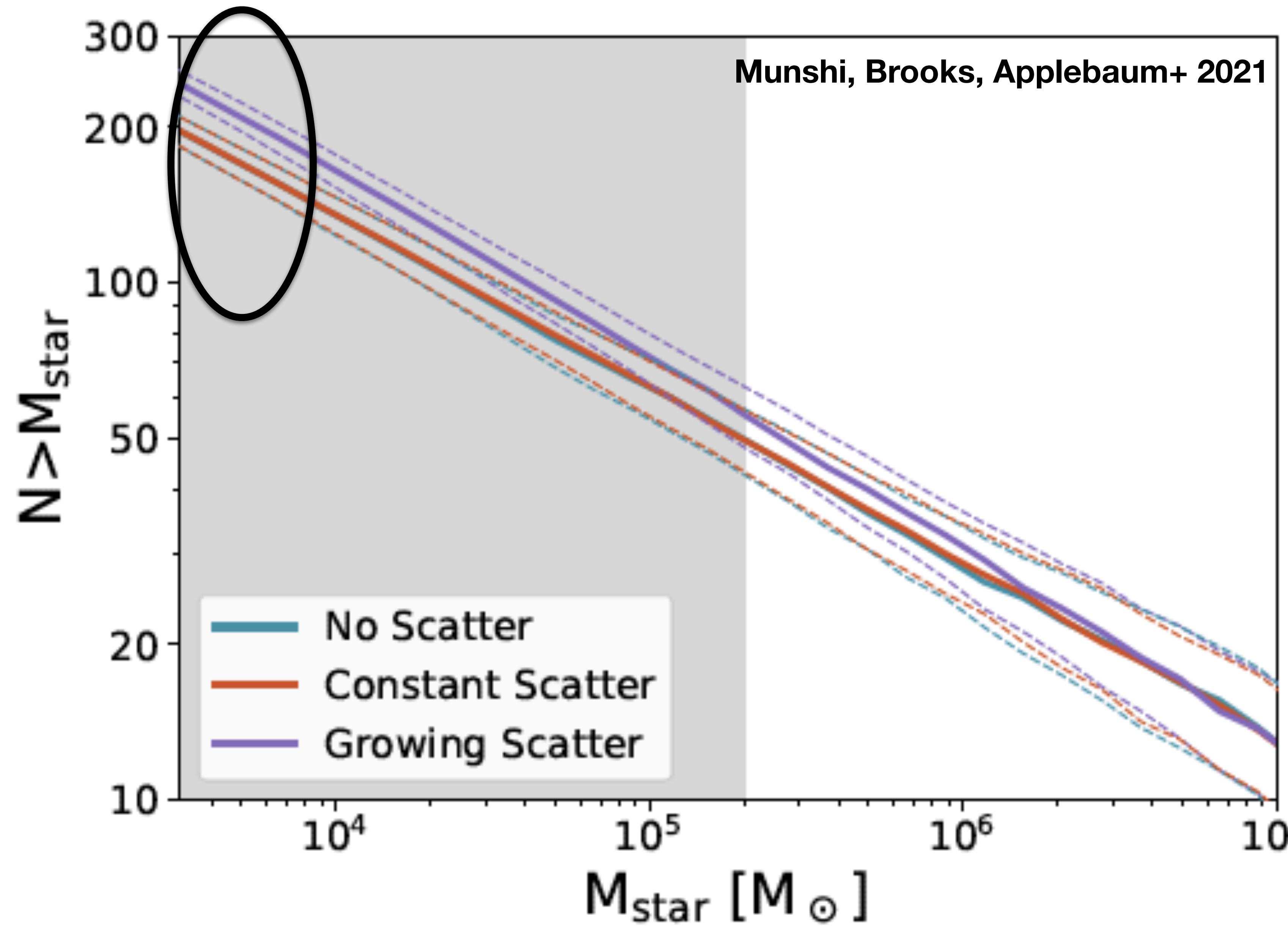
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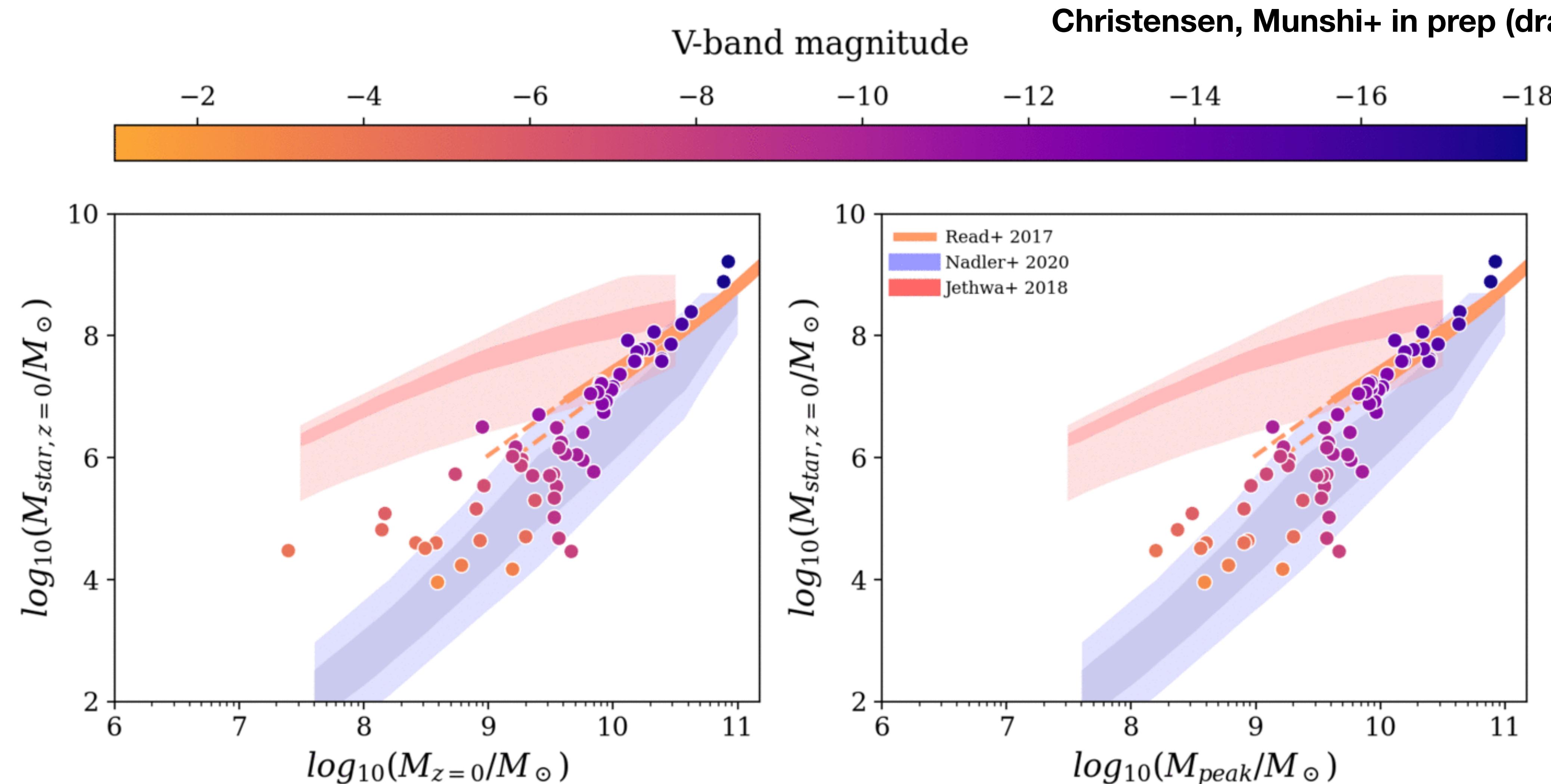
-18



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

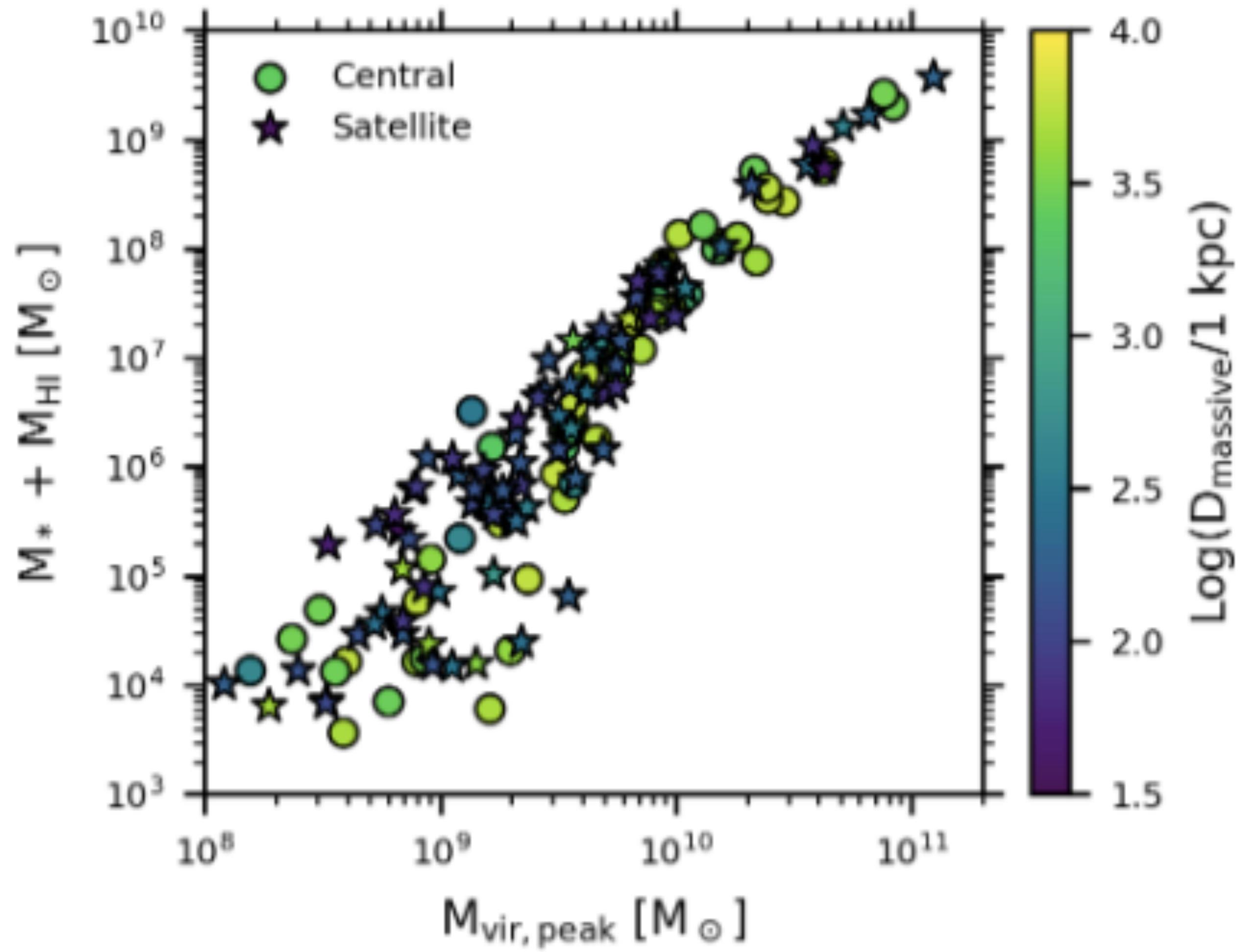
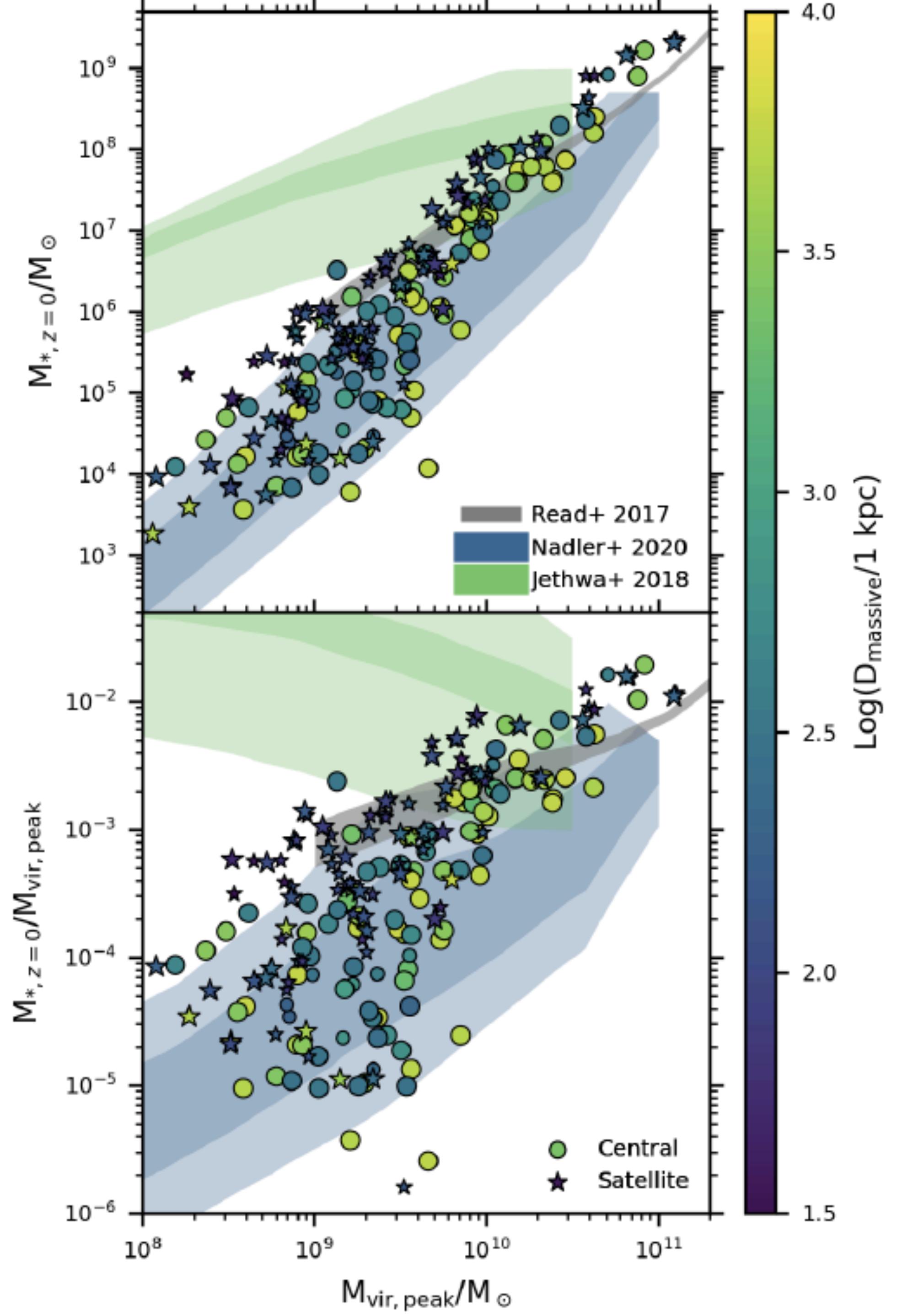


# Upcoming: Effect of Environment



This is in tension with previous work at lower resolution; this series of papers will be the most robust simulated constraints on UFDs that exist

