



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



@theNbodyShop
nbody.shop

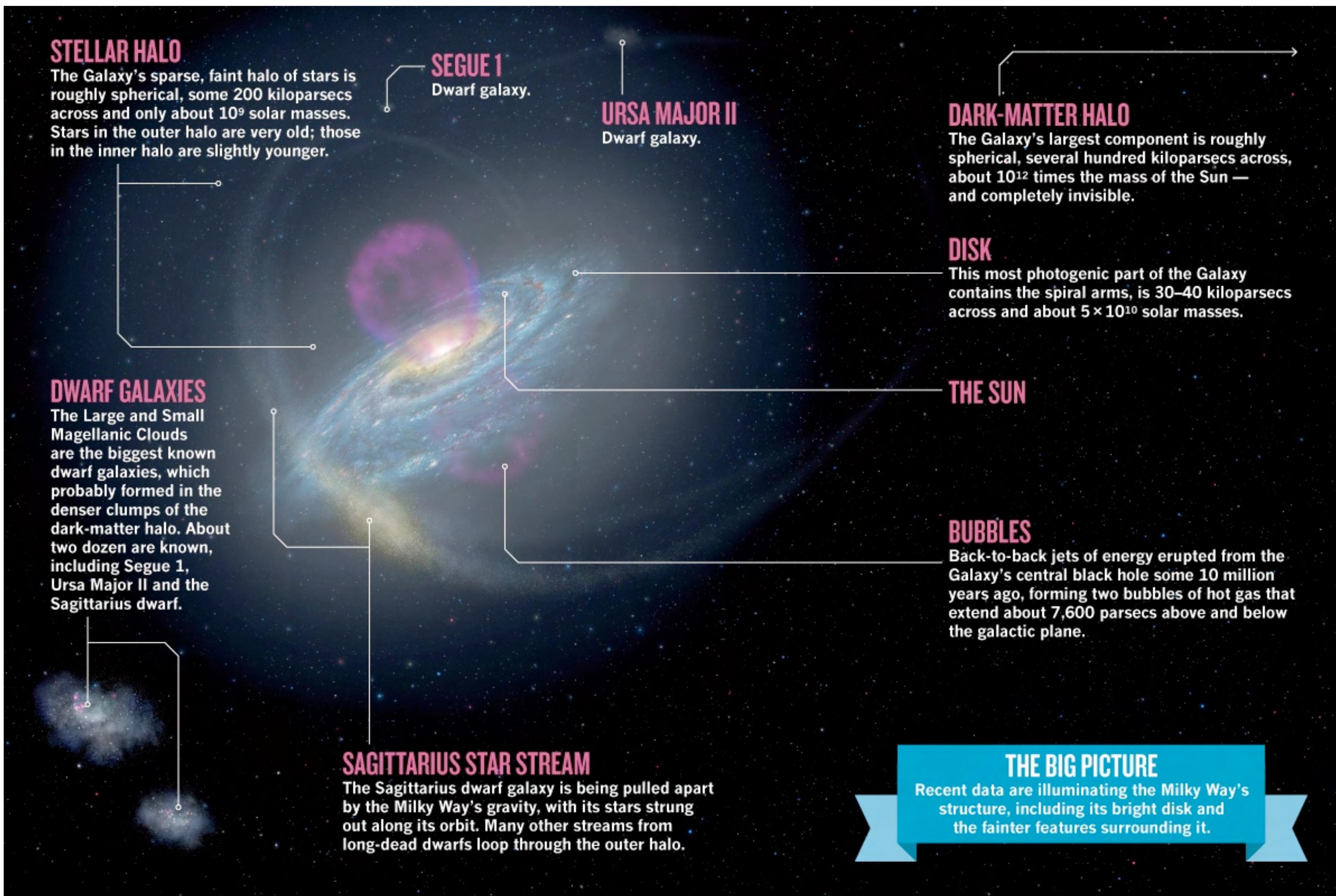
Ferah Munshi

Assistant Professor, University of Oklahoma

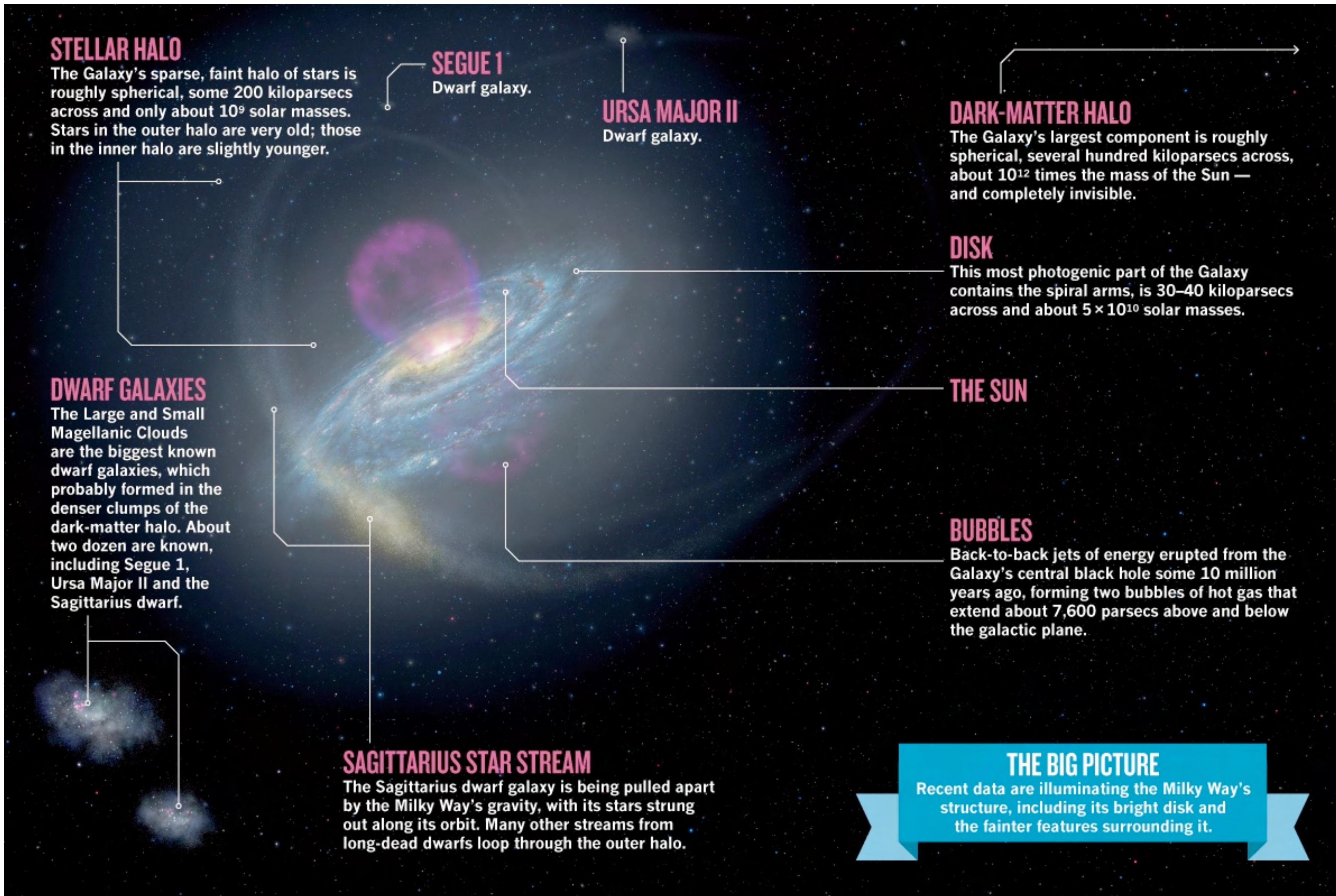
In collaboration with: Alyson Brooks (Rutgers), Jillian Bellovary (QCC/AMNH), Kelly Holley-Bockelmann (Vanderbilt), Charlotte Christensen (Grinnell), Michael Tremmel (Yale)+ UW N-body Shop

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)

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



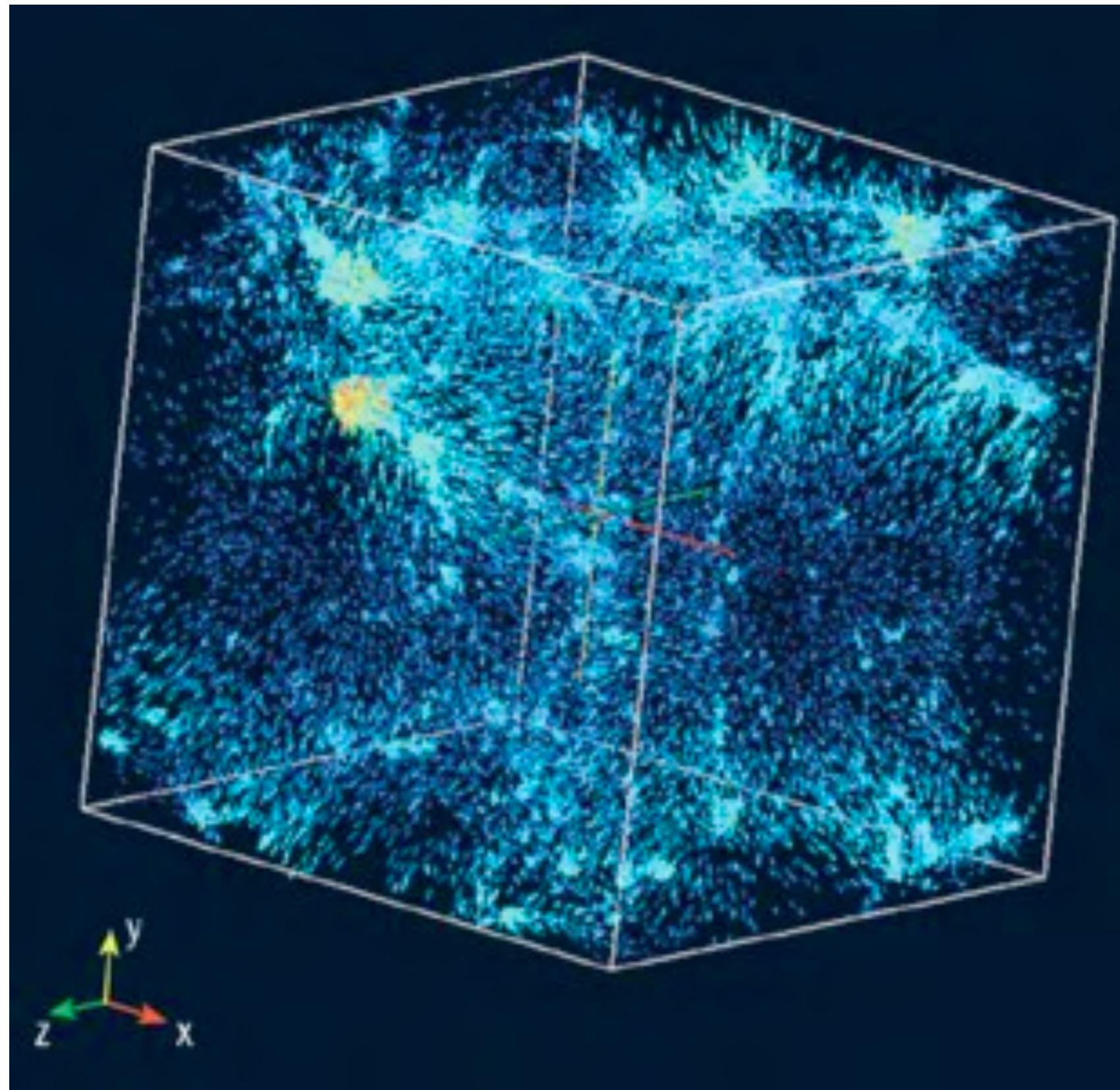
Dwarf galaxies are galaxies smaller than the Milky Way



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.