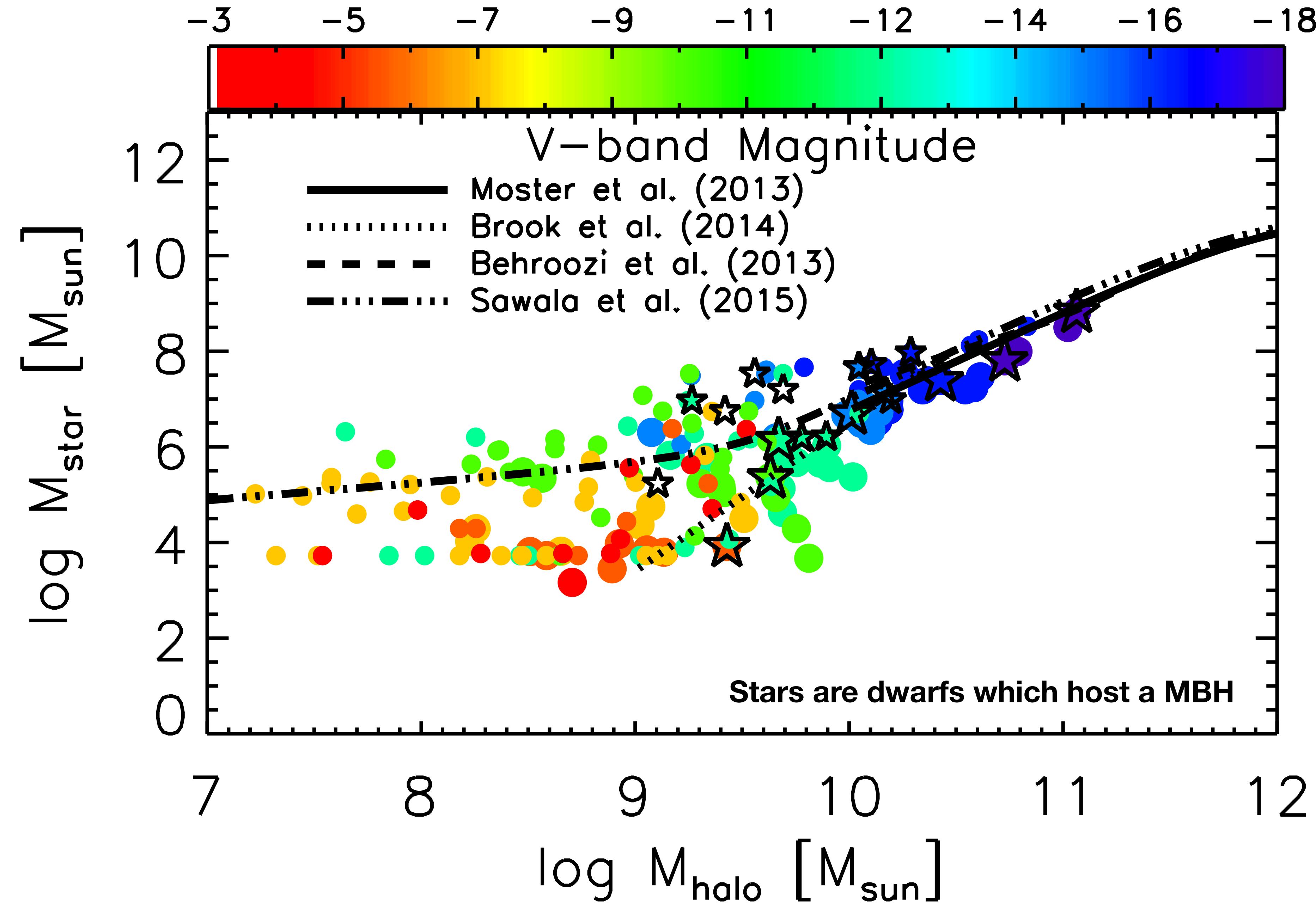
# Upcoming: Effect of Environment

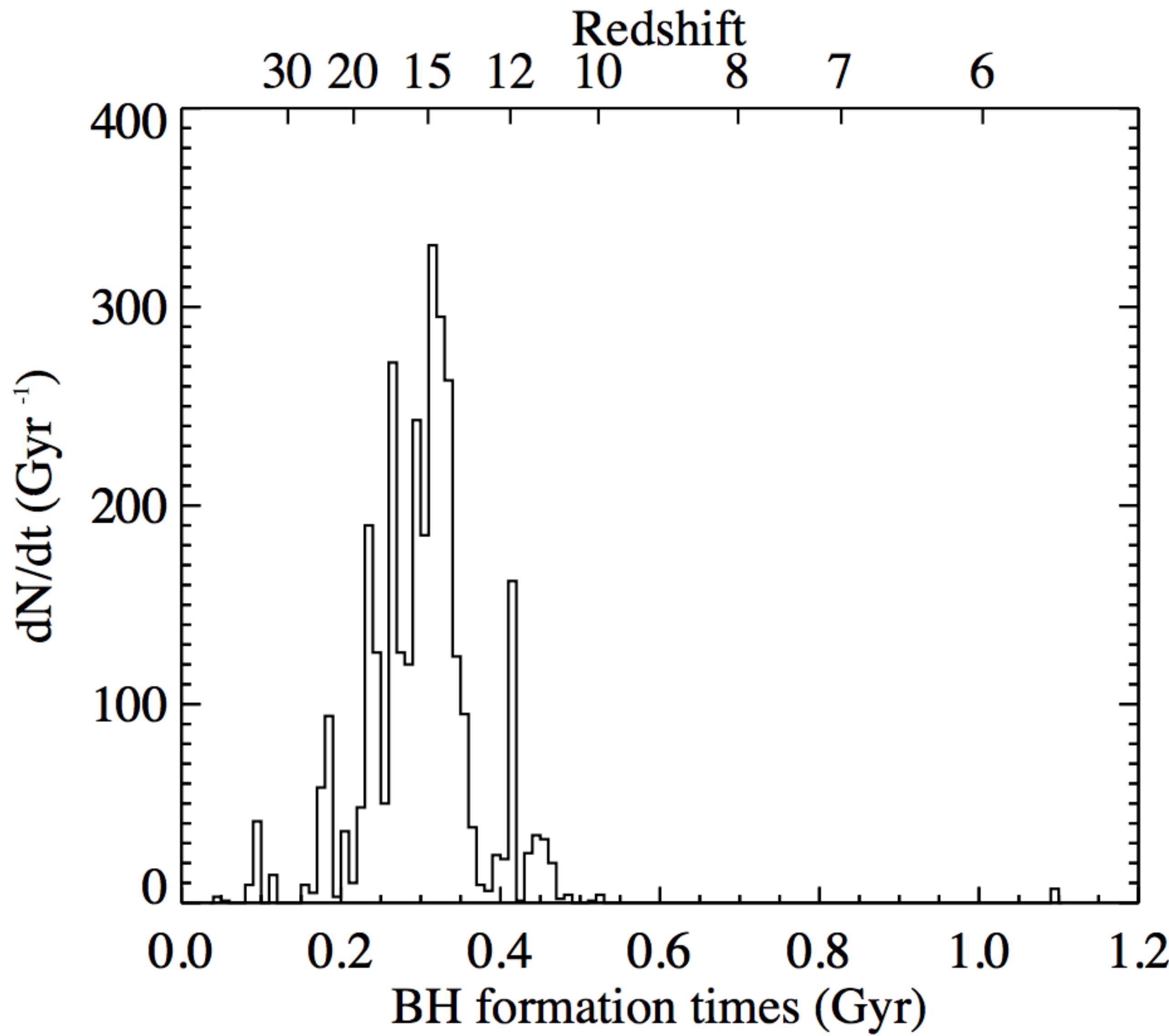


Christensen, Munshi+ in prep (draft circulating!)

Being the *only* simulations that track black hole growth in dwarf zoom sims, can we use these black holes to constrain DM?

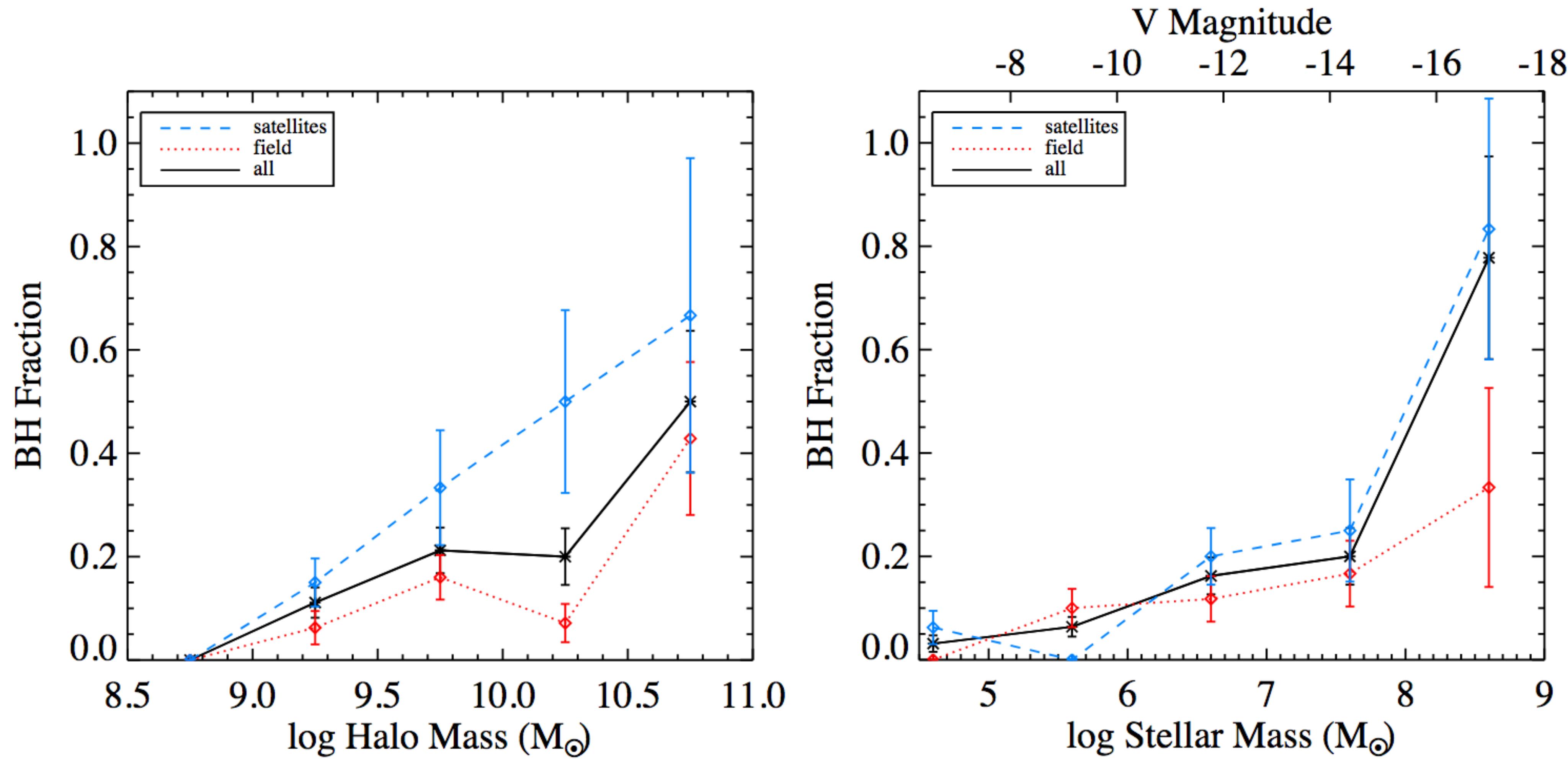
**This is important as these predictions are 1. dependent on DM model and 2. detectable by LISA**





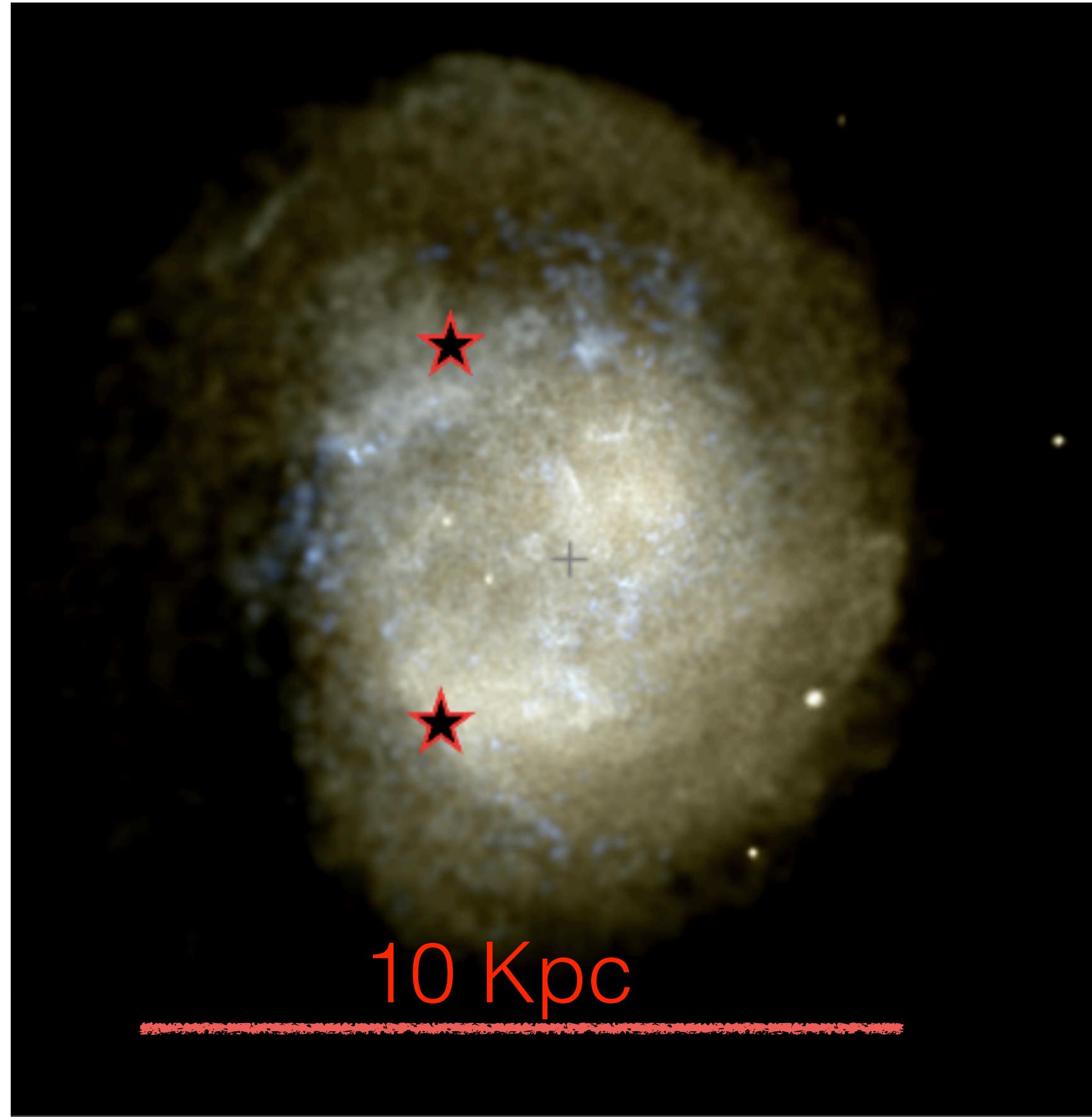
- MBH seeds form via direct collapse
- Probabilistic approach- similar conditions to SF

- MBHs form at high -z
- Truncation due to propagation of metals (need pristine gas)

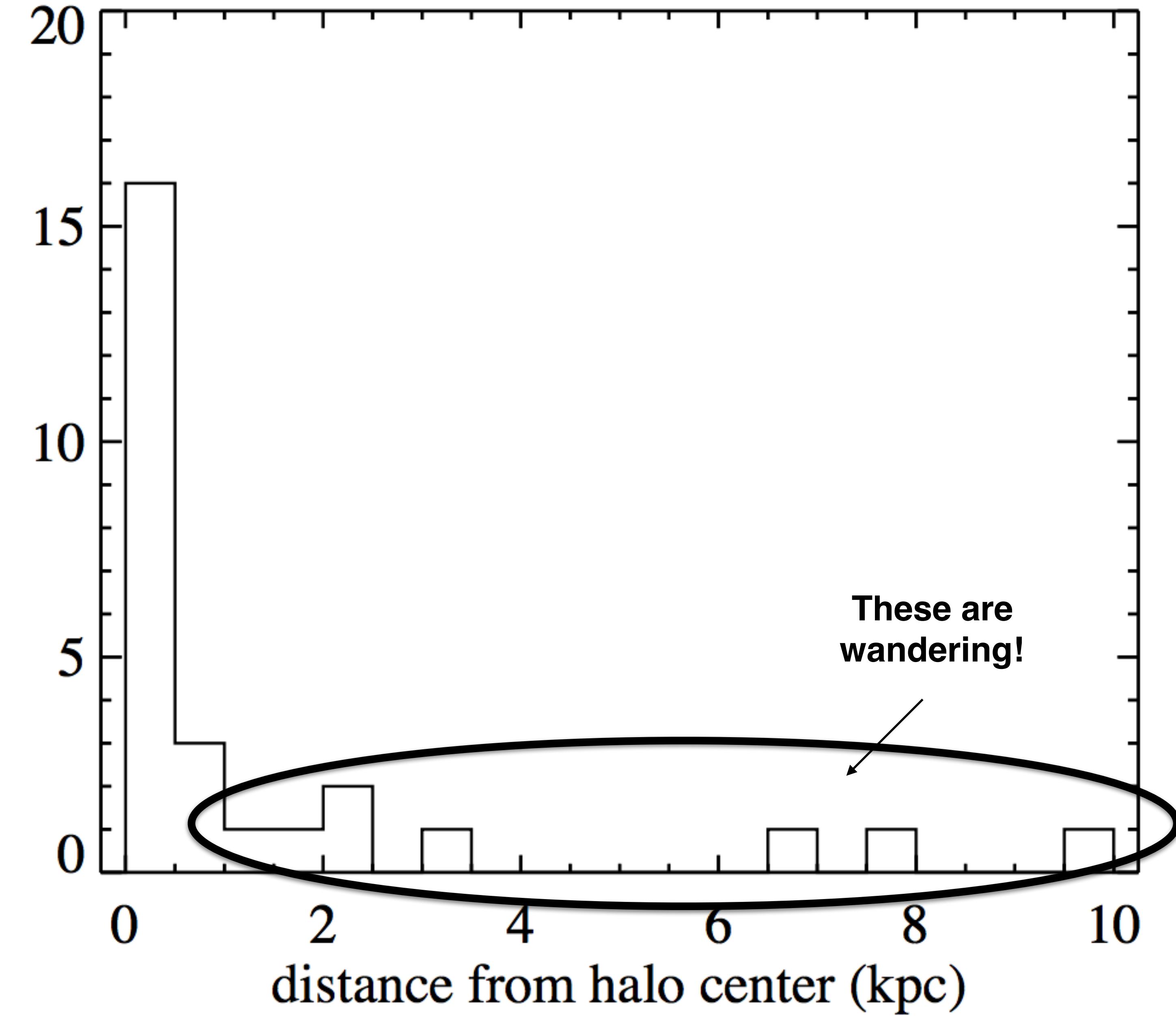


- **No environmental difference in occupation fraction-** halo masses are sensitive to environment due to tidal stripping

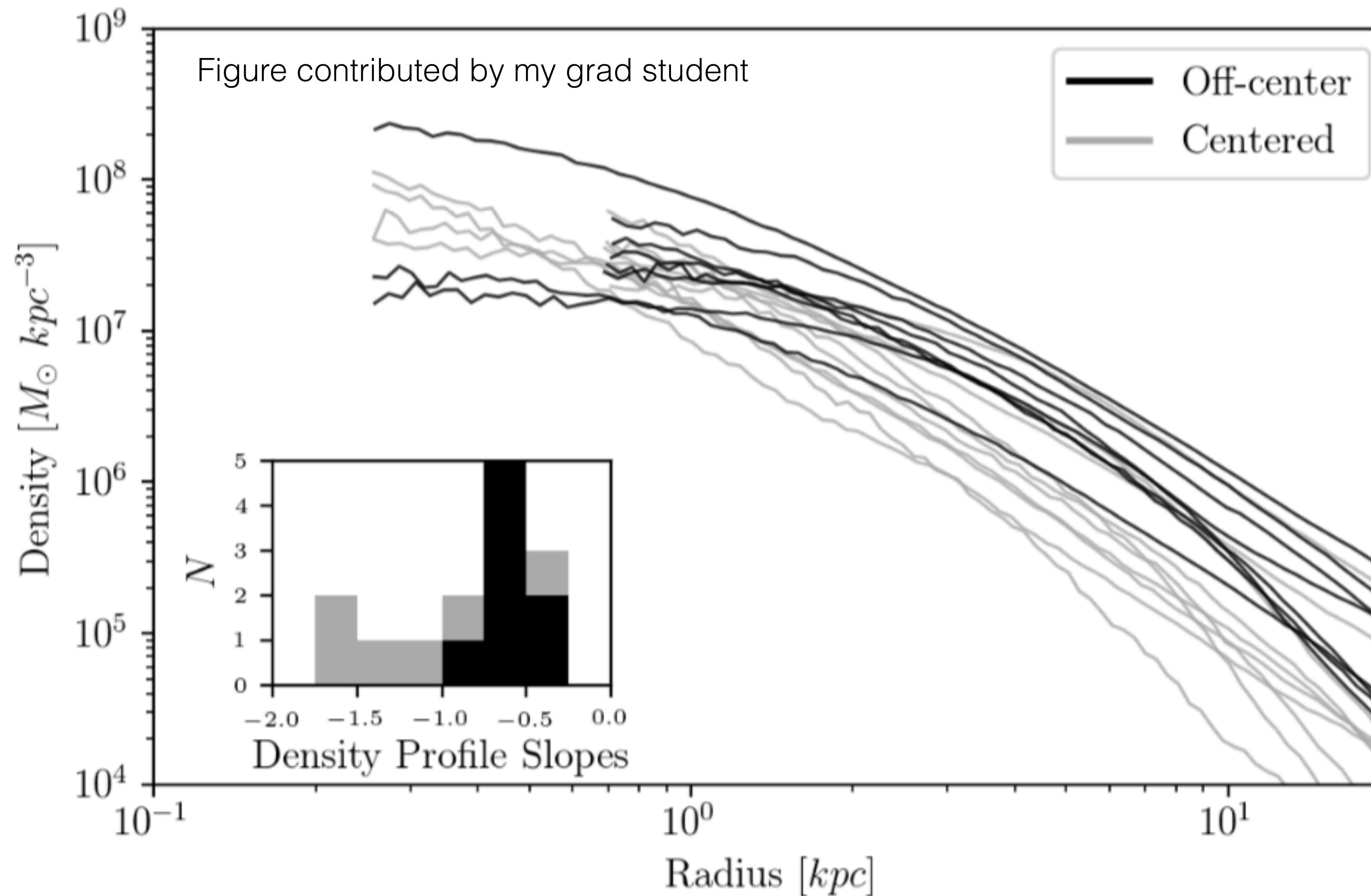
They are not necessarily in the center of dwarf halos!