What is a (N-body) Simulation?

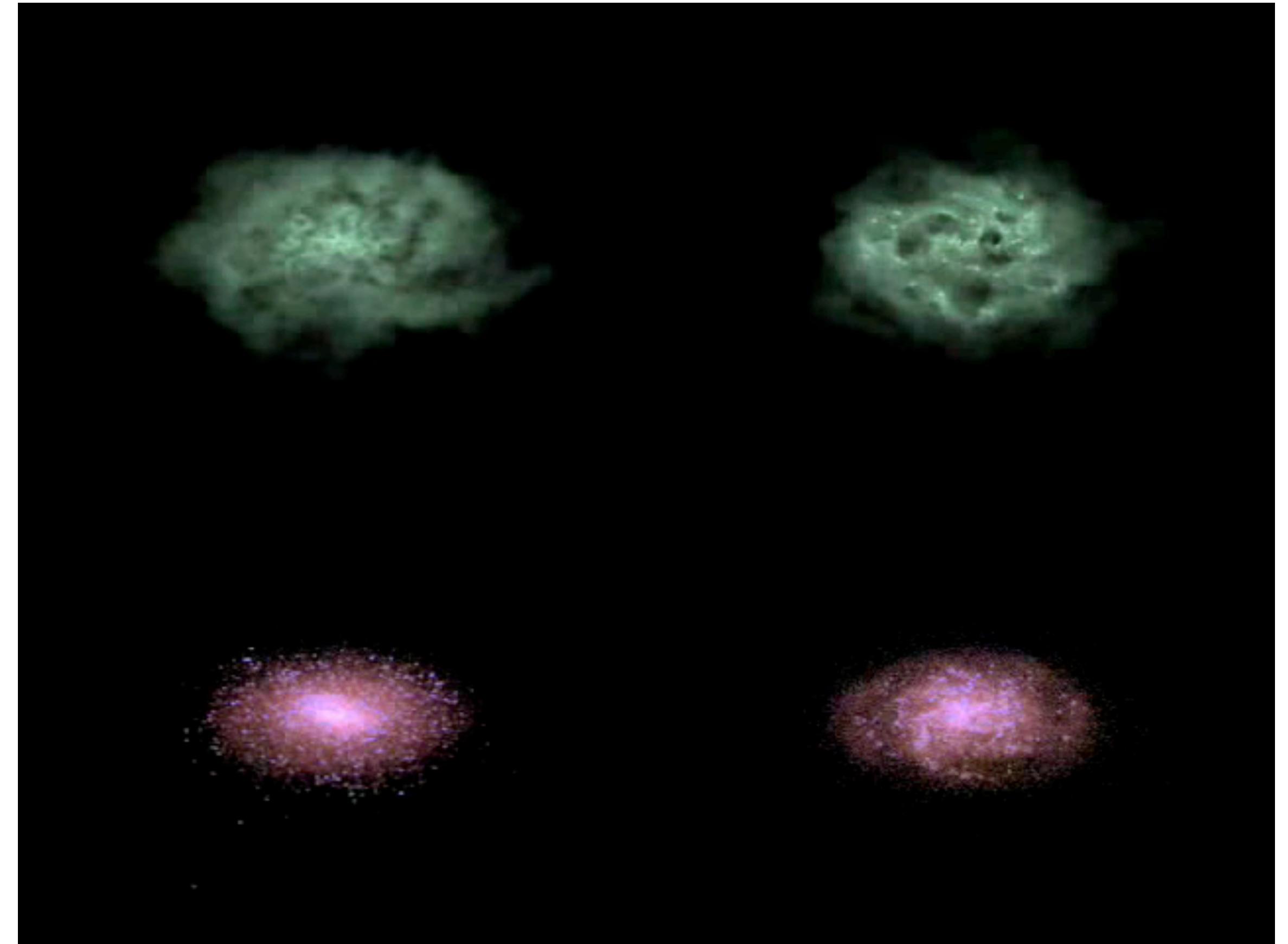


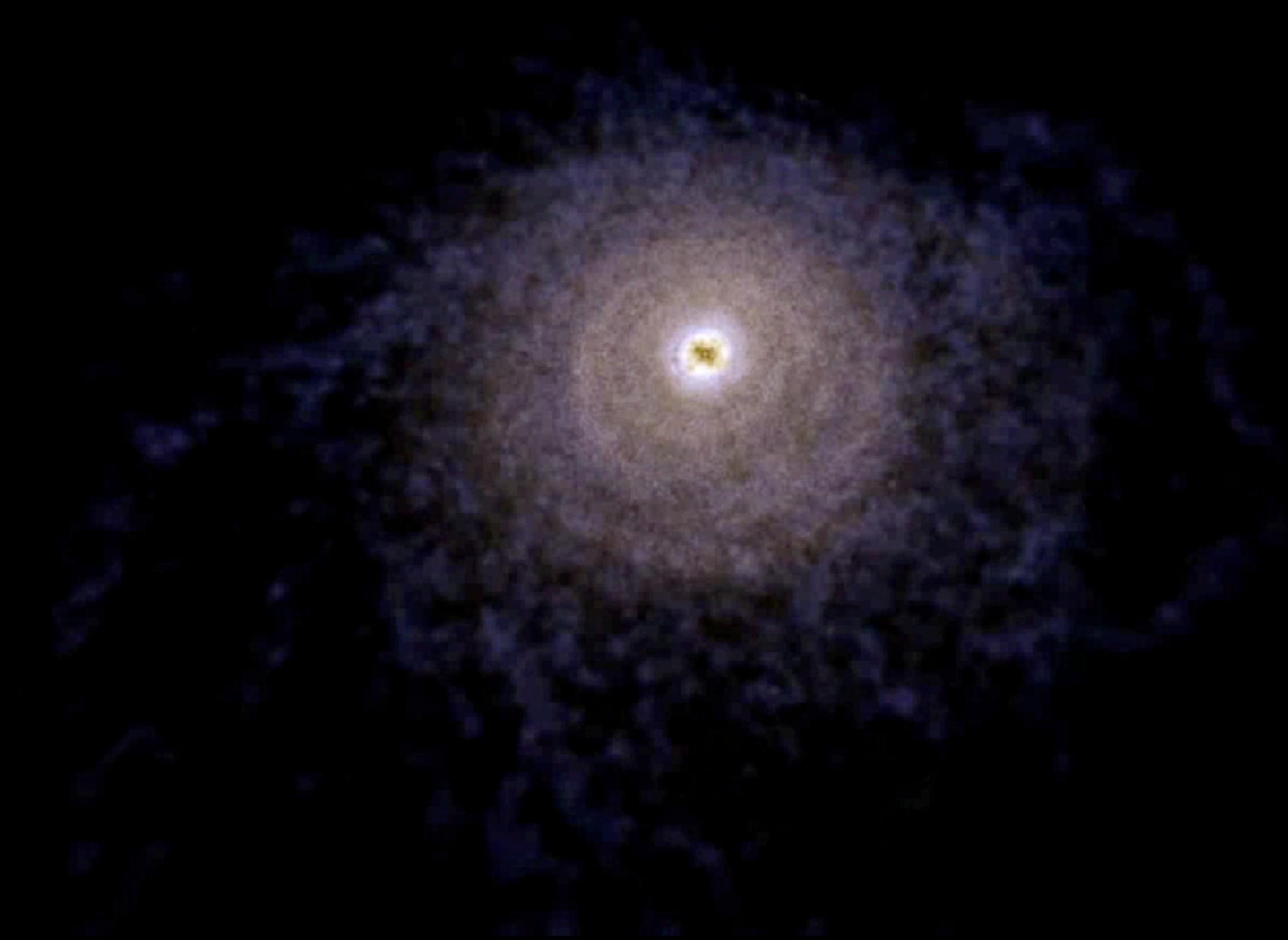
Modeling a dynamical system of particles, usually under the influence of physical forces, in this case: **gravity**

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

What is an N-body + SPH Simulation?