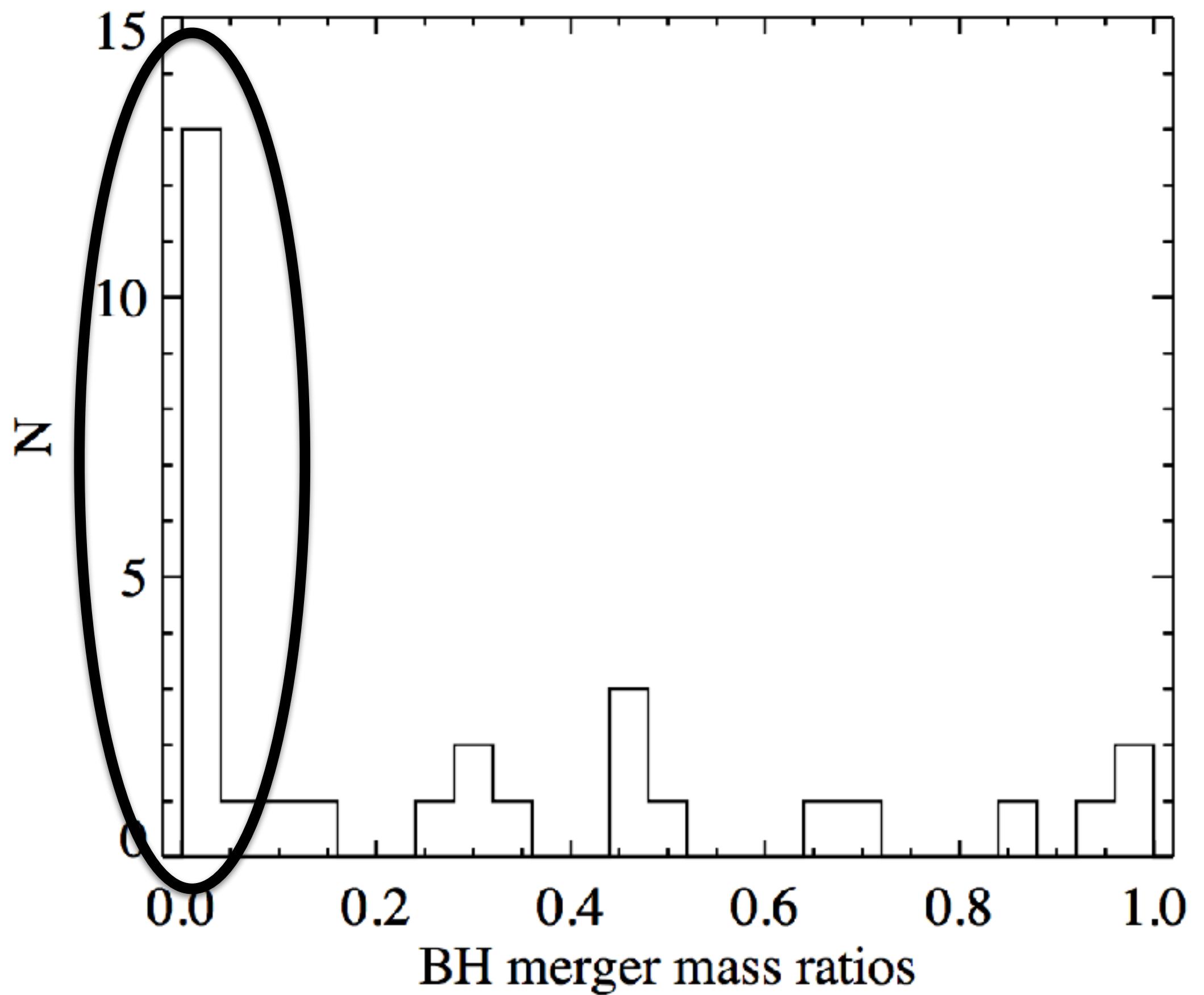


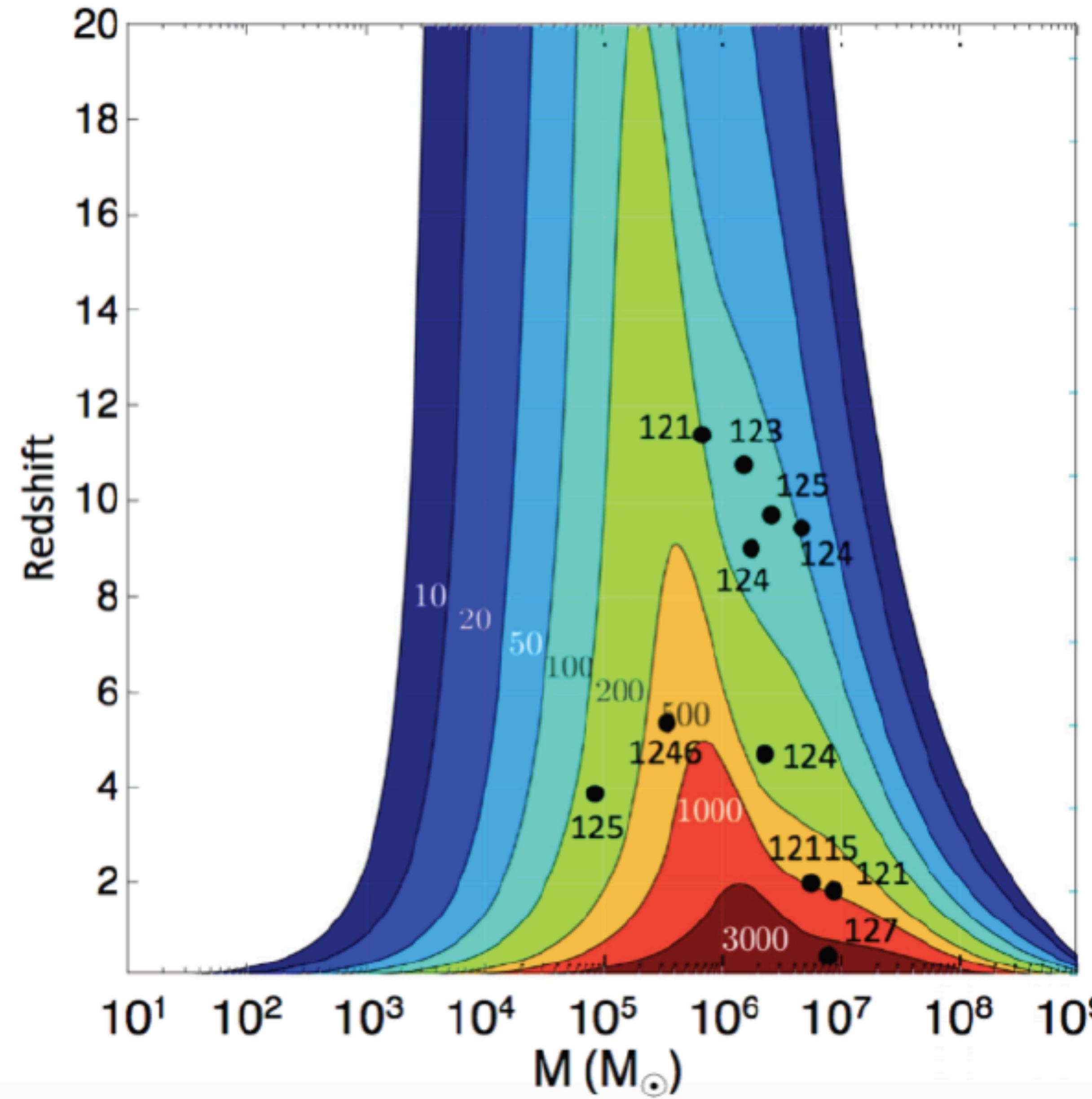
Bellovary, Cleary, Munshi + (2018)



They reside in cored DM halos: the ones with smaller wandering radii are consistent with core-stalling







OU Grad student Jordan Van Nest is working on the SIDM Marvel runs to track BH formation, merger rates and off-center BHs!



MBH mergers happen at all z's. LISA will be sensitive to those at high-z. **LISA is a way to probe structure formation at high-z through these MBH mergers! Can also test DM model.**

# Key Problems

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

We still need baryons in alternative dark matter models. Is there a smoking gun that points to a given dark matter model?

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

To constrain the Dark Matter model, we must understand the impact of baryonic physics on galaxy formation!

Baryonic physics alleviates the current problems with CDM, but that doesn't mean CDM is the correct model! *Very little work has been done to discover whether galaxy formation can be reproduced in models outside of CDM*

Future observations of dwarf galaxies ( $M_{\text{star}} < 10^7 M_{\odot}$ ) are the best probes of both the dark matter model and the physical conditions of the first star formation

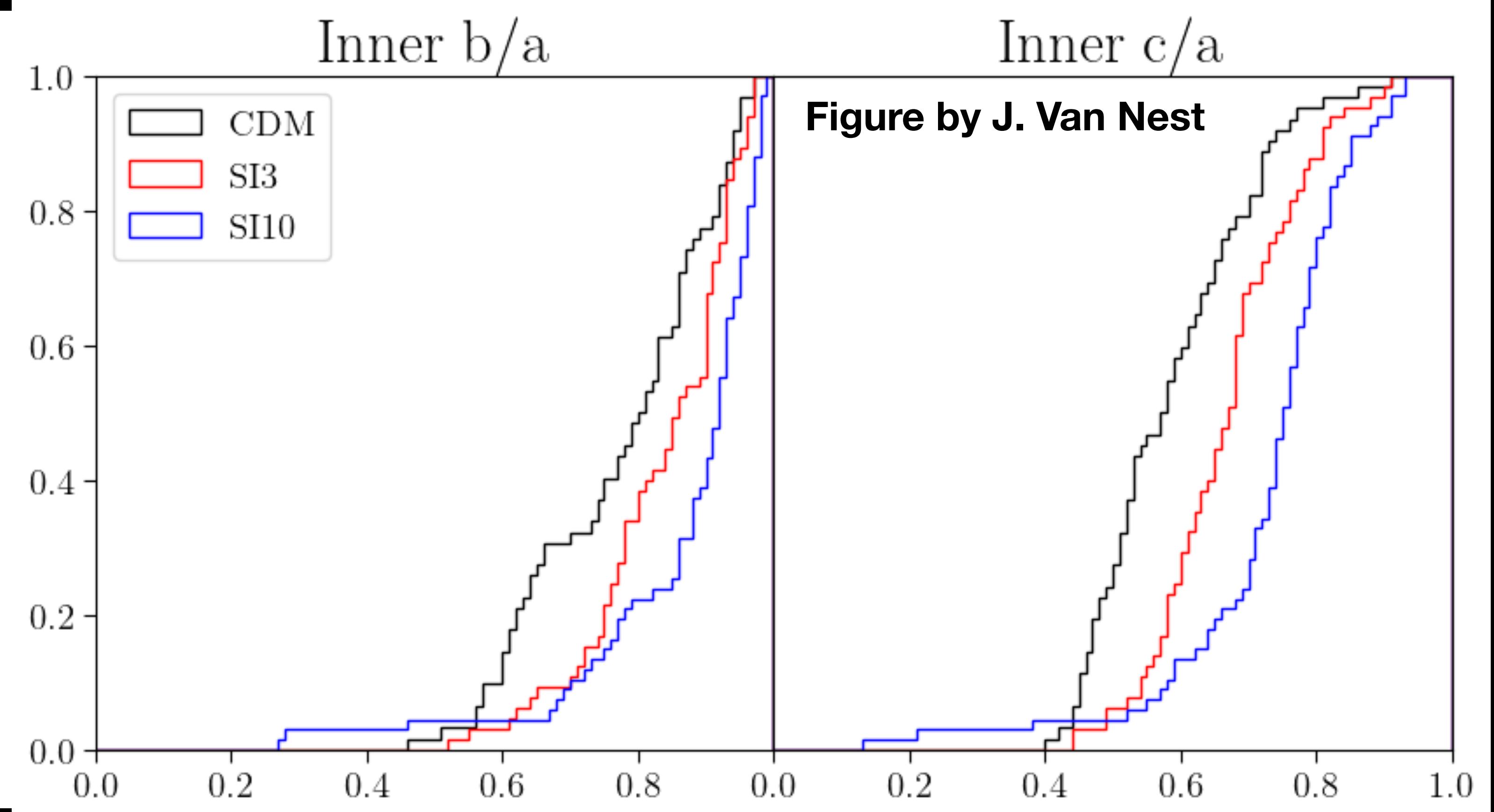
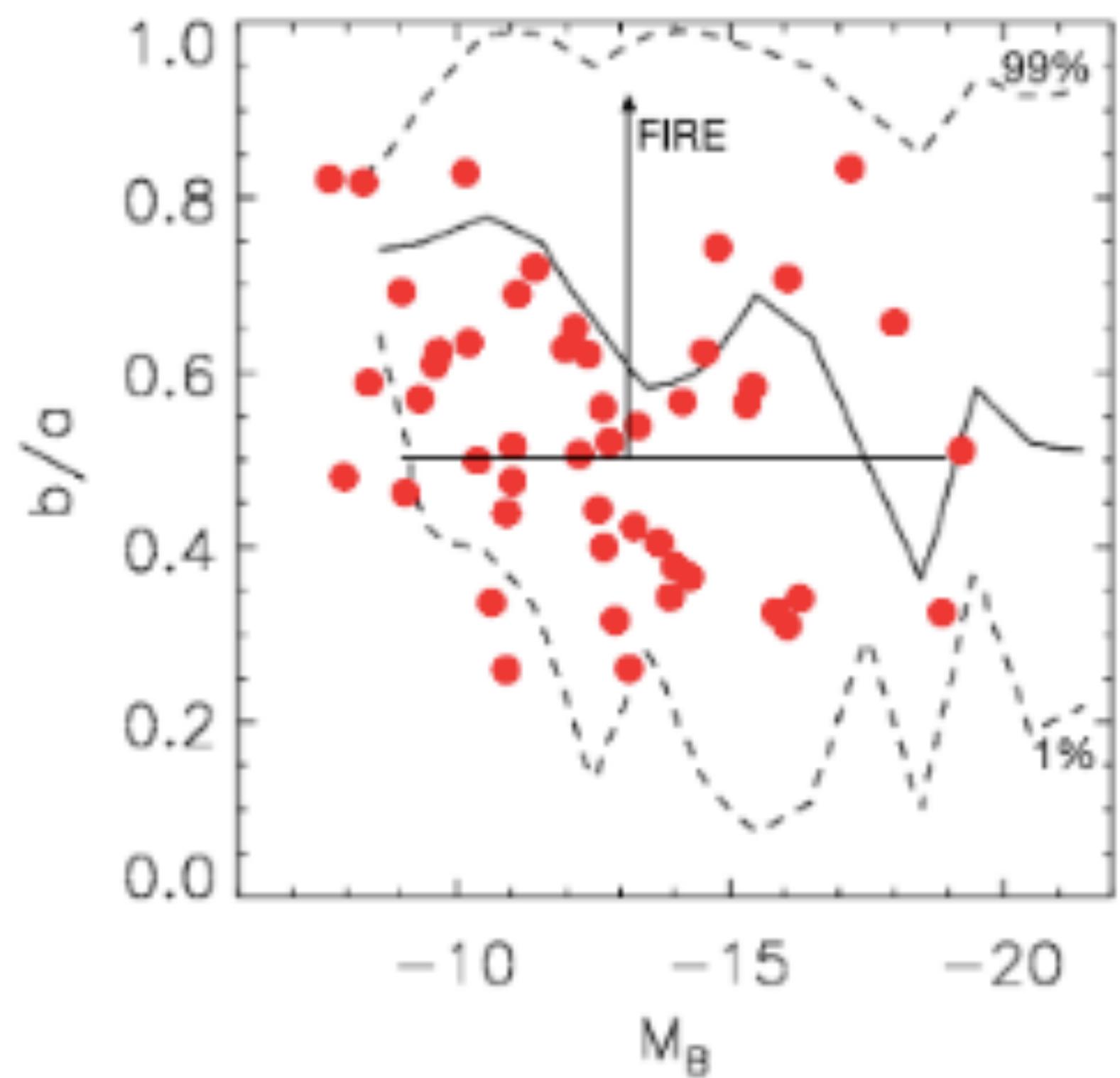
I have created a statistical sample of simulated dwarf galaxies in order to interpret Local Volume observations and prepare for JWST/Roman/Rubin/LISA

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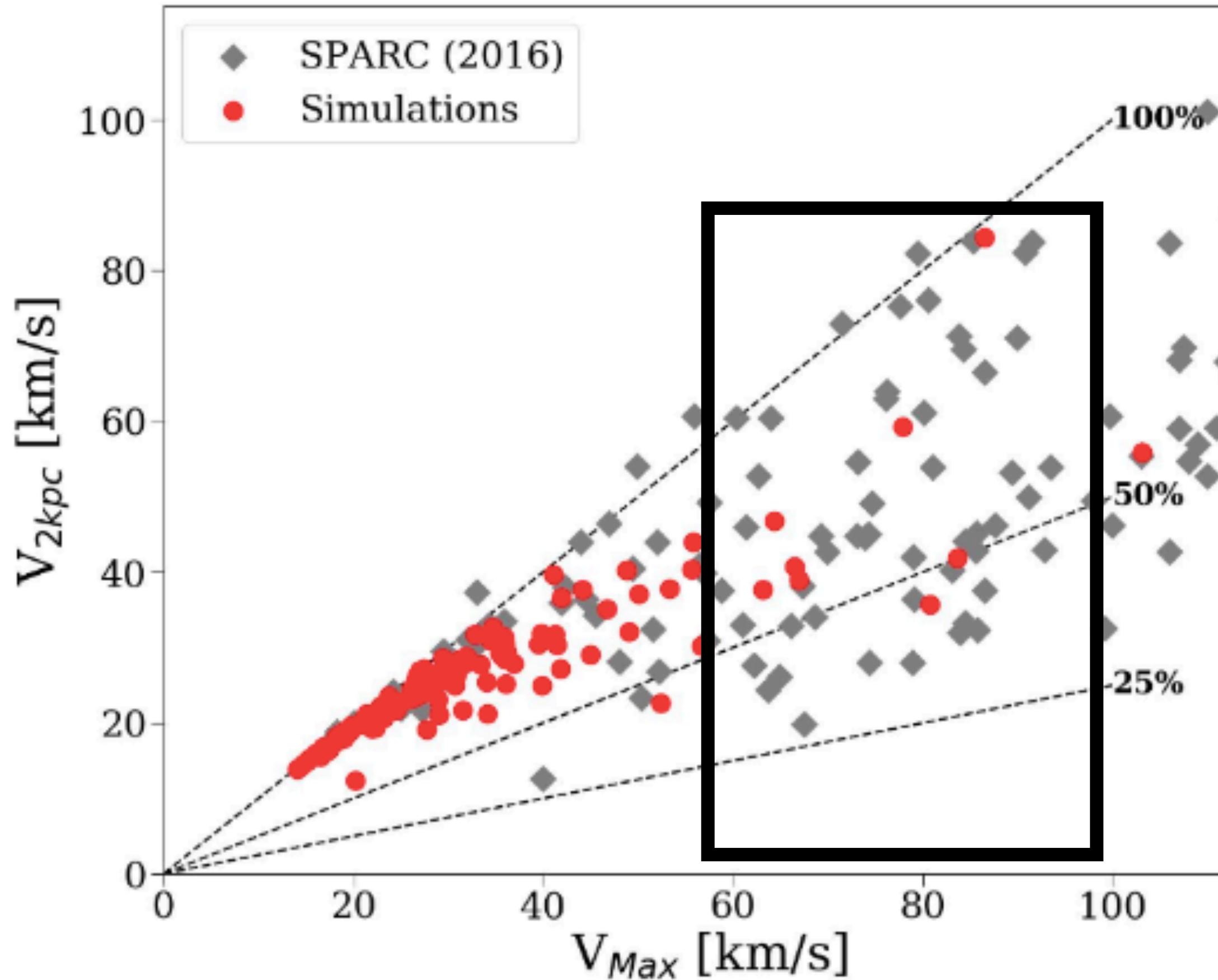
# Dwarf halo shape as a tracer of dark matter physics?



Only simulations to reproduce full range of dwarf shapes

Funded NSF proposal to study SIDM in zooms

# SIDM Dwarfs: smoking gun in rotation curves?



New velocity dependence based on latest literature

New CDM/SIDM dwarfs fill in parameter space

Funded NSF proposal to study SIDM in zooms



MARVELous Dwarfs

Ultra-faints in isolation

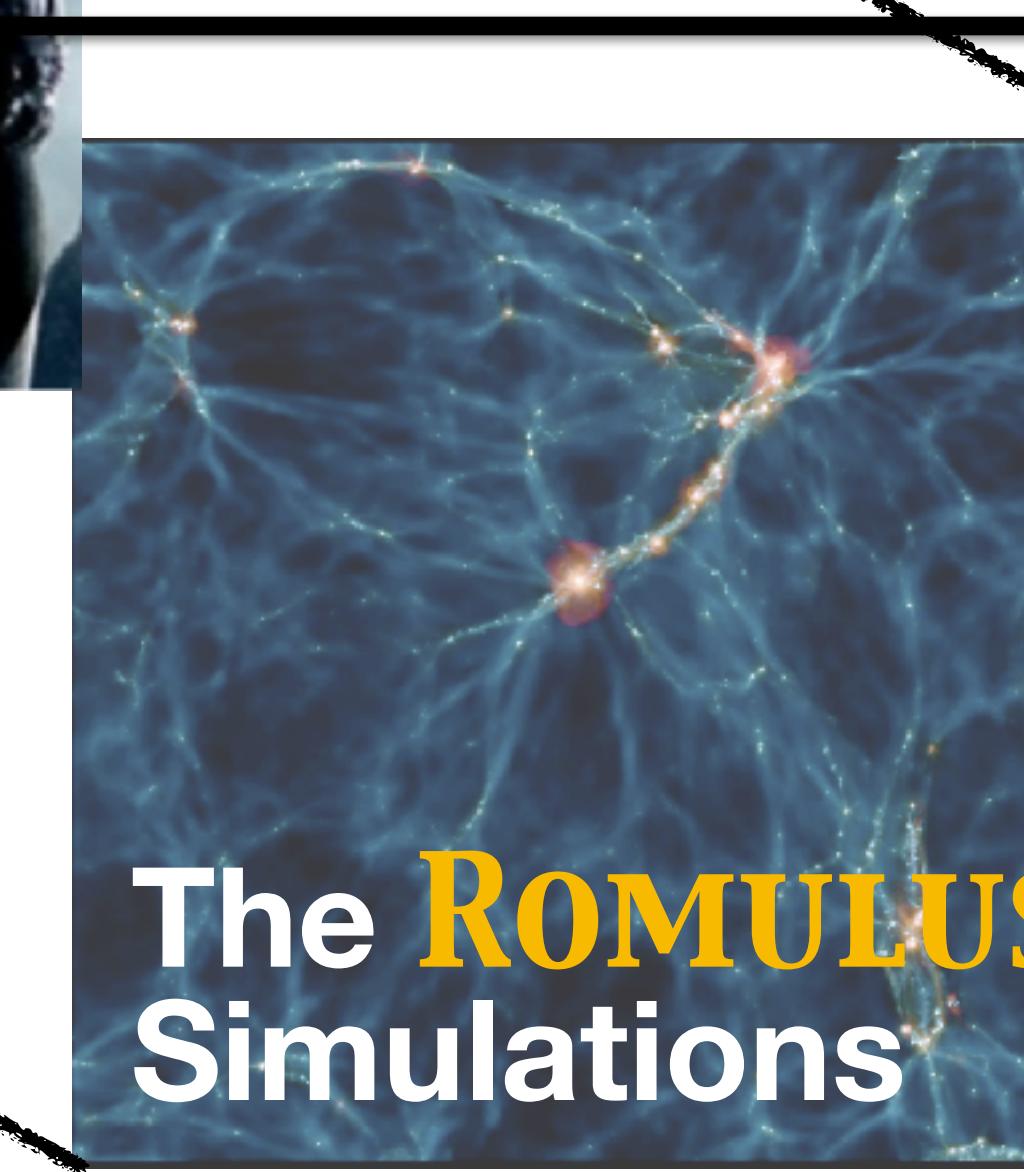
Ultra-faints in the vicinity of a MW



The DC Justice League

Dwarfs (and UDGs) across environments

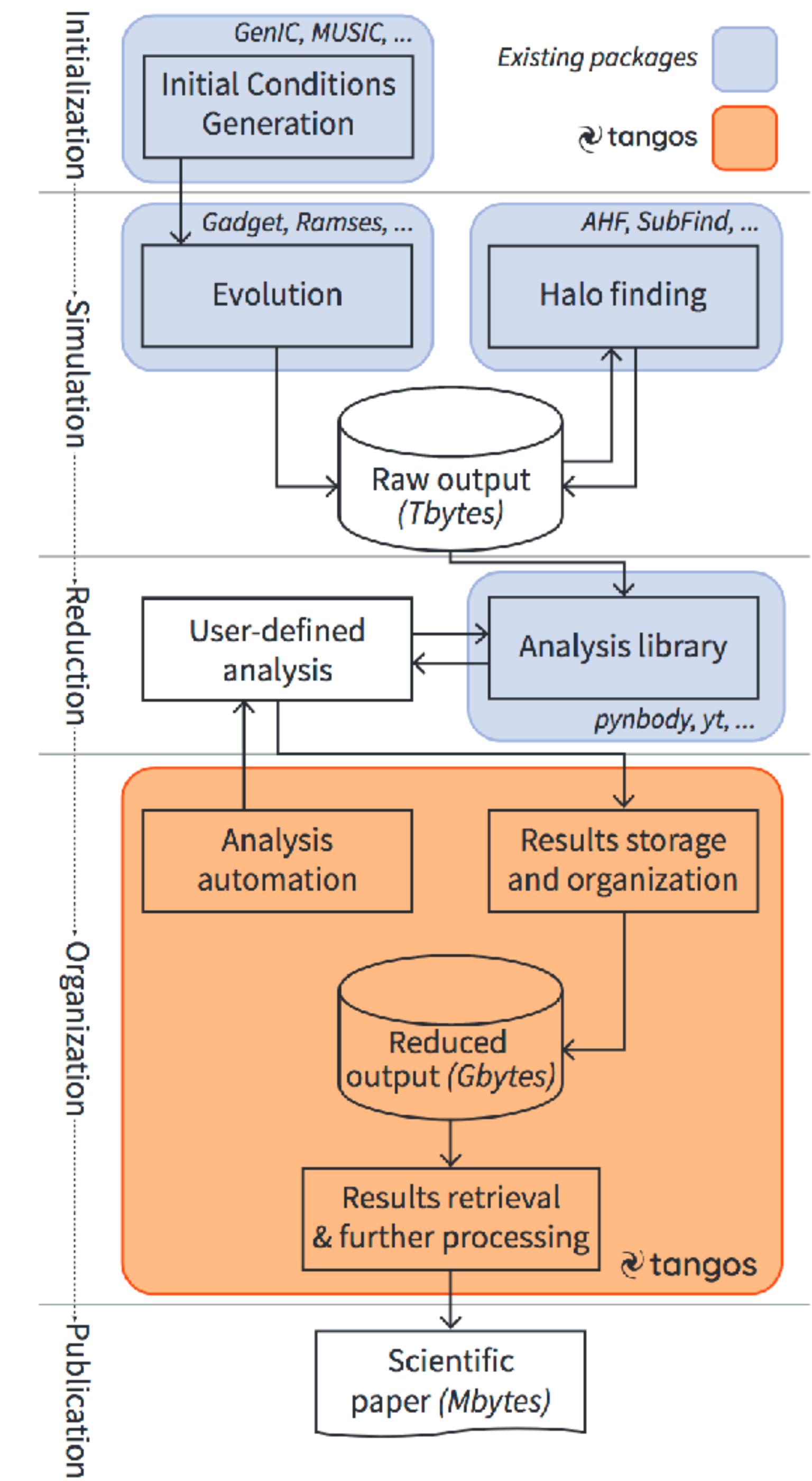
In the N-body Shop, there's been an explosion of dwarf galaxy simulations



The ROMULUS Simulations

# Leveraging “Big Data” techniques

**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.



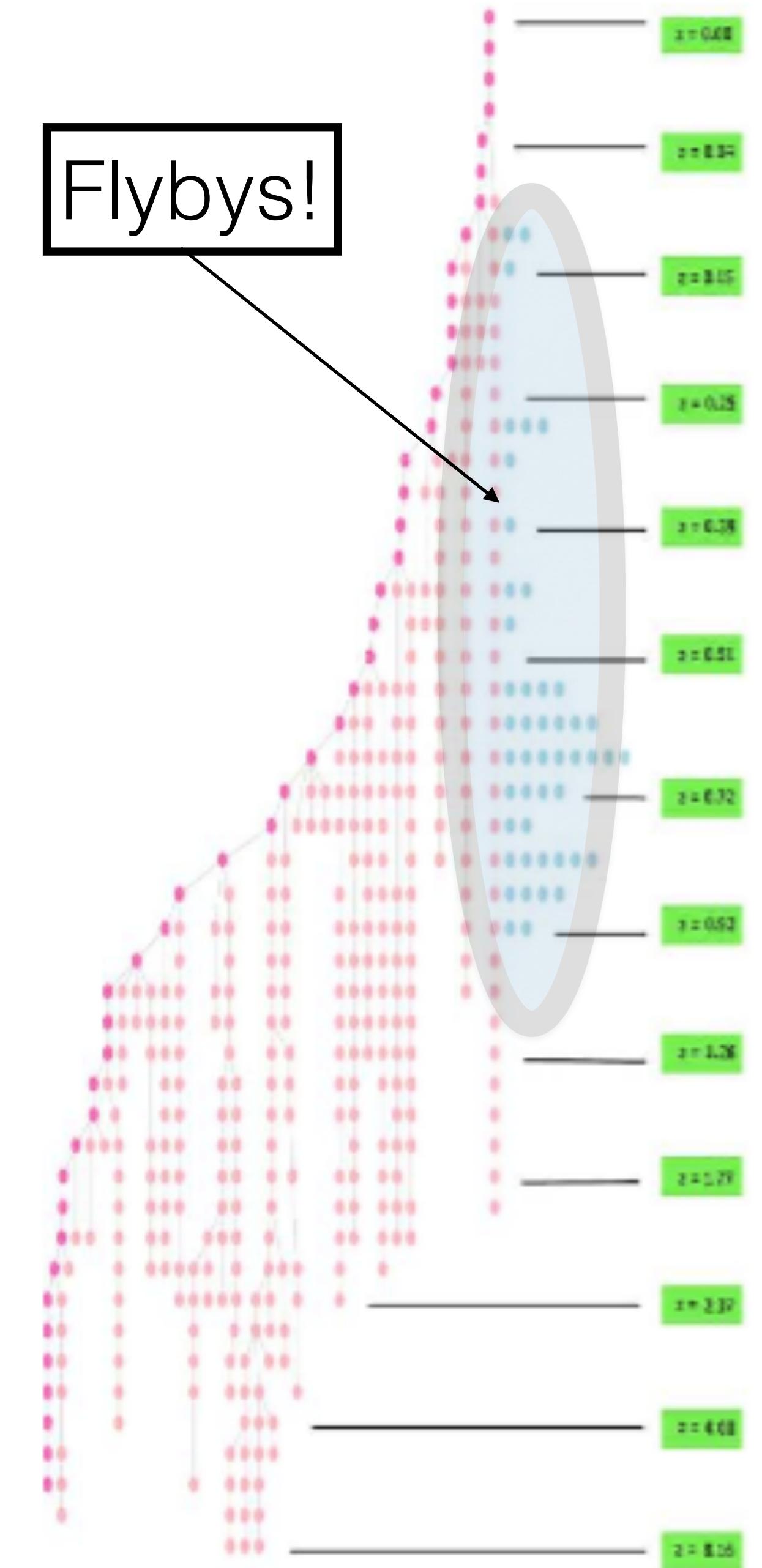
# Leveraging “Big Data” techniques

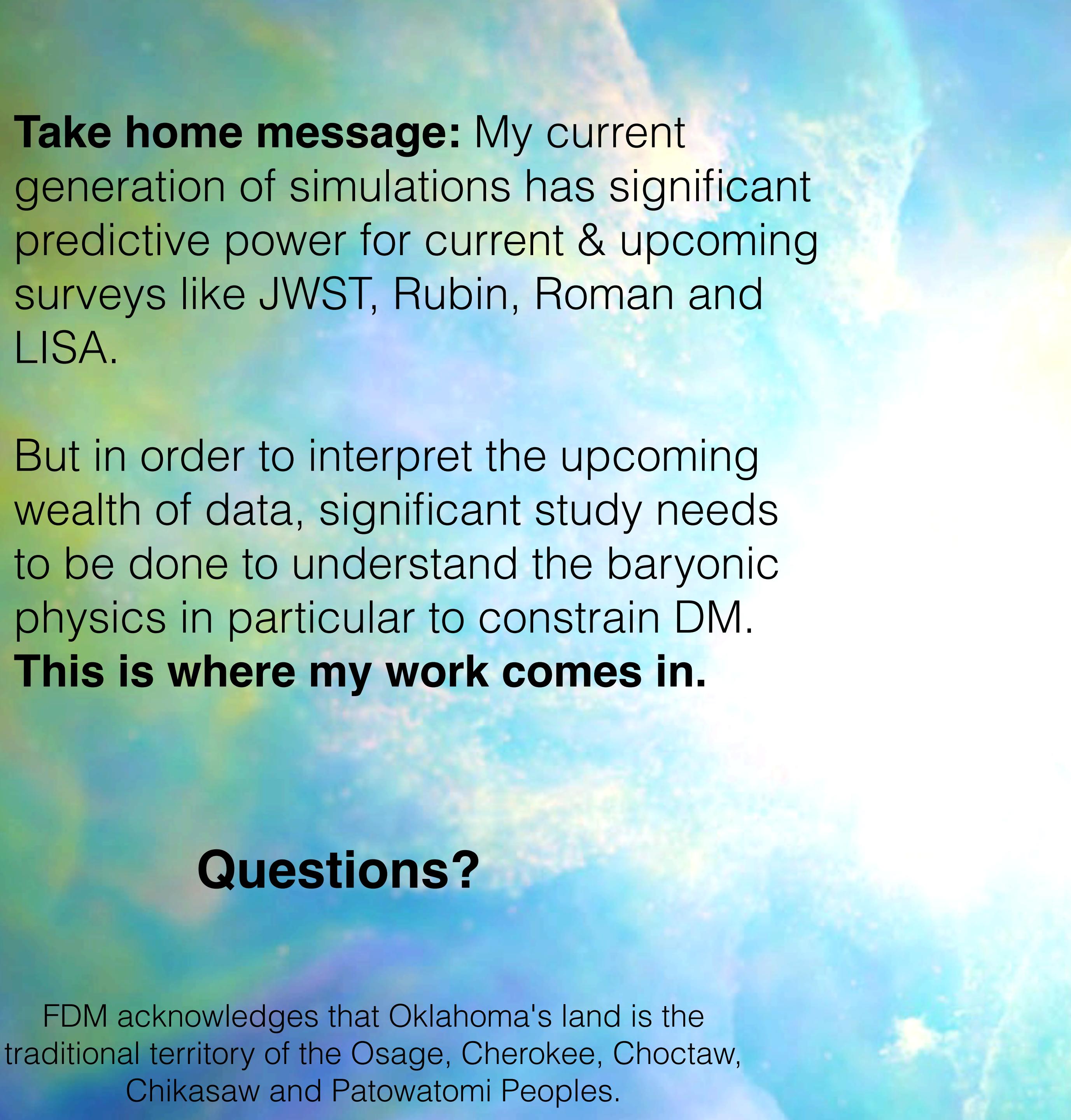
**Machine Learning on Simulation Outputs-**  
*Decision Tree Machine Learning:* Romulus25 studies can leverage machine learning techniques since the sample of galaxies is enormous.

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

e.g. DiCintio+ 2019

*Potential Thesis Project*





**Take home message:** My current generation of simulations has significant predictive power for current & upcoming surveys like JWST, Rubin, Roman and LISA.

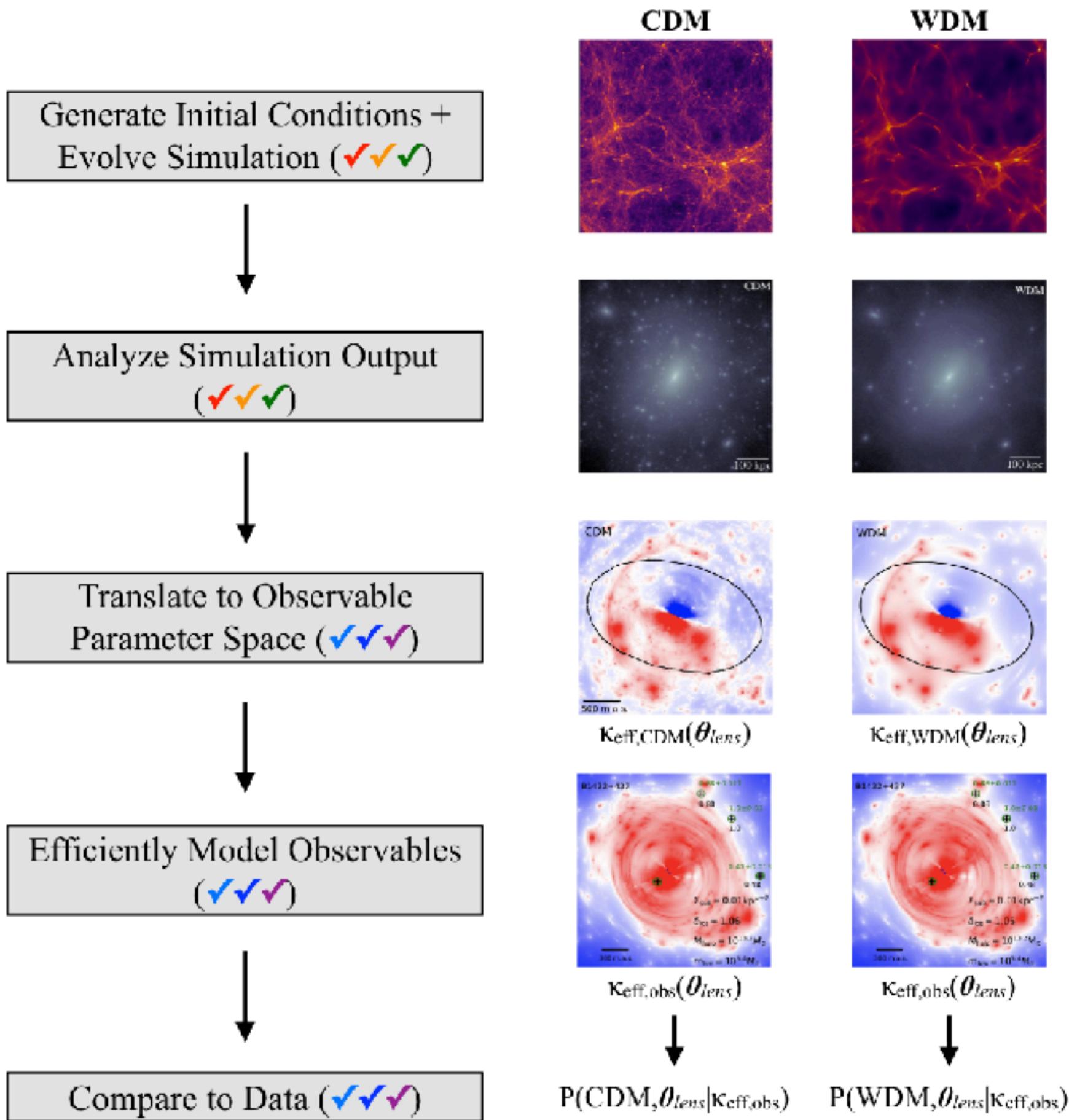
But in order to interpret the upcoming wealth of data, significant study needs to be done to understand the baryonic physics in particular to constrain DM.