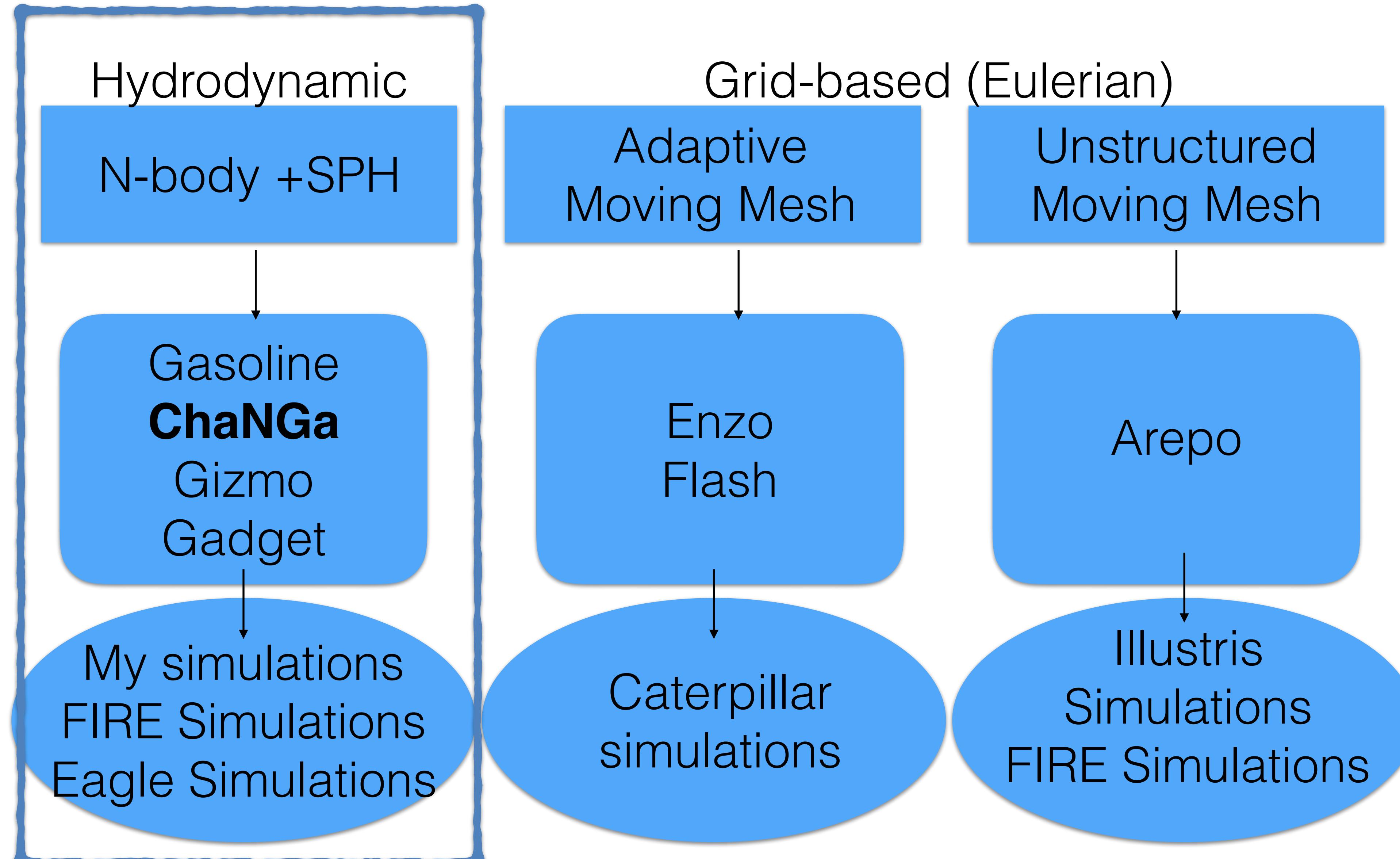
- SPH= “smoothed particle hydrodynamics”
- computational method used for simulating fluid flows- ie, **gas**
- Gas is divided into a set of discrete elements, referred to as “particles”
- “cosmological”= from early times all the way to present day





Video courtesy of A. Pontzen

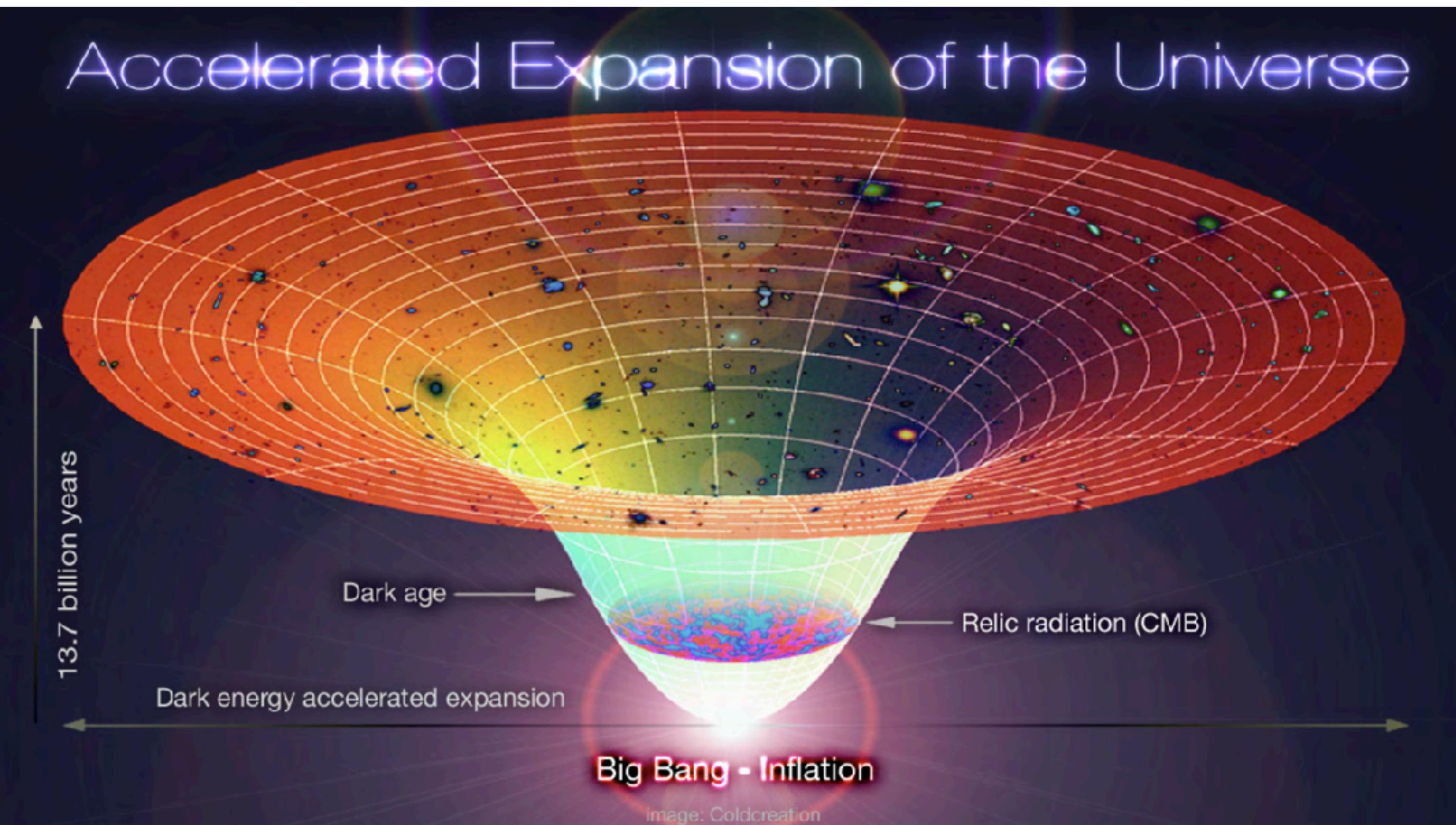
Types of galaxy simulations



Pros & Cons of different simulation suites

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

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 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

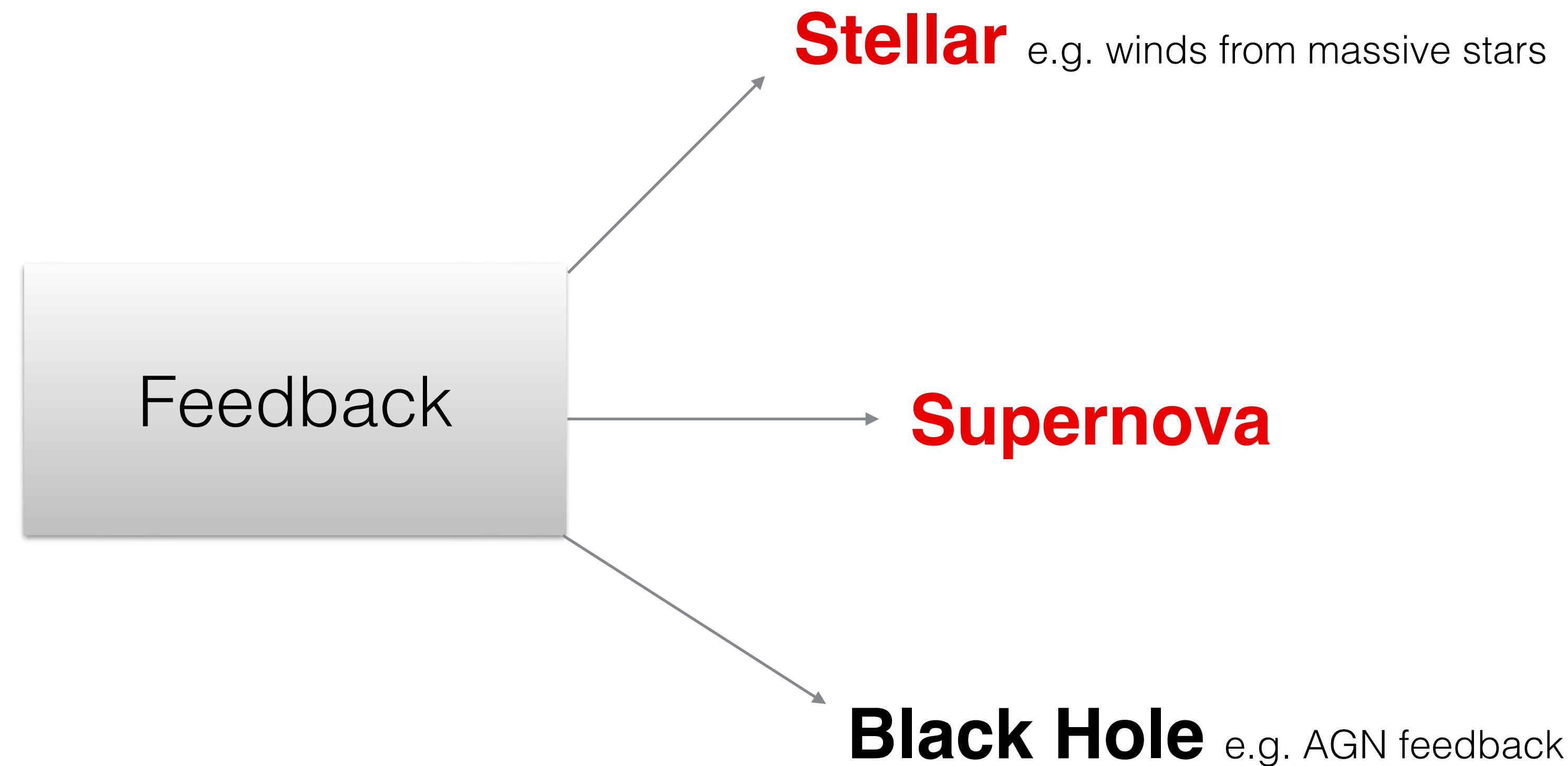
All feedback mechanisms have
this in common:

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

Dwarf galaxies are thought 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

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+Baryons	SIDM+Baryons
Bulge-less disk galaxies	✓	✓	✓
The Cusp/Core Problem	✓	✓	✓
Too Big to Fail	✓	✓	✓
Missing Satellites	✓	✓	✓
Missing Dwarfs	✓	✓	✓
Diversity	✓?	?	✓
Planes of Satellites	Still to be explored		

**Scorecard adapted from A. Brooks

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+Baryons	SIDM+Baryons
Bulge-less disk galaxies	✓	✓	✓
The Cusp/Core Problem	✓	✓	✓
Too Big to Fail	✓	✓	✓
Missing Satellites	✓	✓	✓
Missing Dwarfs	✓	✓	✓
Diversity	✓?	?	✓
Planes of Satellites	Still to be explored		

Dwarf Galaxies

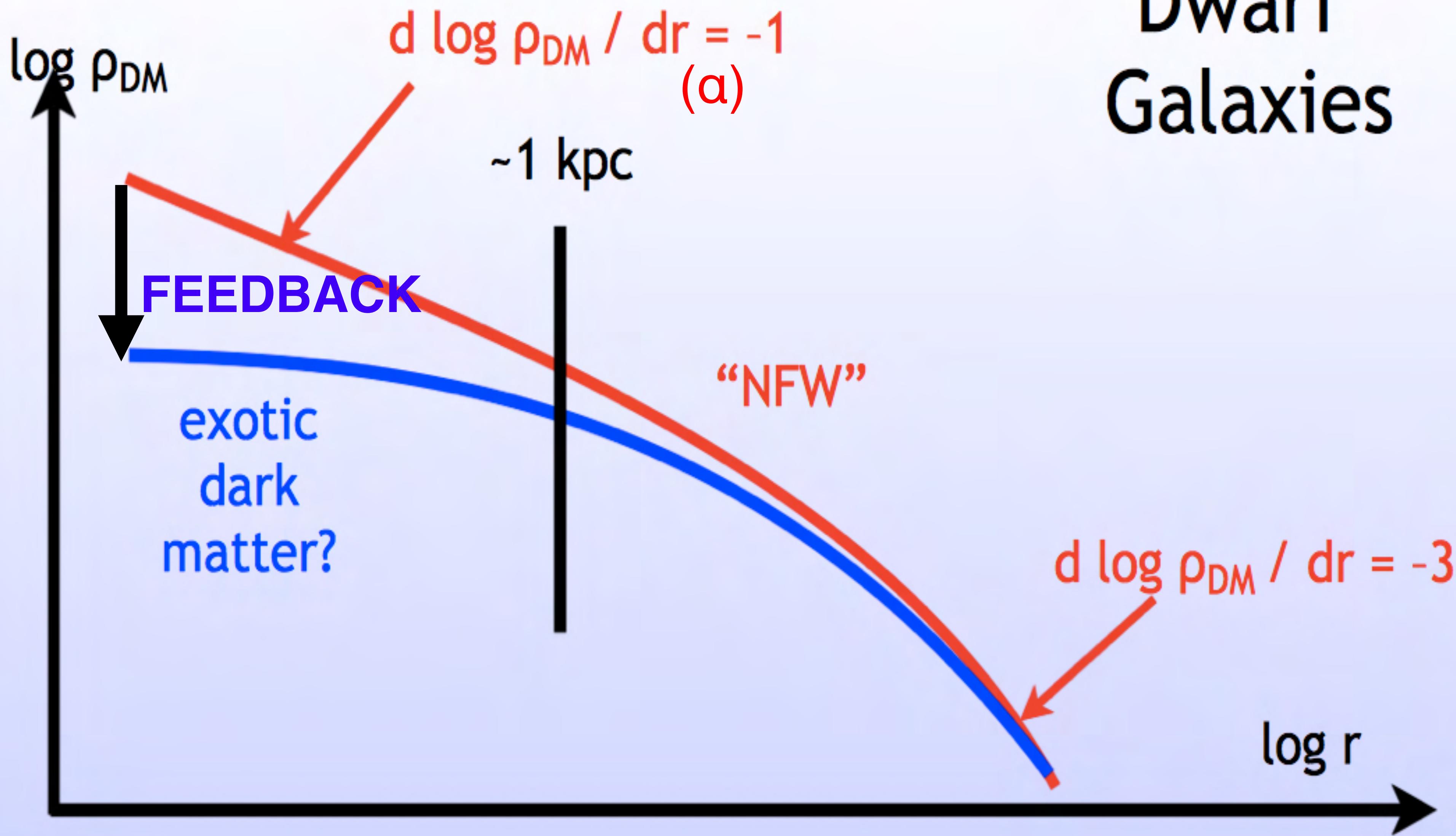
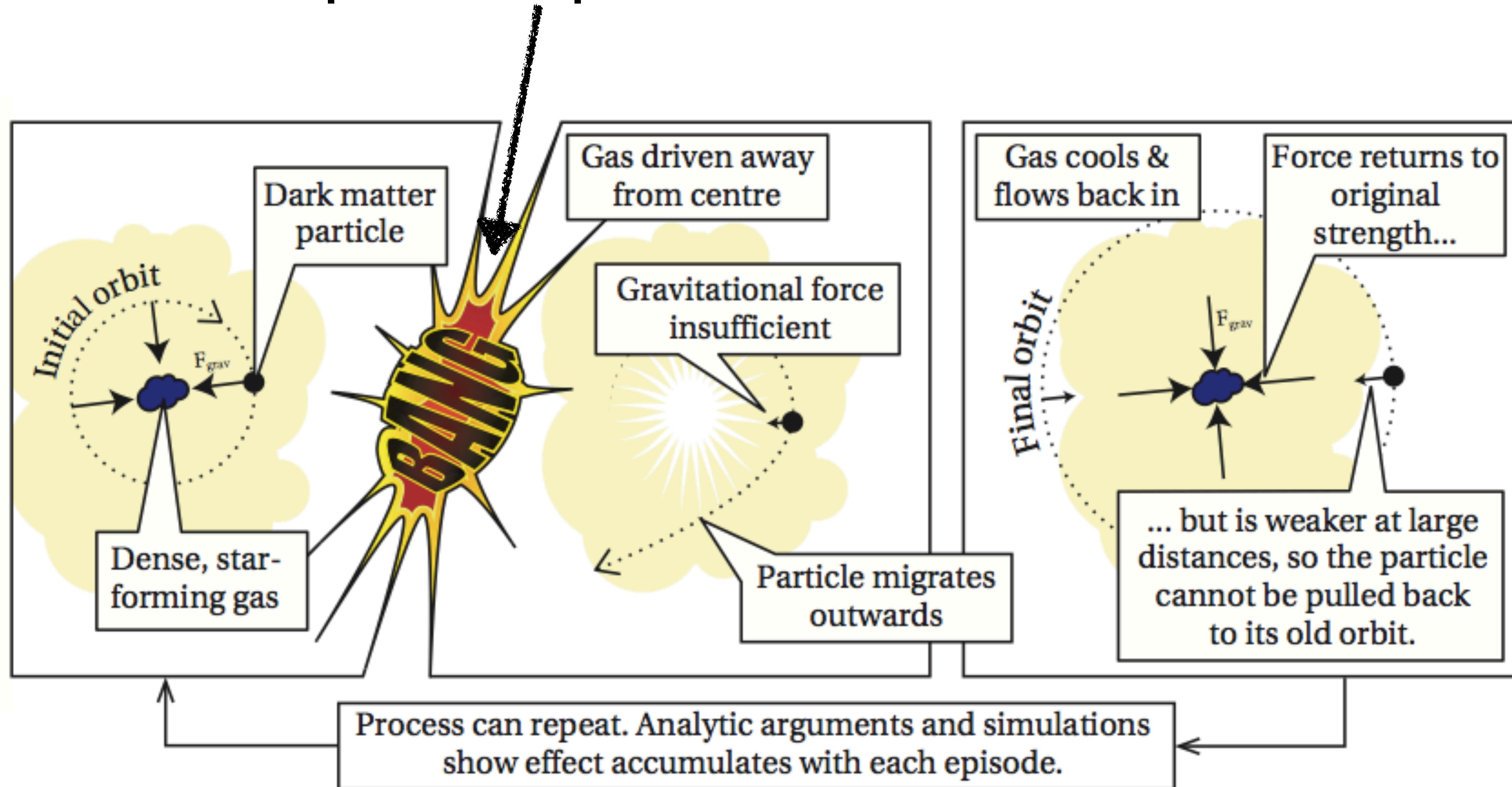
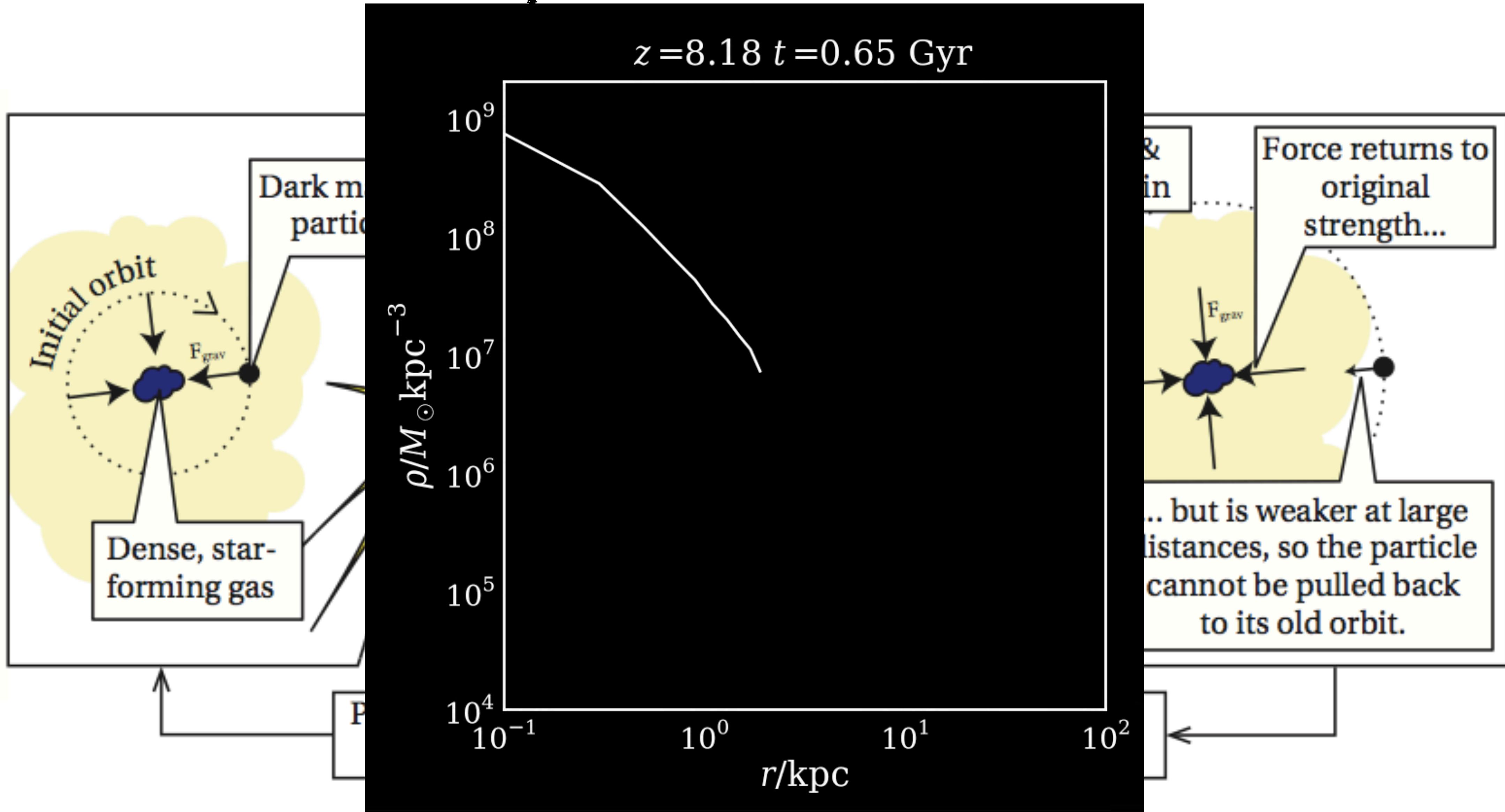