**This is where my work comes in.**

## Questions?

FDM acknowledges that Oklahoma's land is the traditional territory of the Osage, Cherokee, Choctaw, Chickasaw and Patowatomi Peoples.

### 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

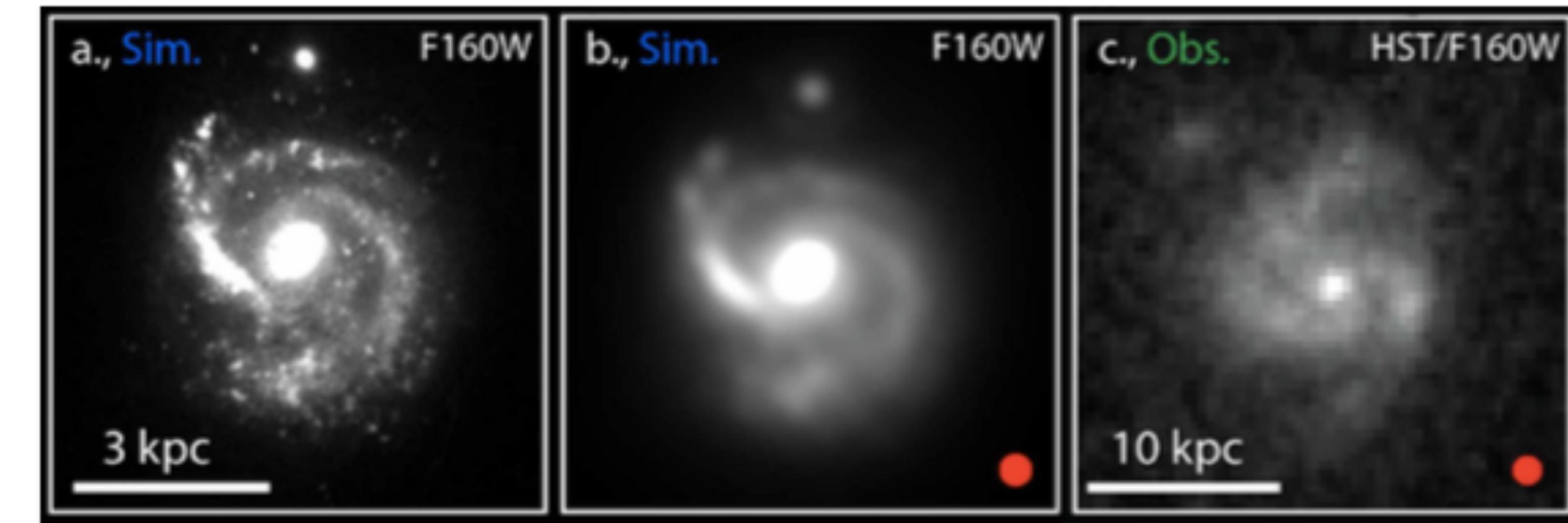
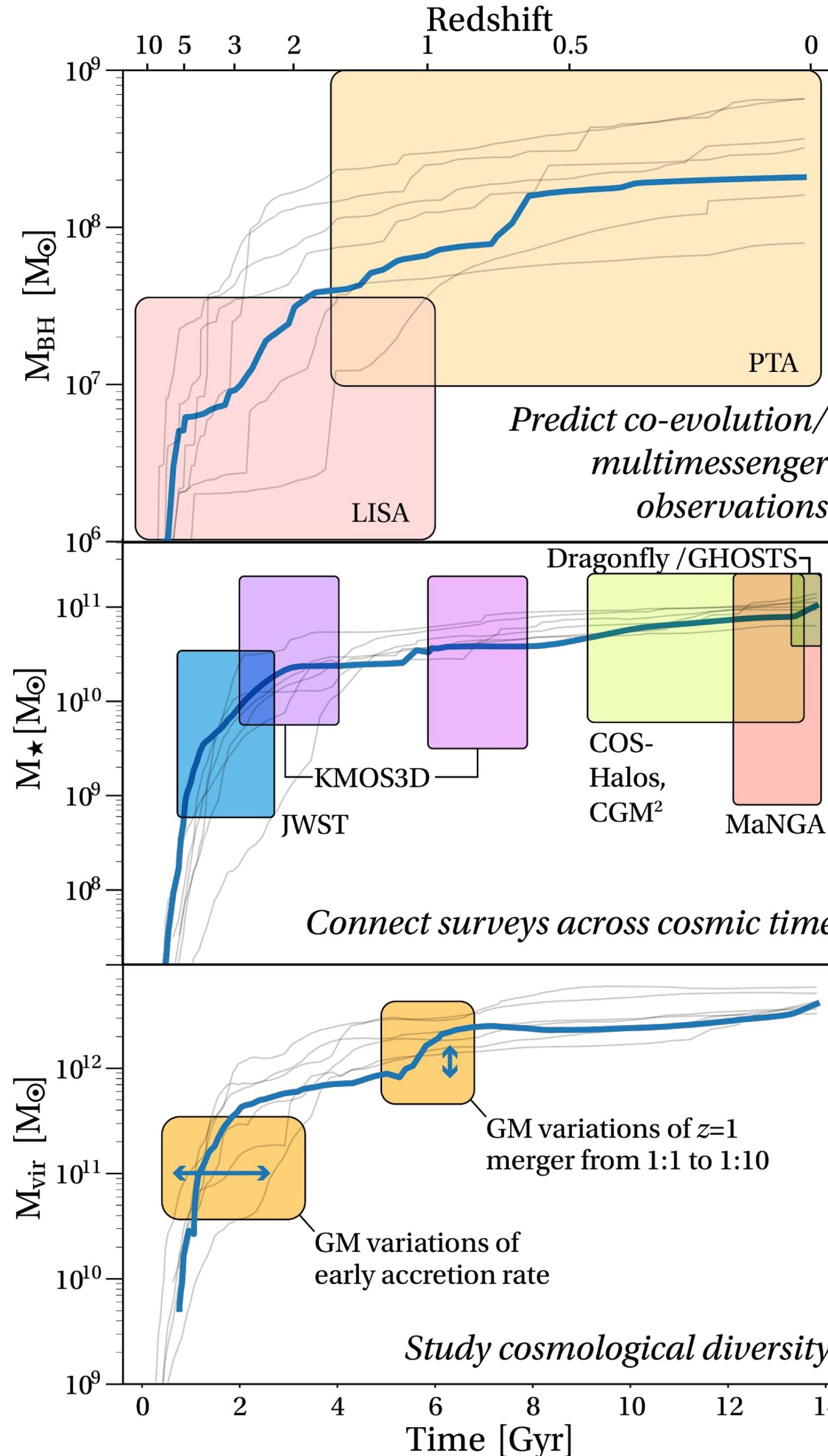
**Need #5:** Fast realizations of observed systems to constrain dark matter

**Need #6:** Provide guidance to observers about dark matter signatures

From the Snowmass draft cosmic frontier numerical simulation white paper (FDM lead)

**Bonus Content  
begins here**

# There are new flagship runs on the horizon...



Large compute project currently in progress to study the formation and evolution of Milky Way mass galaxies (and slightly above) at the **highest resolutions ever yet achieved**. These simulations will yield a **legacy dataset** that will provide a diverse range of astrophysical science to be accomplished for years to come.

**In the context of DM:** a larger sample of UFDs, wandering BHs in dwarfs \*\*in the environment of a MW\*\* —> more robust constraints for Rubin, Roman, JWST

# Key Research Questions:

- Can we leverage upcoming observations (Rubin, Roman, JWST) to constrain dark matter? Is there a particular observation (or set of observations) that will discriminate between dark matter models?
- Can we disentangle the role of **baryons vs. the DM** in observations?
- Can we continue to use **baryons + CDM** to explain the low surface brightness universe?
- Detailed observations are happening in our neighborhood. But is our neighborhood “normal”? Is our MW (+ satellites) typical?

“**baryons**” = gas, dust, stars etc [the stuff we can see]

# Where we are at, where we are going with MARVEL + DCJL

4 dwarf volumes galaxies  
in CDM (LMC and smaller)

4 MW mass + satellites in  
CDM

~20 bright dwarfs in CDM

CDM constraints on baryonic  
processes in dwarf galaxies

Lensing signatures in CDM

4-5 more MW mass galaxies

2 dwarf volumes in SIDM

~20 matching bright dwarfs in  
SIDM

SIDM + baryons- what can we  
learn about shapes, BH offsets,  
rotation curves?

Lensing signatures in SIDM

5 years- short term

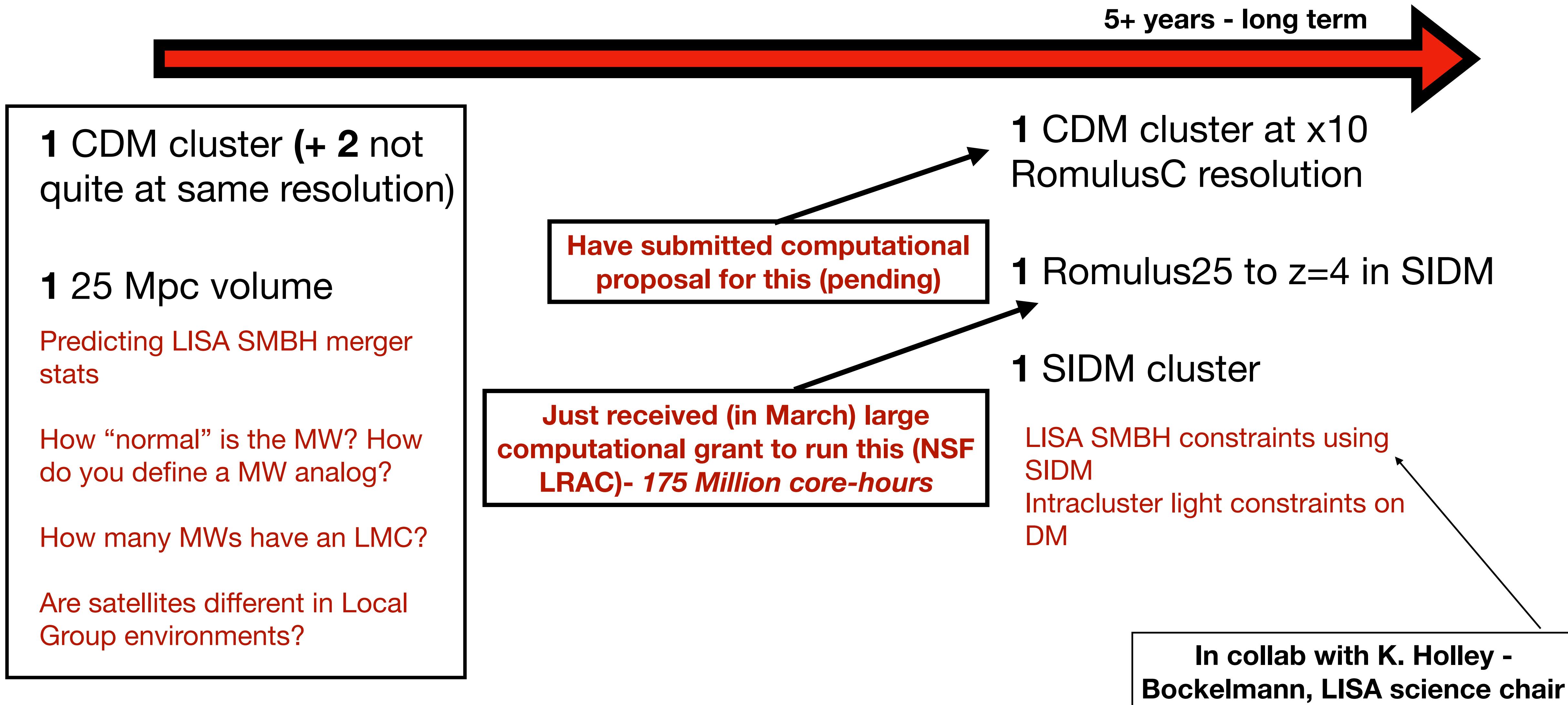
Have current computational grant to run  
these MWs (NSF LRAC)- *currently  
running*

Large computational grant to run these  
dwarfs (NSF LRAC)- *175 Million core-  
hours*

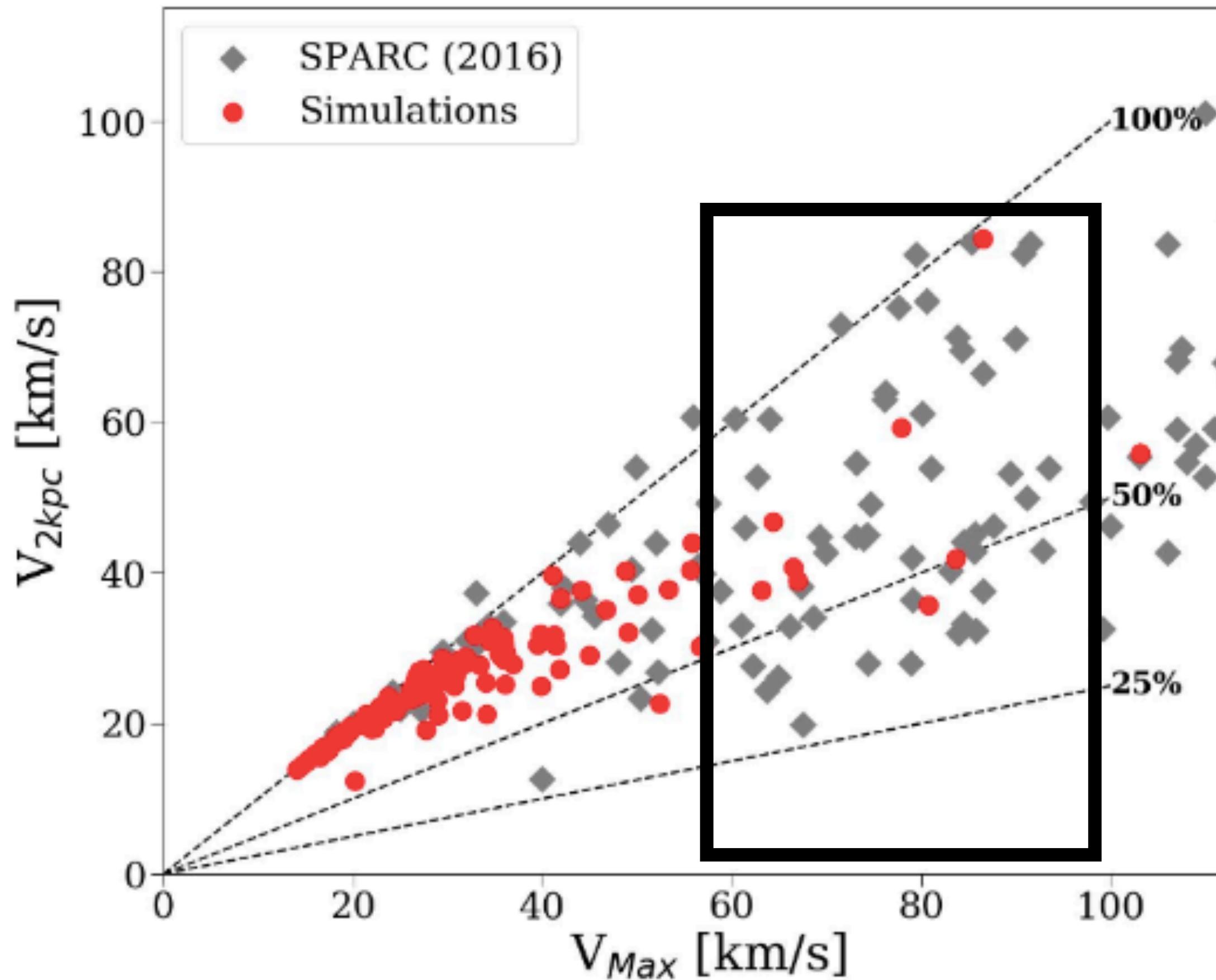
2 MW mass galaxies in SIDM  
(+satellites)

Tidal stripping, gravothermal  
collapse, orbits and central  
densities of satellites

# Where we are at, where we are going with Romulus Suite



# SIDM Dwarfs: smoking gun in rotation curves?



New velocity dependence based on latest literature

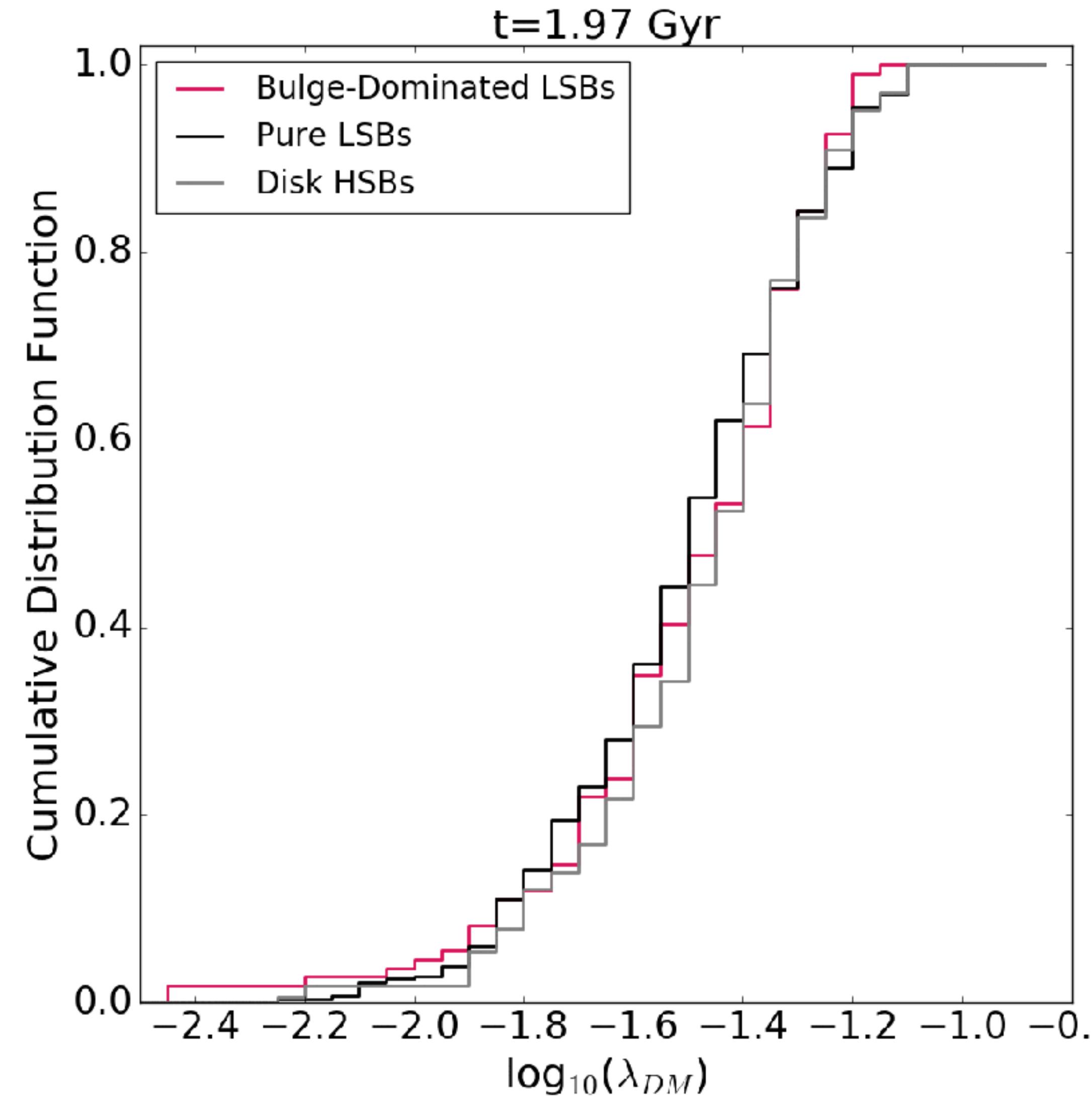
New CDM/SIDM dwarfs fill in parameter space

In collaboration with Annika Peter (OSU), Alexi Leauthaud (UCSC), Jenny Greene (Princeton), Merian Survey

Just received (in March) large computational grant to run these dwarfs (NSF LRAC)- 175 Million core-hours

Funded NSF proposal to study SIDM in zooms

# The low surface brightness universe from Romulus



- This is not true when they form!
- What causes this?