Figure courtesy of F. Governato

Supernova explosion/feedback



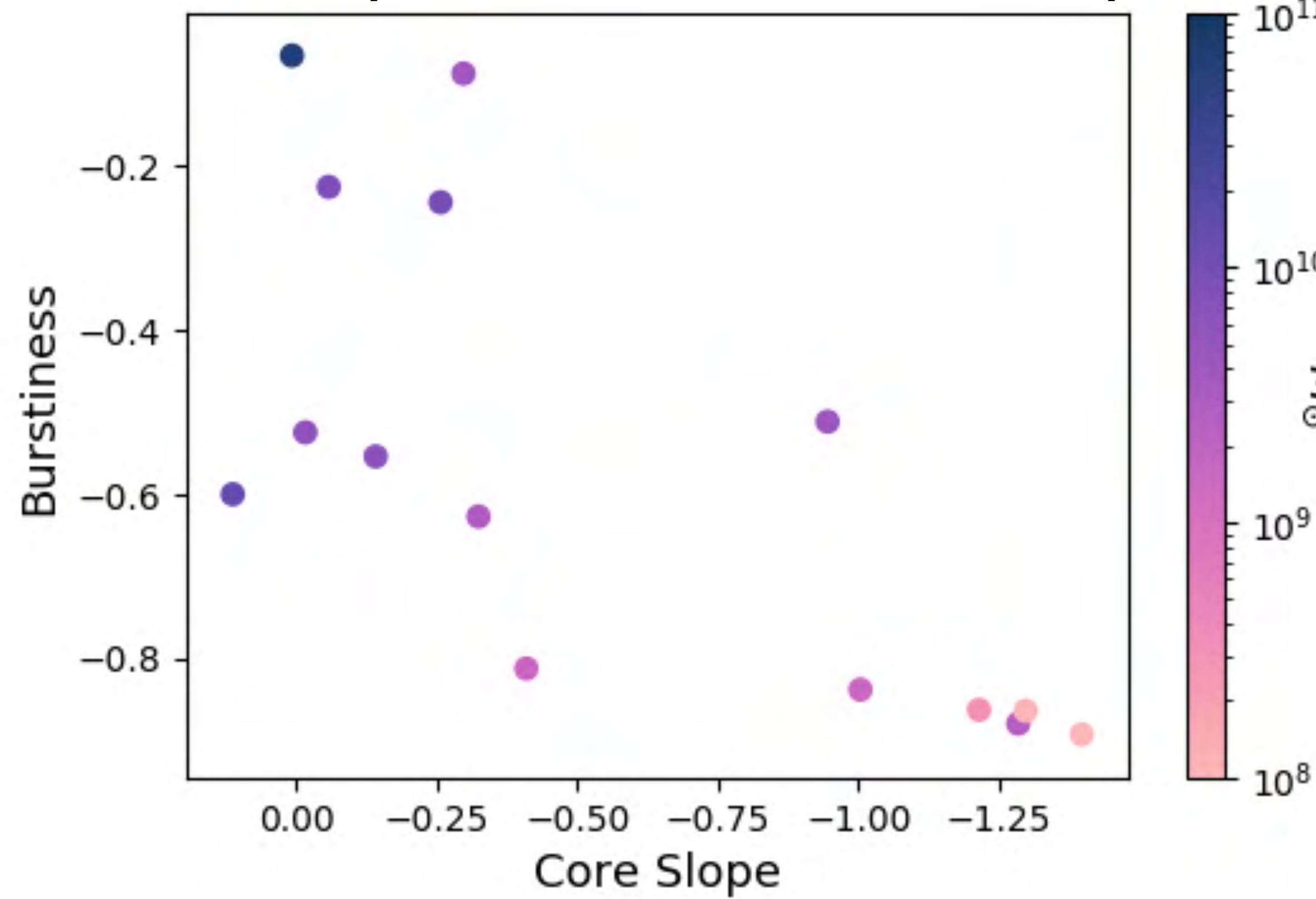
Supernova explosion/feedback



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

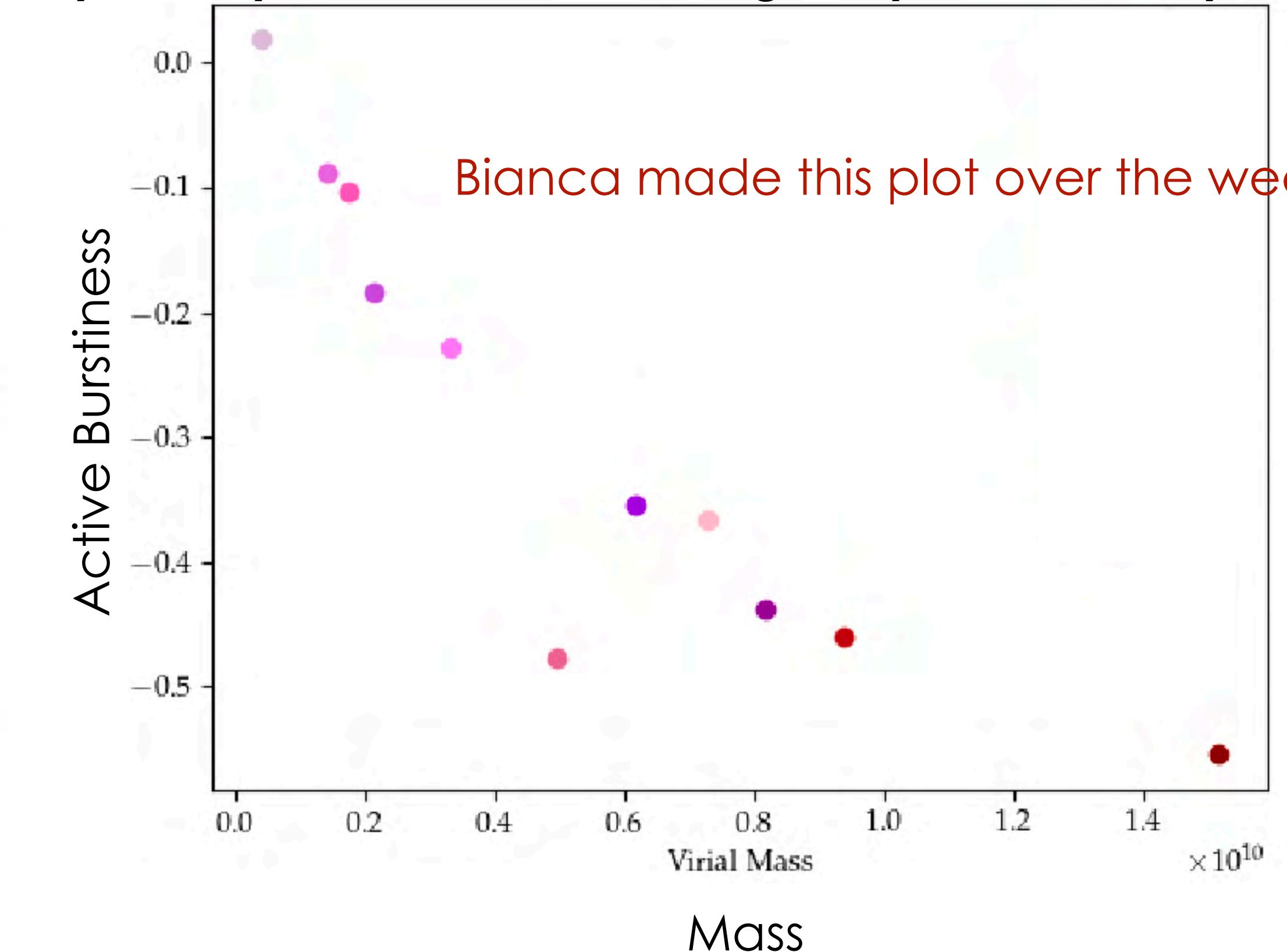


corea



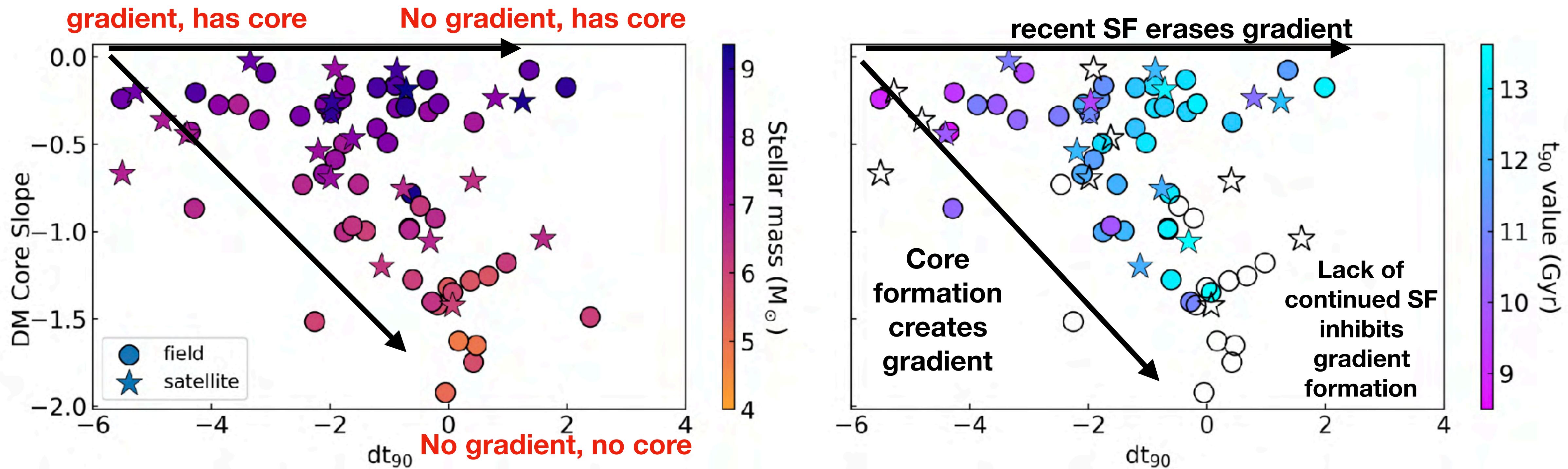
cuspy

No, if you only consider when the galaxy was actively forming stars



Bianca made this plot over the weekend!!

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.

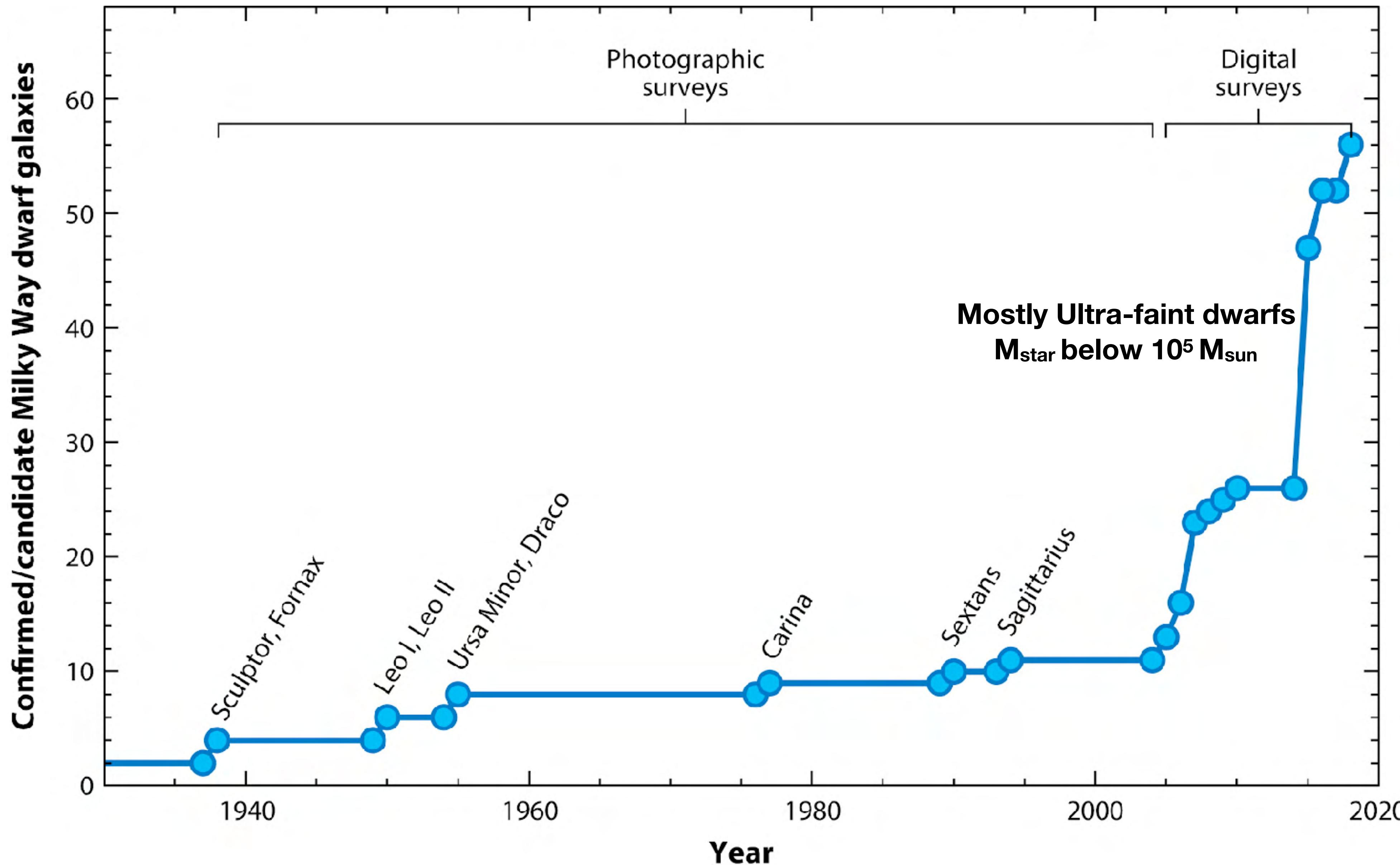
Lack of age gradient does not mean the galaxy does not have a core!