# LSB zoom-in simulations

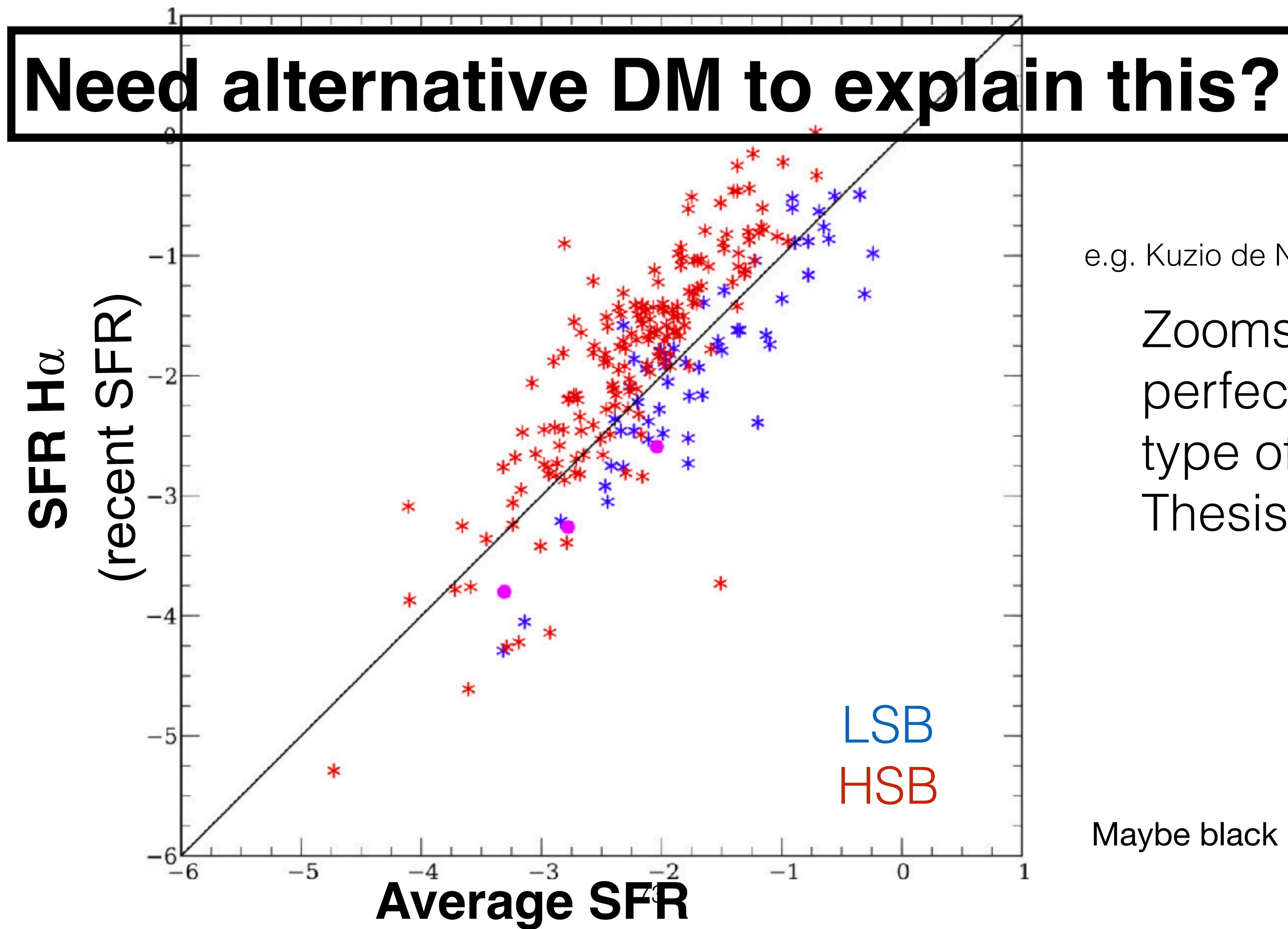
- Massive LSBs have cored profiles, but do not have bursty SFHs
- Romulus cannot resolve core-formation ==> need zooms!



In collaboration with A.  
Wright (JHU/STScI)

e.g. Malin 1

# LSB zoom-in simulations

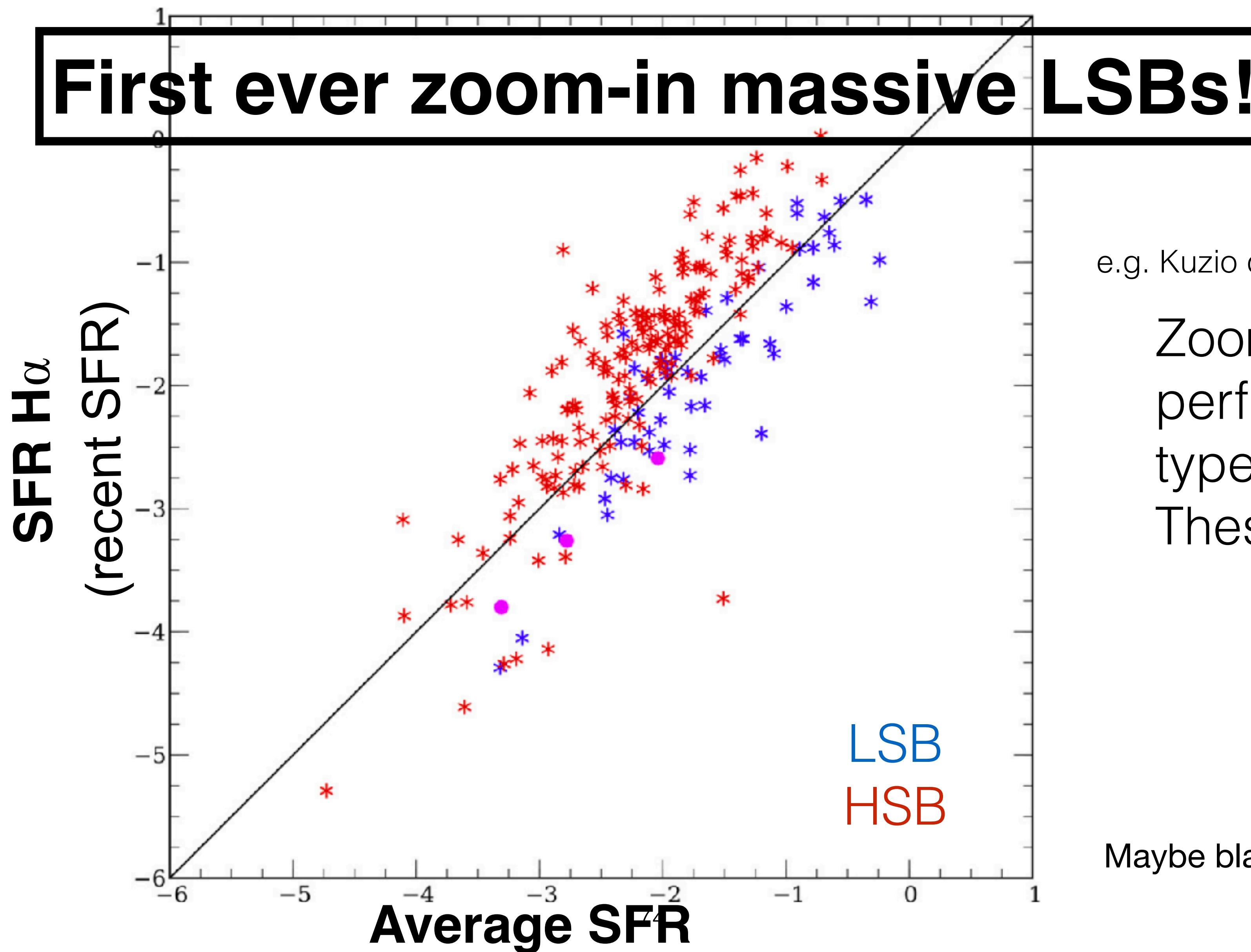


e.g. Kuzio de Naray + (2010)

Zooms are perfect for this type of study!  
Thesis project!

Maybe black holes?

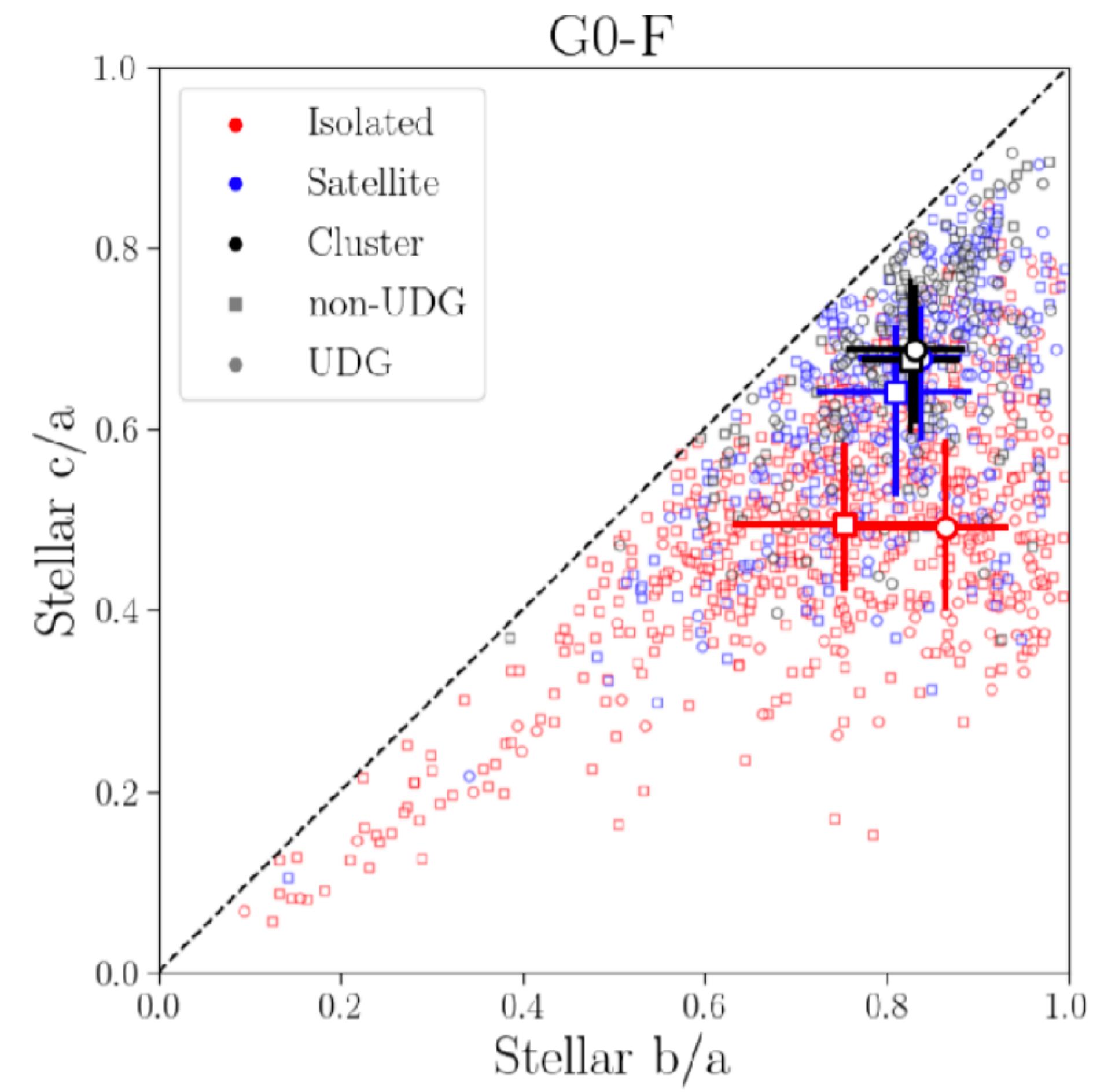
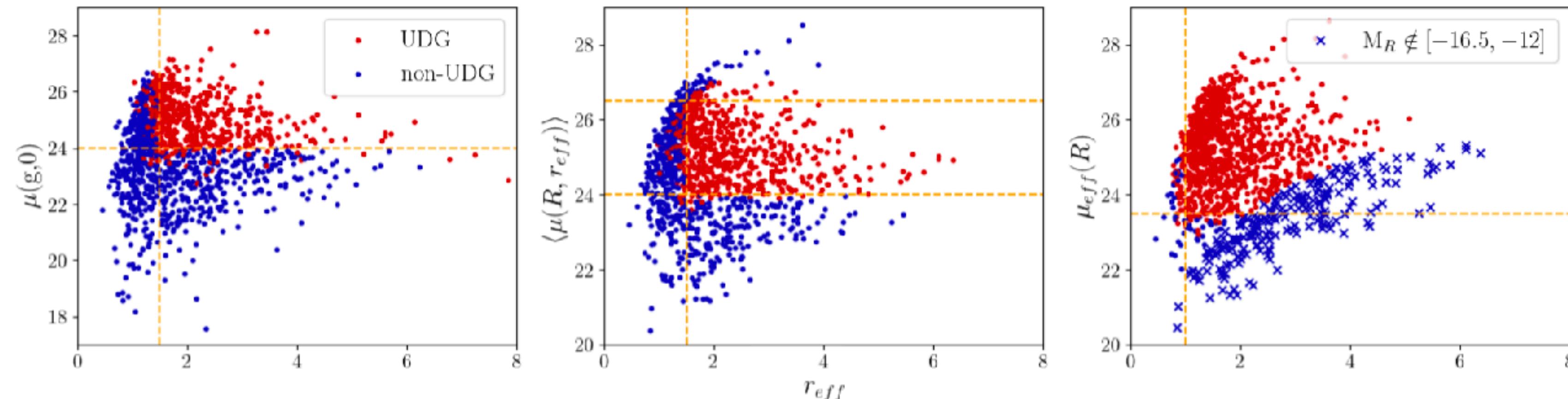
# LSB zoom-in simulations



# The Low Surface Brightness Universe: UDGs

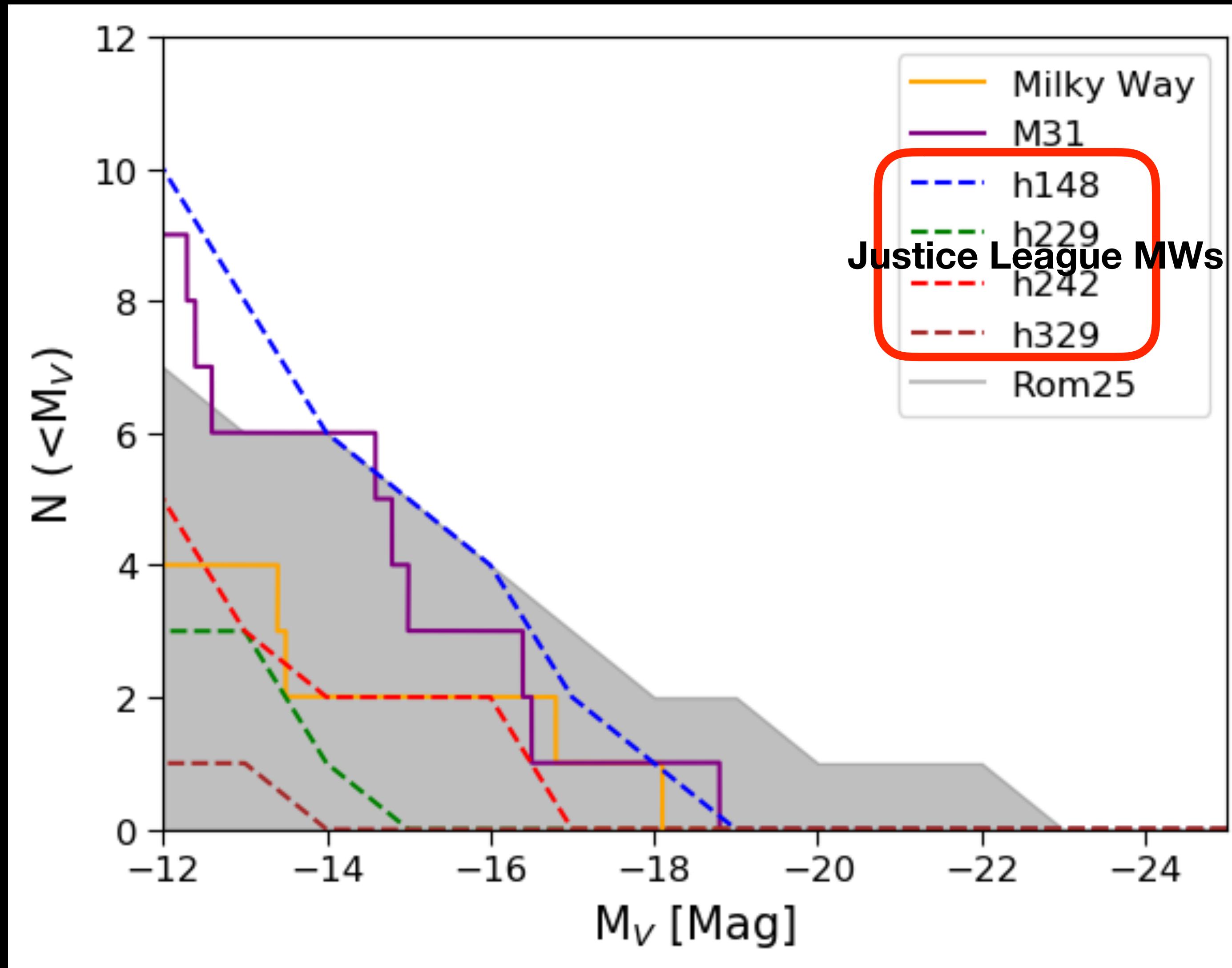
**How do they form? Are they really a distinct population? What do their DM halos look like?**