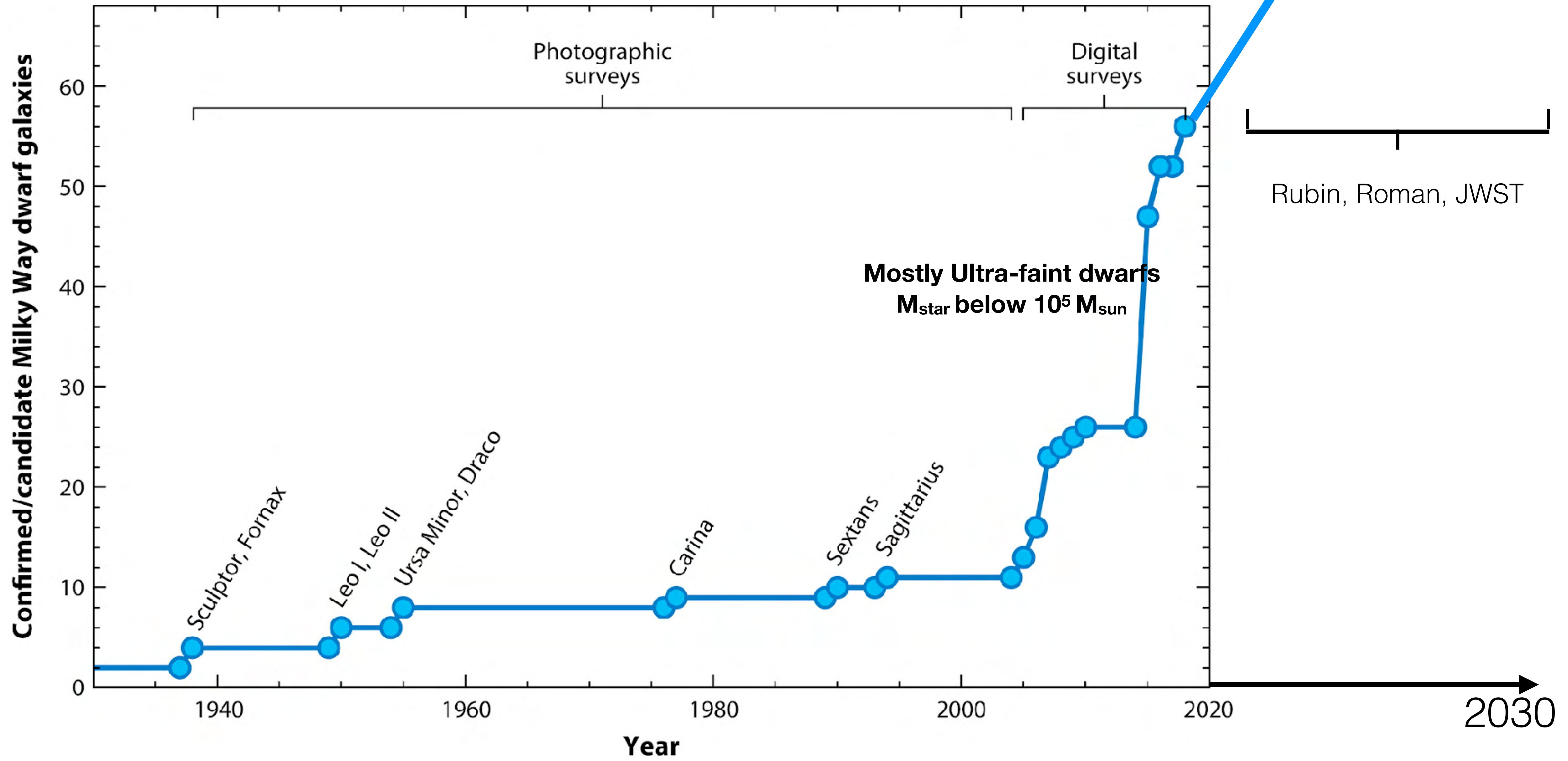
Key Problem #1

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



There has been an explosion in finding fainter and fainter dwarfs





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

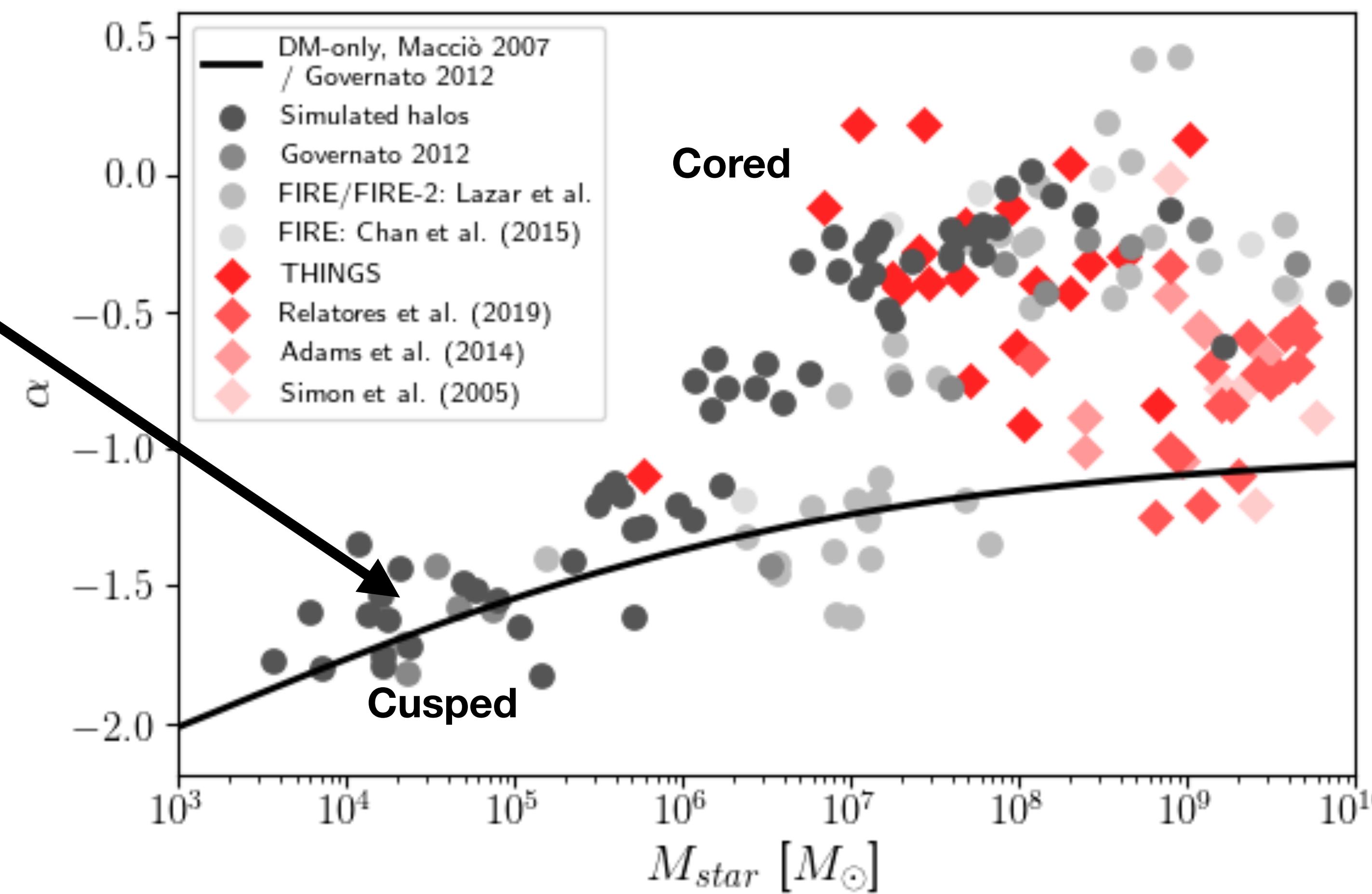


Figure from my grad student, J. Van Nest



MARVELous Dwarfs

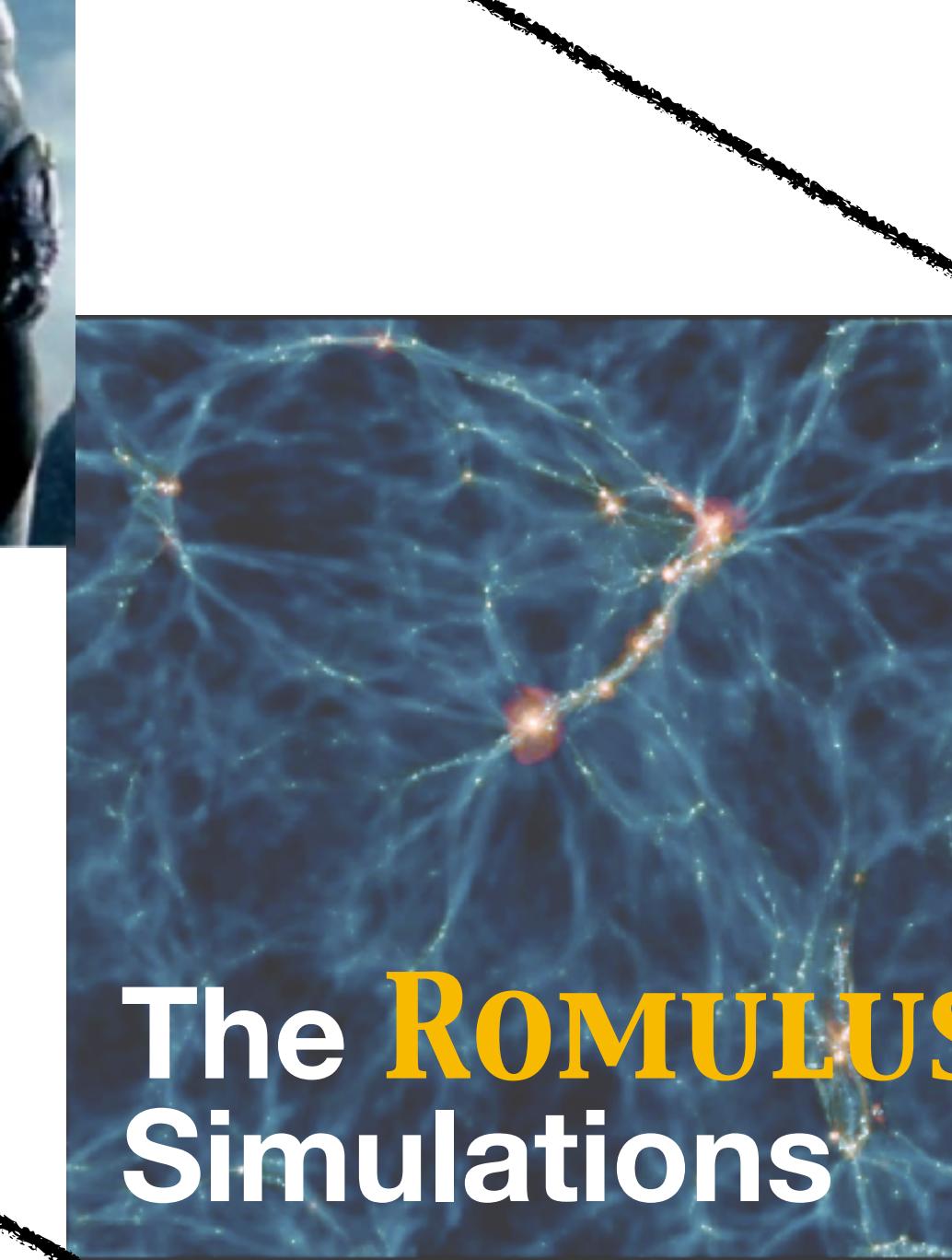
Ultra-faints in isolation

Ultra-faints in the vicinity of a MW



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

Dwarfs (and UDGs) across environments



The ROMULUS Simulations