**Observational comparison with Kado-Fong (Princeton), Greene (Princeton)- paper submitted, Munshi, Van Nest coauthors**

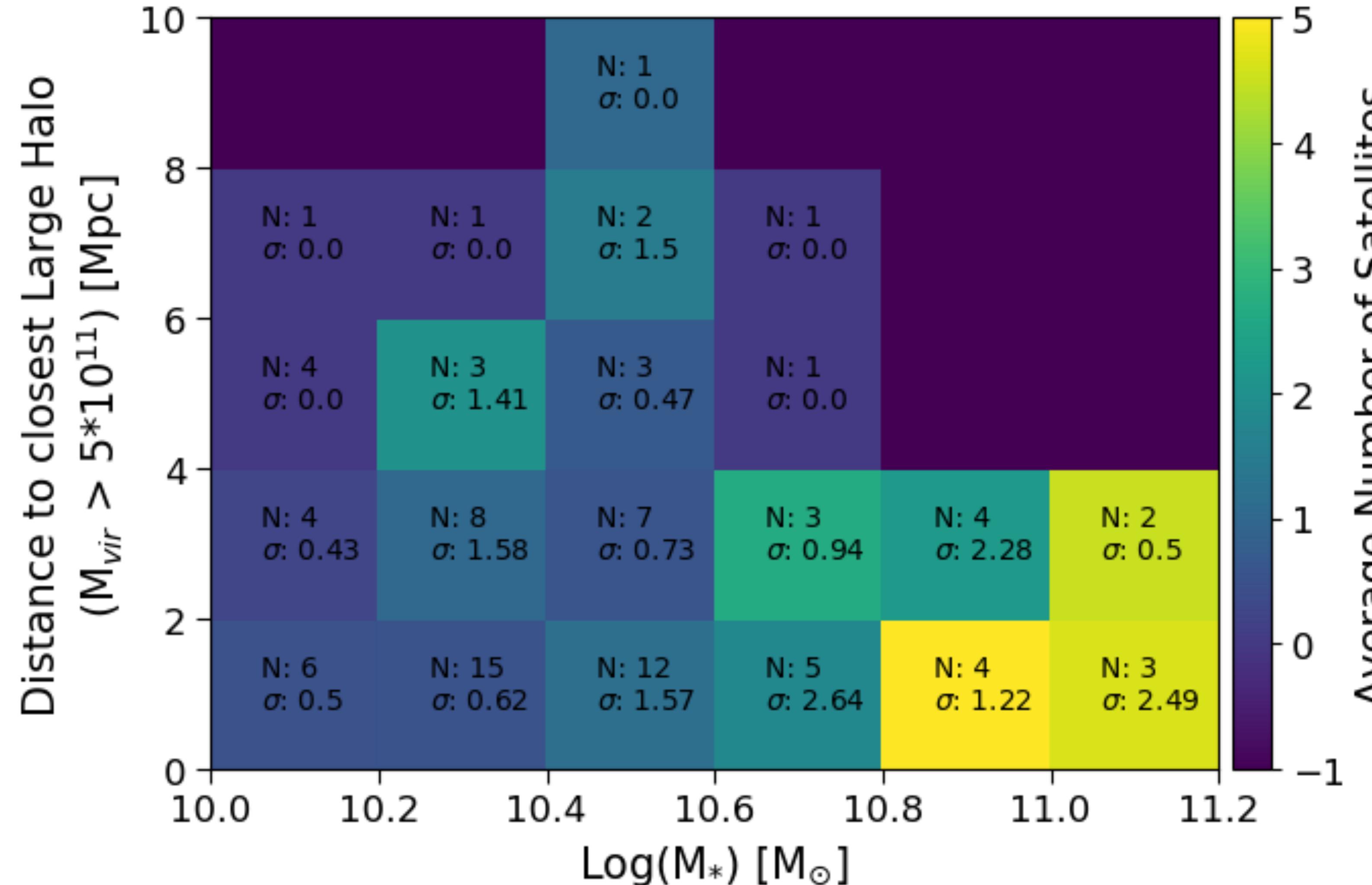


My current graduate student Jordan Van Nest has had his first paper accepted on this work.

# 120 Milky-Way analogs with satellites resolved down to $M_{\text{star}} = 10^7 M_{\odot}$ (includes MW/M31-like systems)



# Romulus25 Milky-Way analogs with satellites resolved down to $M_{\text{star}} = 10^7 M_{\odot}$



Theoretical complement to  
the SAGA survey;

Working with Geha, Mao,  
Weschler (SAGA leadership)

**More massive halos, in a more dense environment, tend to have more satellites.**

# Interested in modifying/contributing to the code? [e.g. potential thesis coding projects]

Different dark matter models to be implemented

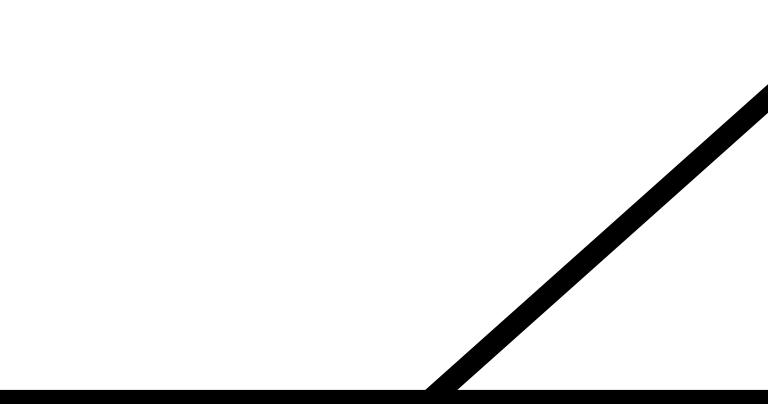
Different star formation/feedback methods

MHD version of the code (MaNGa) is being developed- can contribute

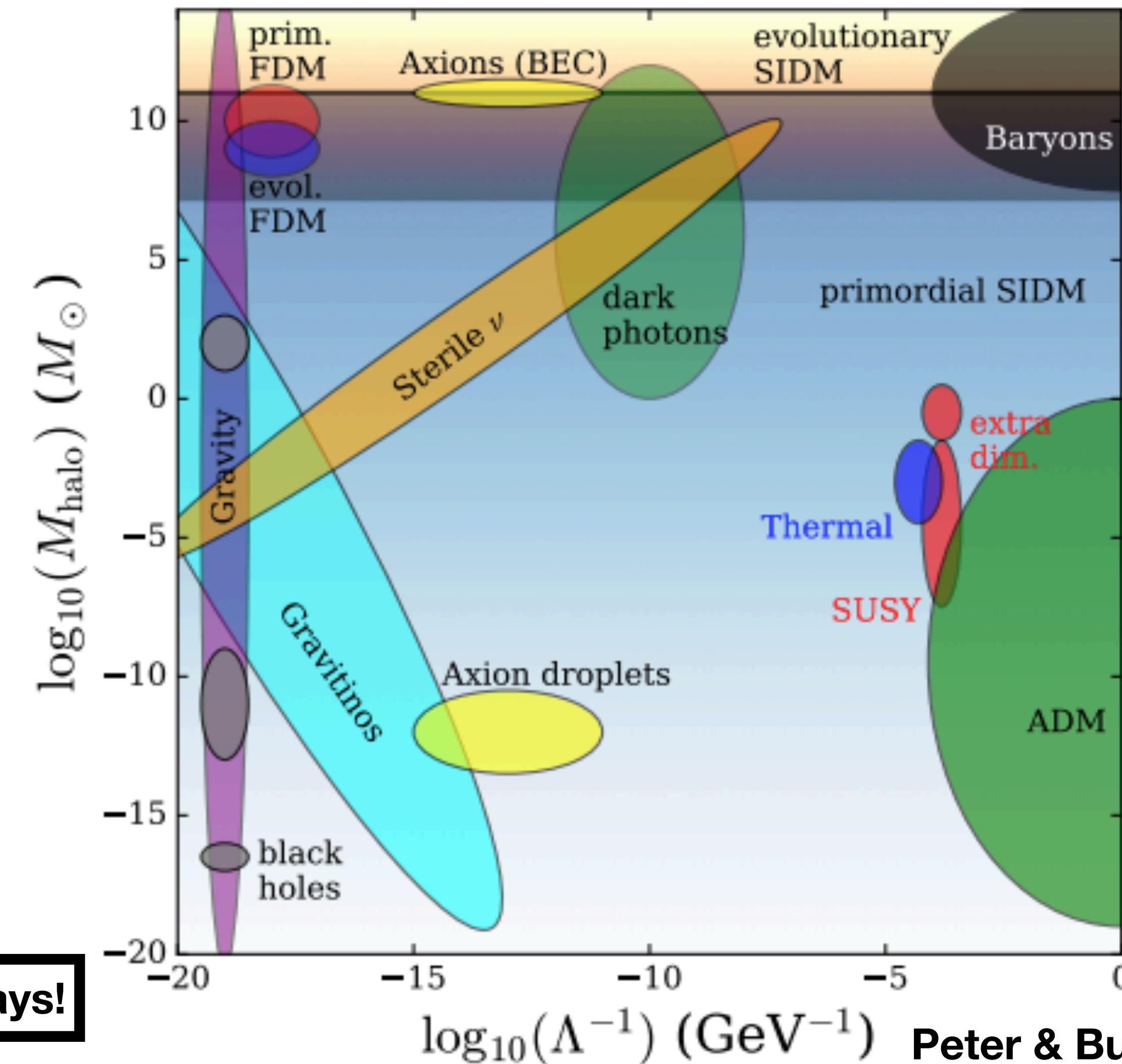
Radiative transfer being developed- can contribute

# Other DM implementations

- In progress: SIDM with energy dissipation (composite strongly interacting dark matter, massless dark carriers, interactions mediated by light gauge bosons)
- Thesis project: implement DM self-annihilation at high z



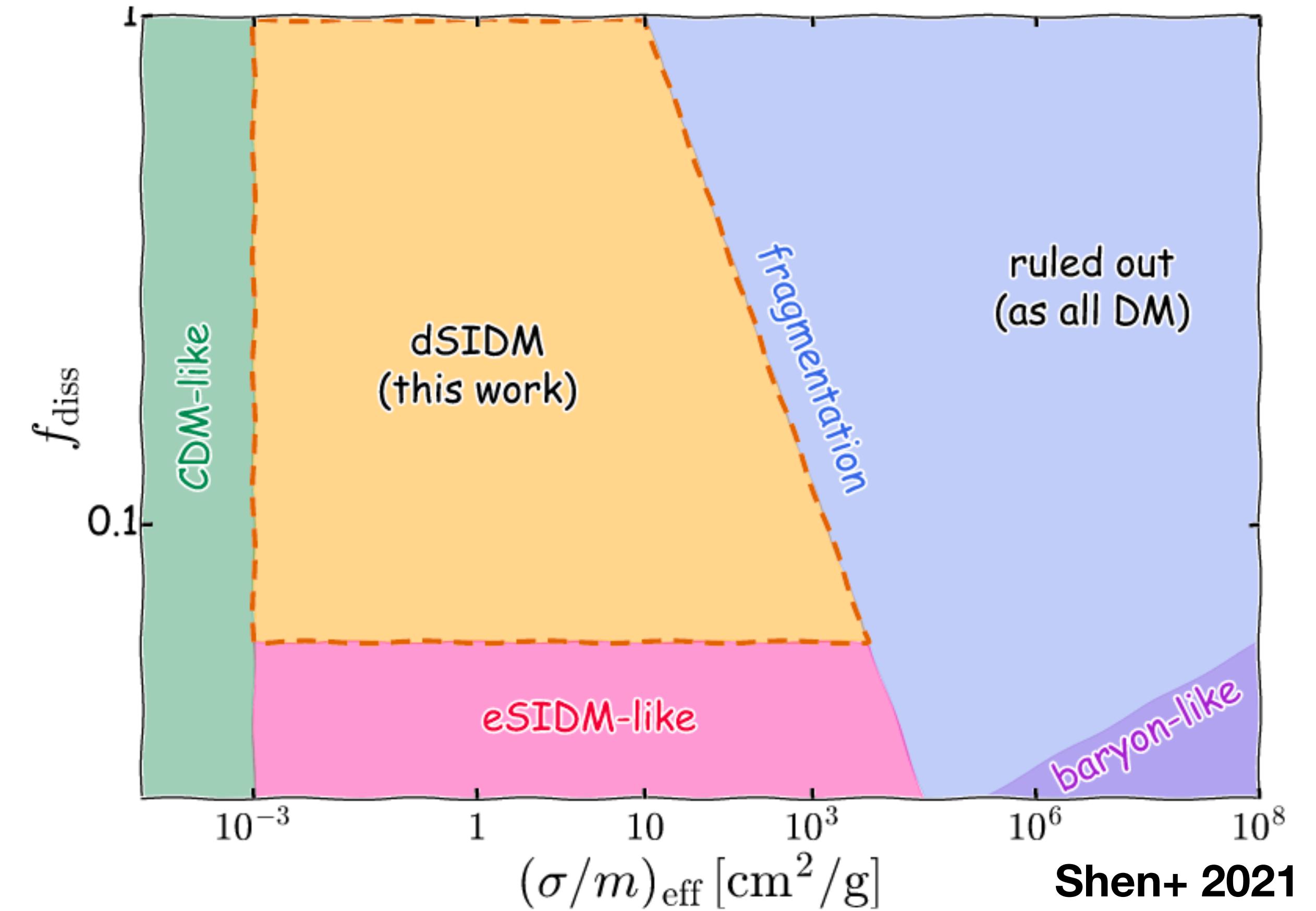
Complementary to dept and research in gamma rays!



Peter & Buckley 2019

# Other DM implementations

- In progress: SIDM with energy dissipation (composite strongly interacting dark matter, massless dark carriers, interactions mediated by light gauge bosons)
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# Big Idea: Create the “collaboratory”

collaborative center for computing, databases and data visualization

## Databases and database creation

Large storage space for databases (primary and backup storage)

## High performance computing

Both CPUs and GPUs, queue management system (e.g. SLURM, PBS)

Build partnerships- Microsoft, Nvidia, Intel

## Massive data visualization

State of the art virtual environment: ability to immersively interact with data, meeting/teaching and visualization spaces

**The collaboratory could be a multi-department, multi-discipline endeavor.**

# 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.

**Work towards making GMU Phy/Astro an APS bridge site:** Recruit more graduate students; graduate students with more diverse backgrounds (this is a long term goal)

**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. Potentially a summer program with other DTI departments to host high school students.

**Funding sources for large-scale initiatives: NSF S-STEM funding, Sloan Foundation bridge funding, will use potential CAREER funding**

# (recent) Professional Leadership

- Facilitator for Snowmass 2021 cosmic frontier simulations white paper
- Virtual organizing committee for NBSE21 virtual conference January 2021
- LOC & speaker for CuWiP 2020 at the University of Oklahoma
- LOC for PPC 2021
- Leadership for developing the N-body Shop Code of Conduct
- Working toward KITP workshop on dark matter
- Women in Physics faculty mentor
- Part of committee (4 faculty) working with the dean of the graduate college at OU to create inclusive admissions trainings and guidance materials.
- OU sub-committee working on APS bridge program application

# Funding sources:

Sloan fellowship eligible

NSF AAG, PHY, Wou-MMA

NASA ATP

HST/JWST theory

NSF CAREER (2 attempts remain)

DOE Early Career?

Packard Fellowship

**Microsoft Research Faculty Fellowship**

I've attempted ATP 2x as PI

AAG 3x as PI

PHY 1x as PI (successful- \$360,000)

HST 4x as PI

NSF CAREER 1x

Review panels: HST x3, AAG x2, ATP x2, ADAPx1

Within my close collaboration- 1 CAREER, 1 Sloan Fellowship- science is demonstrably fundable

I have a consistent, demonstrated record of applying for grants, success in attaining funding, and insight into future success through proposal review

# Path to NSF CAREER

Innovative Research Plan

+

Education Plan

+

Alignment with Dept mission

“Comprehensive constraints on DM at the edge of galaxy formation”

CHaNGa is the only code that scales well enough to simulate UFDs across environment- develop largest and most comprehensive suite of simulations using GM & multiple DM implementations (SIDM, eSIDM, SADM). Make predictions about how we can constrain DM with upcoming missions (e.g. Rubin, Roman)

Dept/University engagement

1. Develop planetarium shows, VR lessons that address various state K-12 education goals
2. Connect VR initiative to other STEM/DTI departments
3. Connect VR initiative with digital humanities: “science as art”

Community engagement

Astronomy & galaxy formation education in K-12:  
VR galaxy formation, Mobile Planetaria

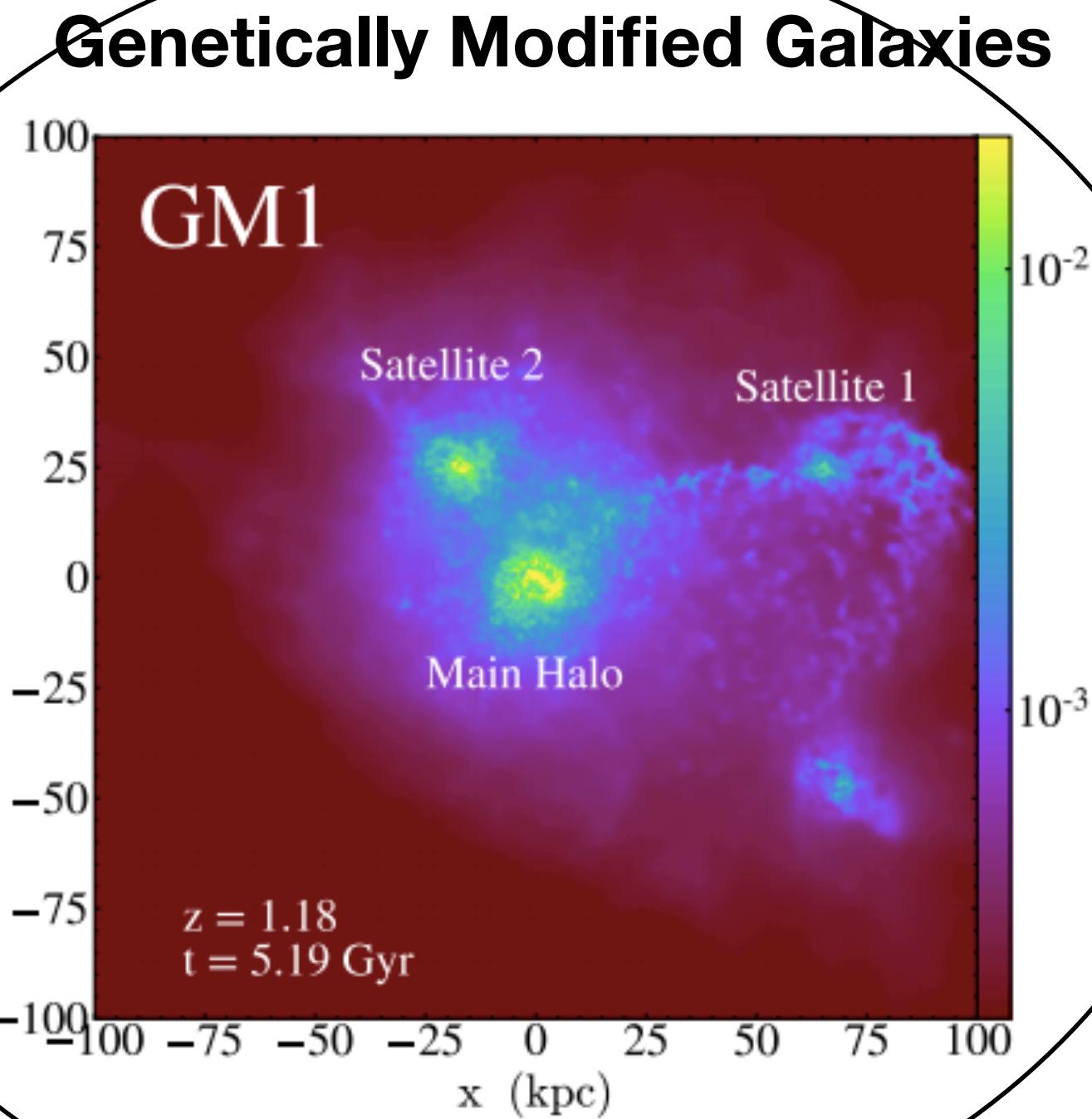
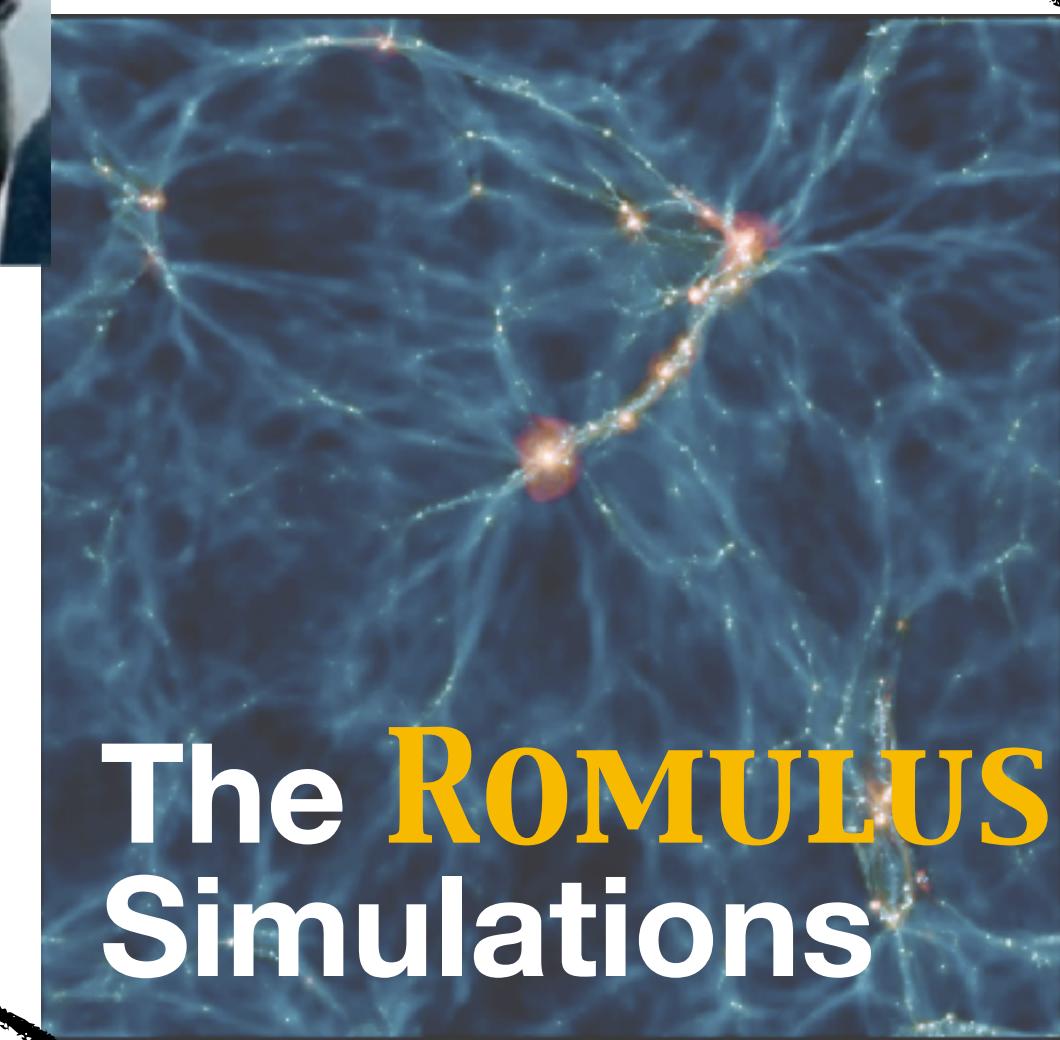
1. Enhance Dept's inclusion and equity goals
2. Broaden department's visibility both within the university and community
3. Grow diversity of both the graduate and undergraduate students in the Dept



**Dwarfs in isolation**

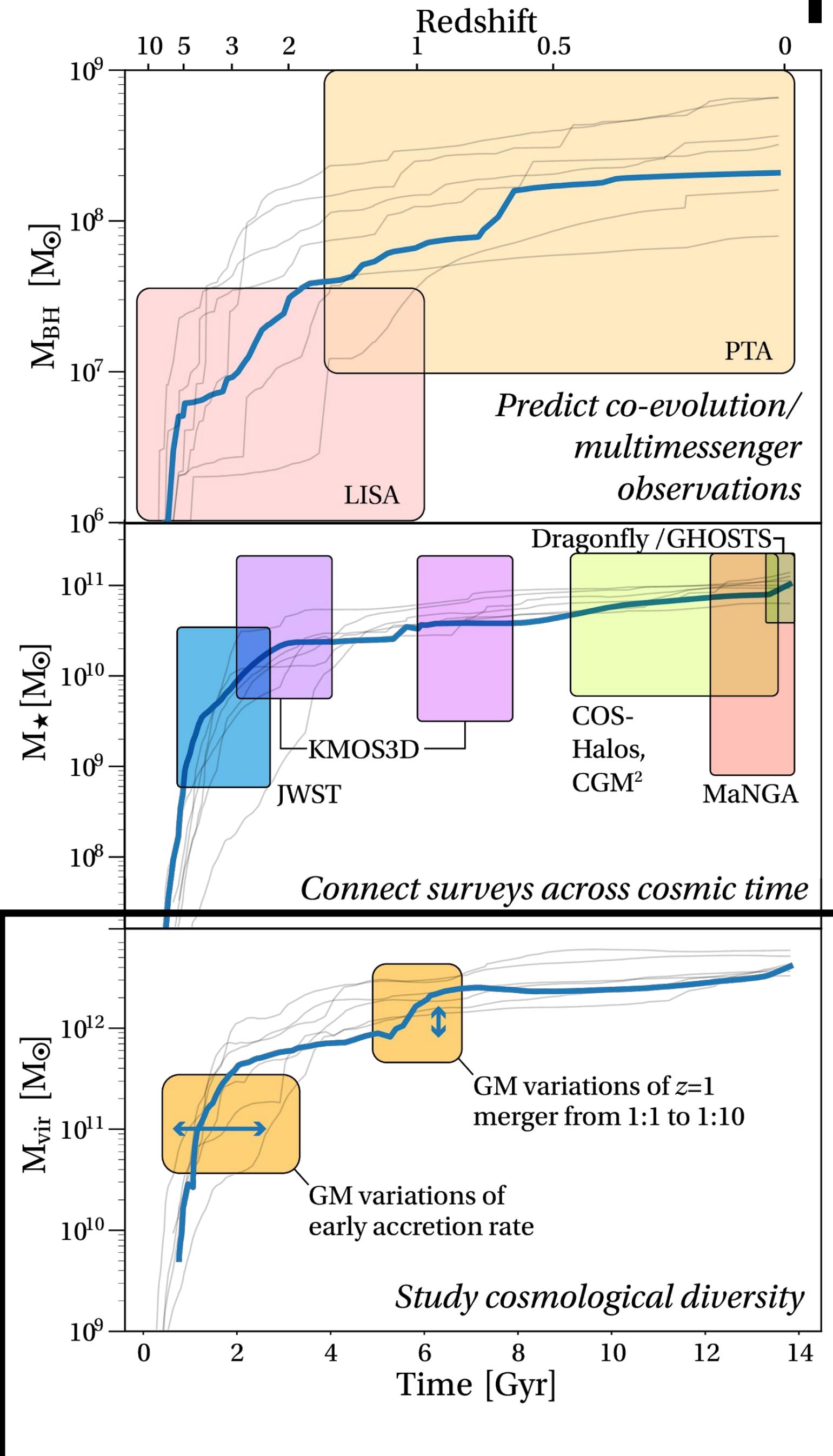


**Dwarfs (and UDGs) across environments**



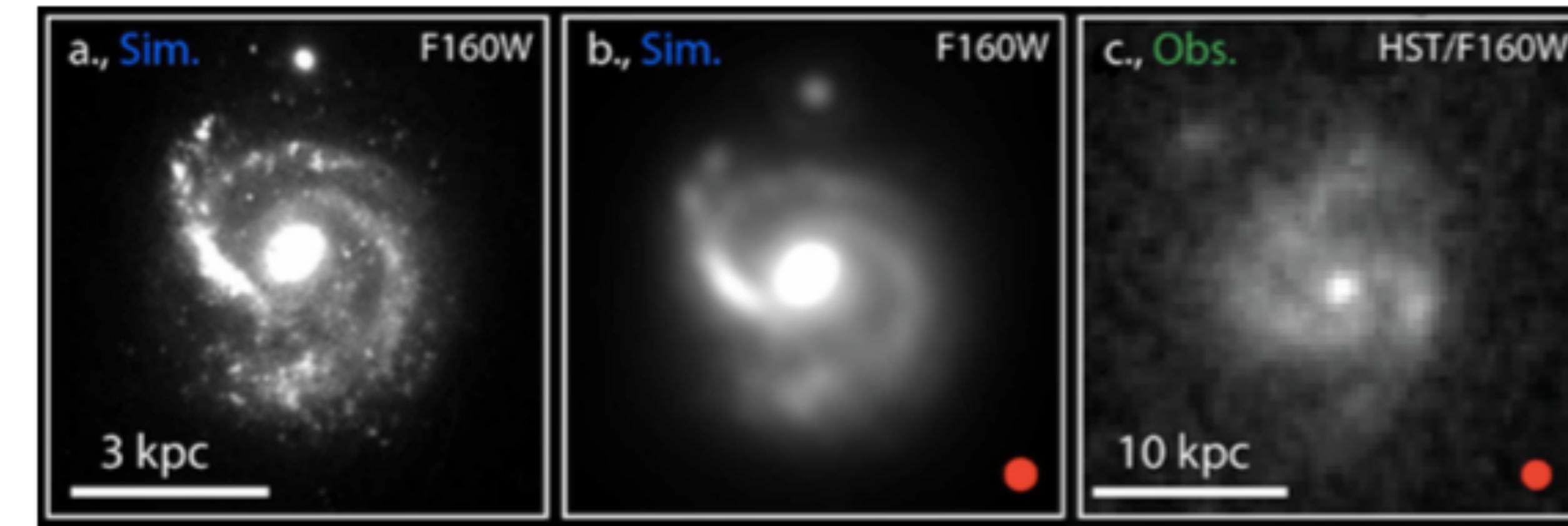
**Current Data Sets**

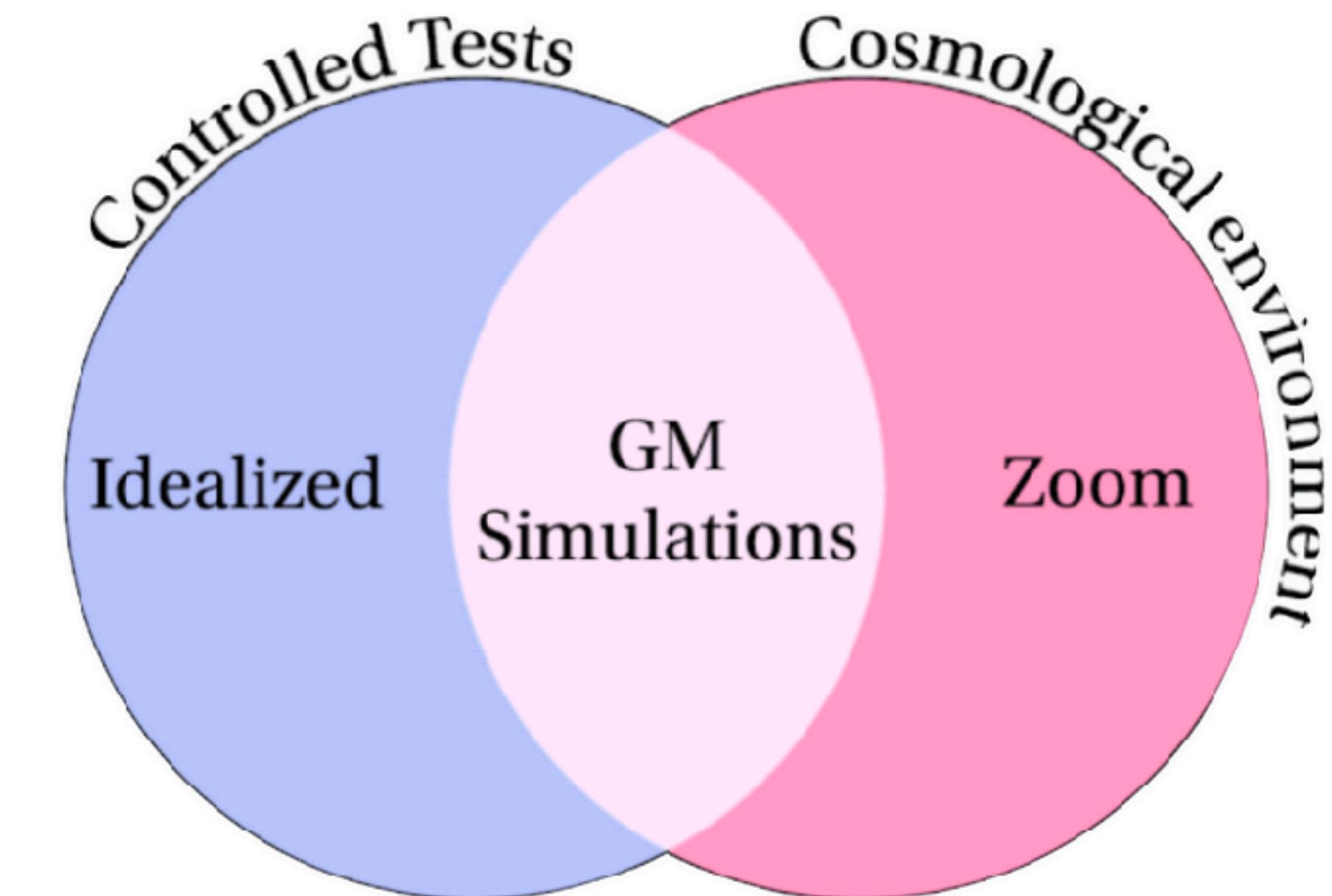
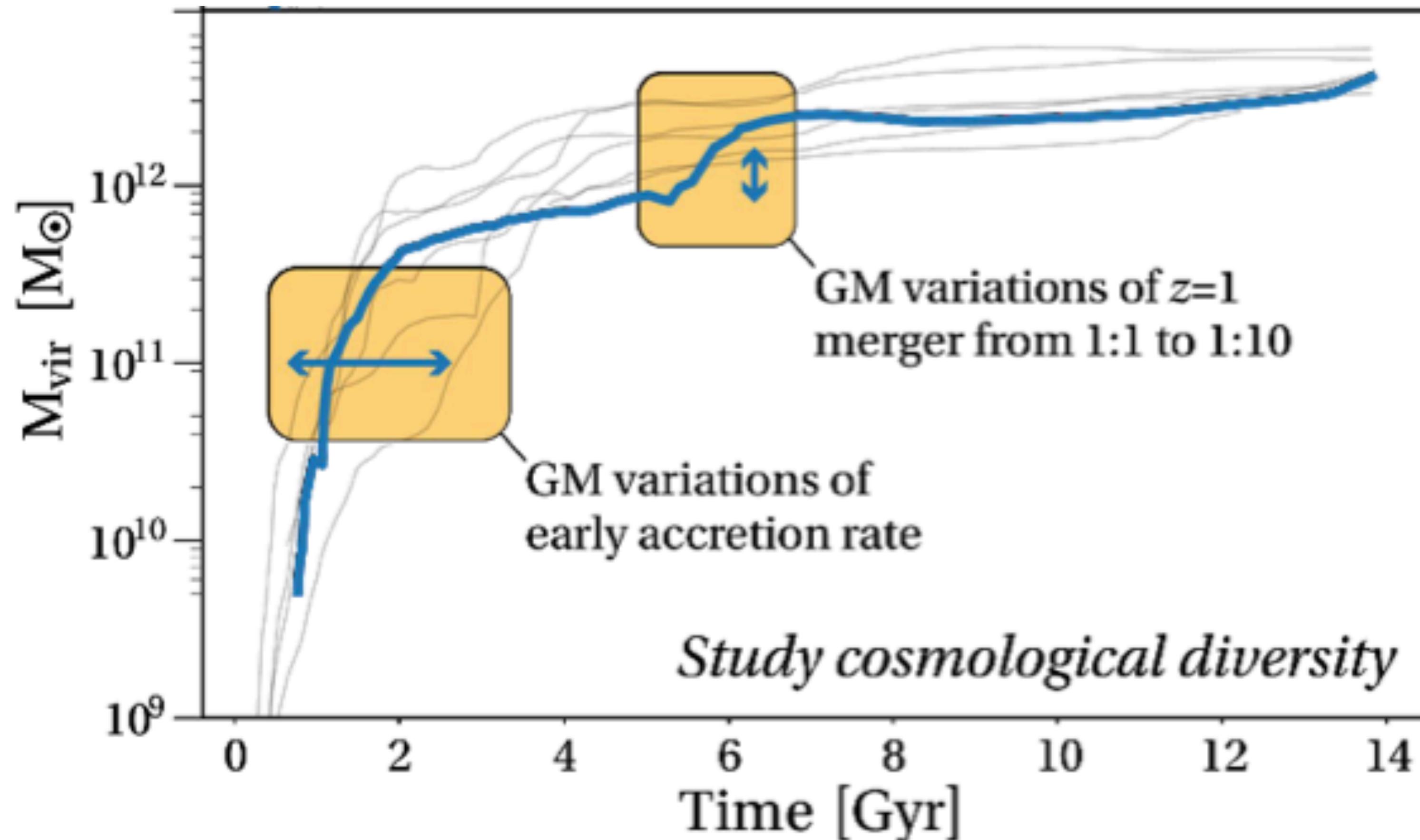
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**In the context of DM:** a larger sample of UFDs, wandering BHs in dwarfs \*\*in the environment of a MW\*\* —> more robust constraints for Rubin, Roman, JWST





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