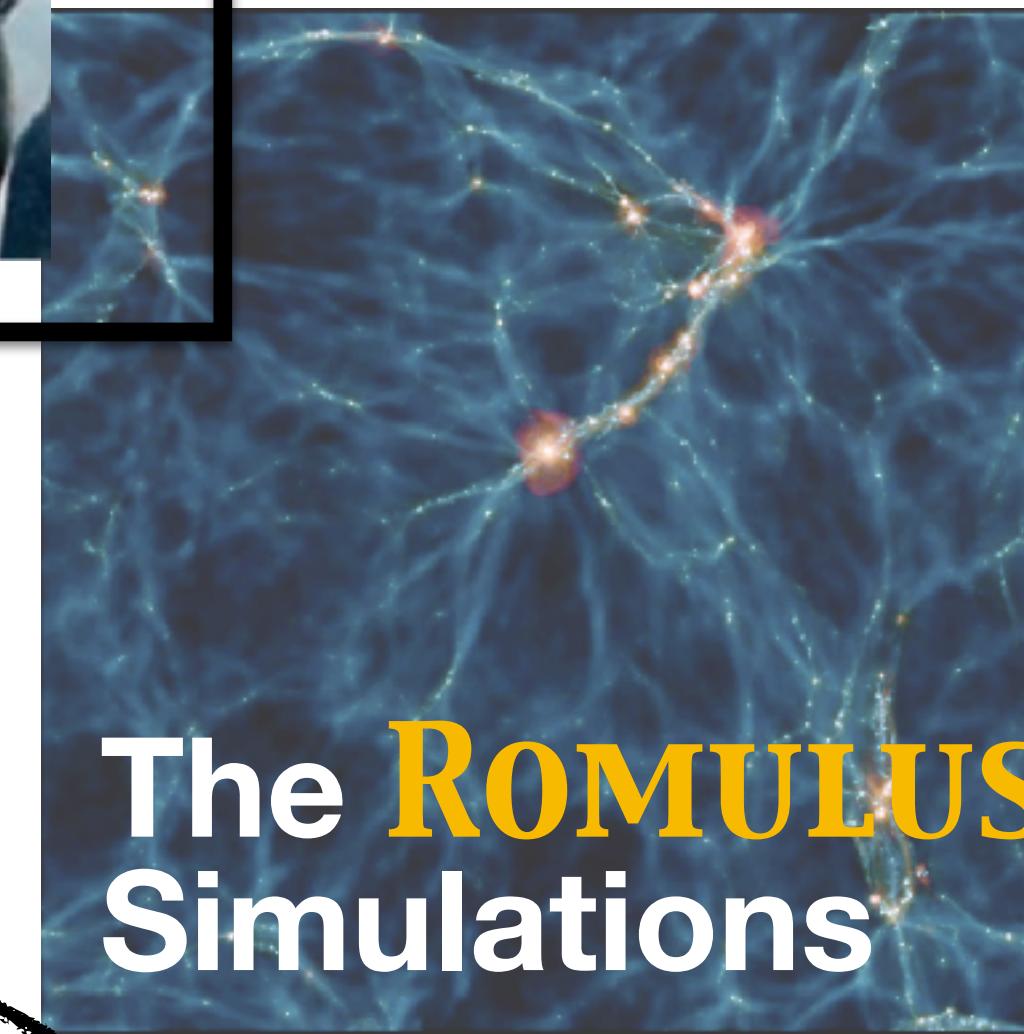
Ultra-faints in isolation

Ultra-faints in the vicinity of a MW



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

Dwarfs (and UDGs) across environments



MARVELous Dwarf Volumes + Justice

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



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

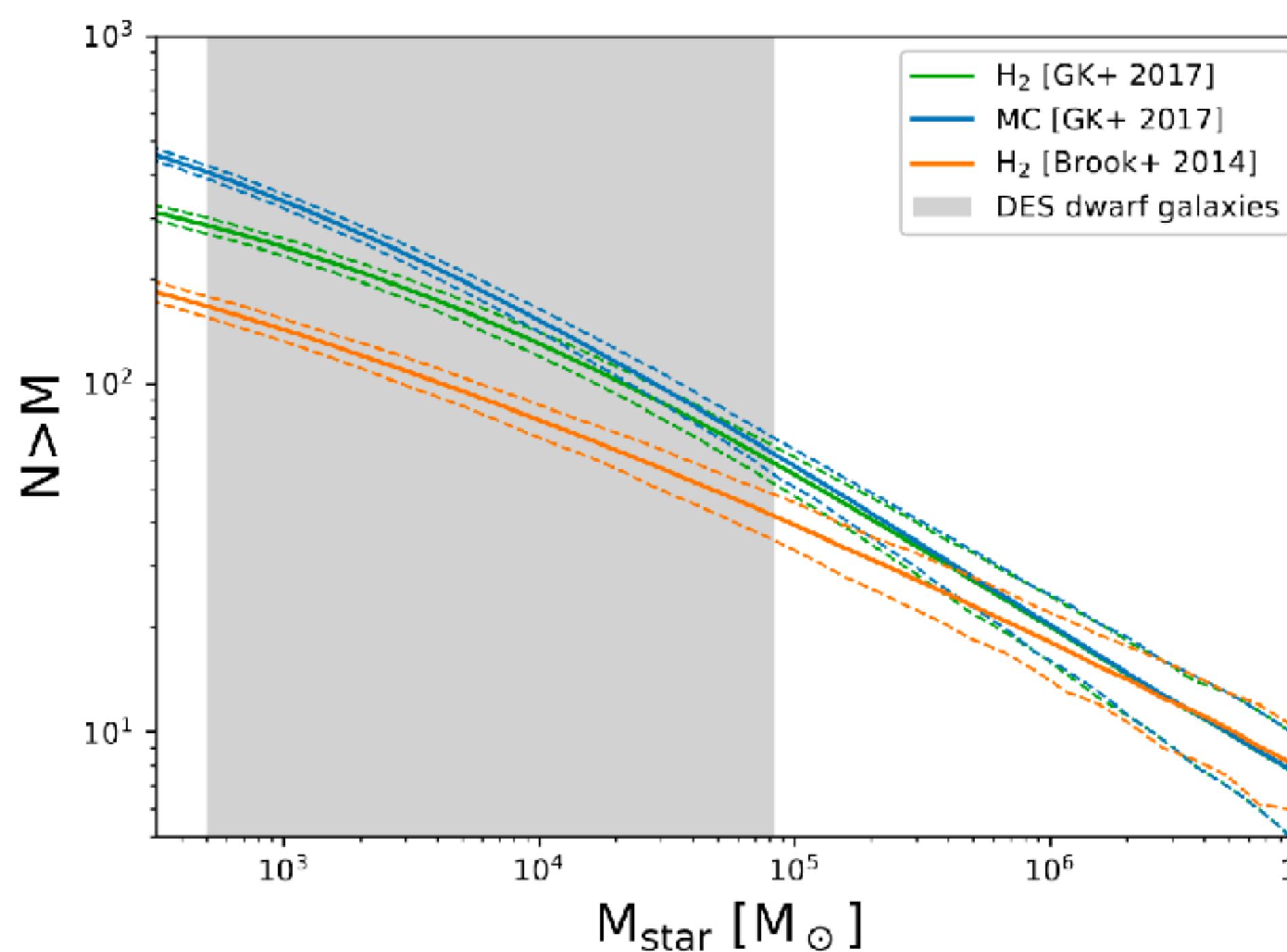
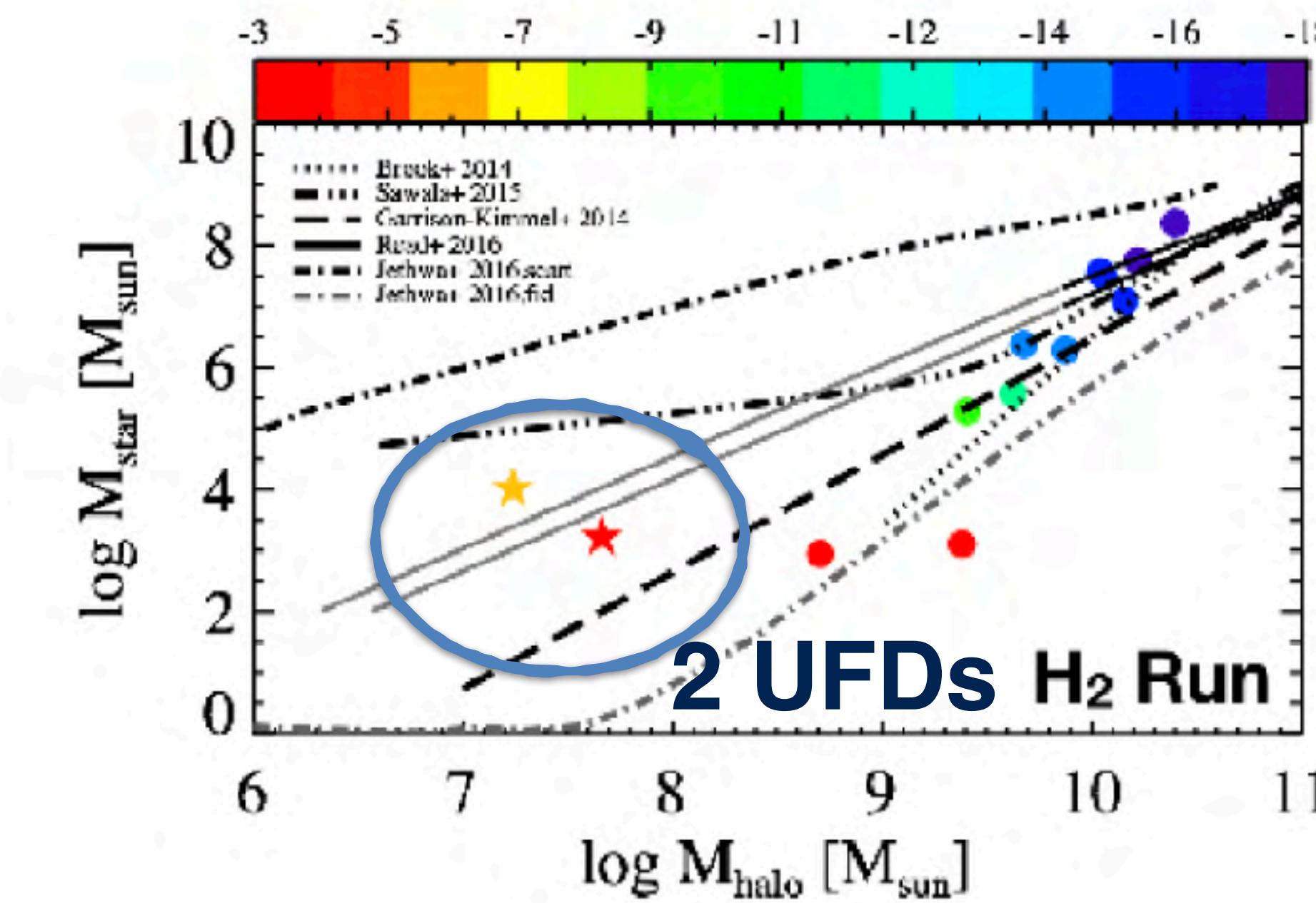
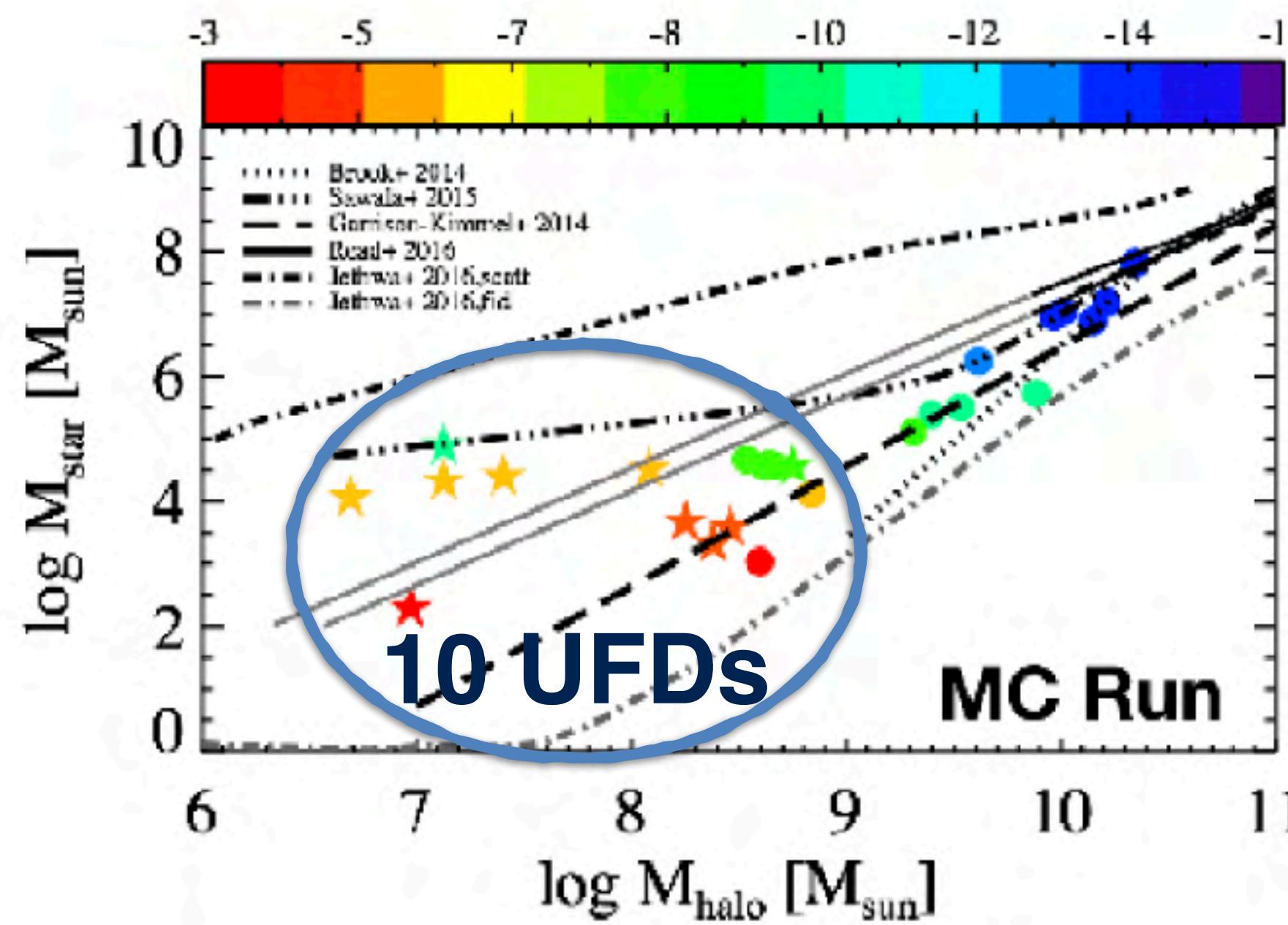
Left: dark matter
Right: gas

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

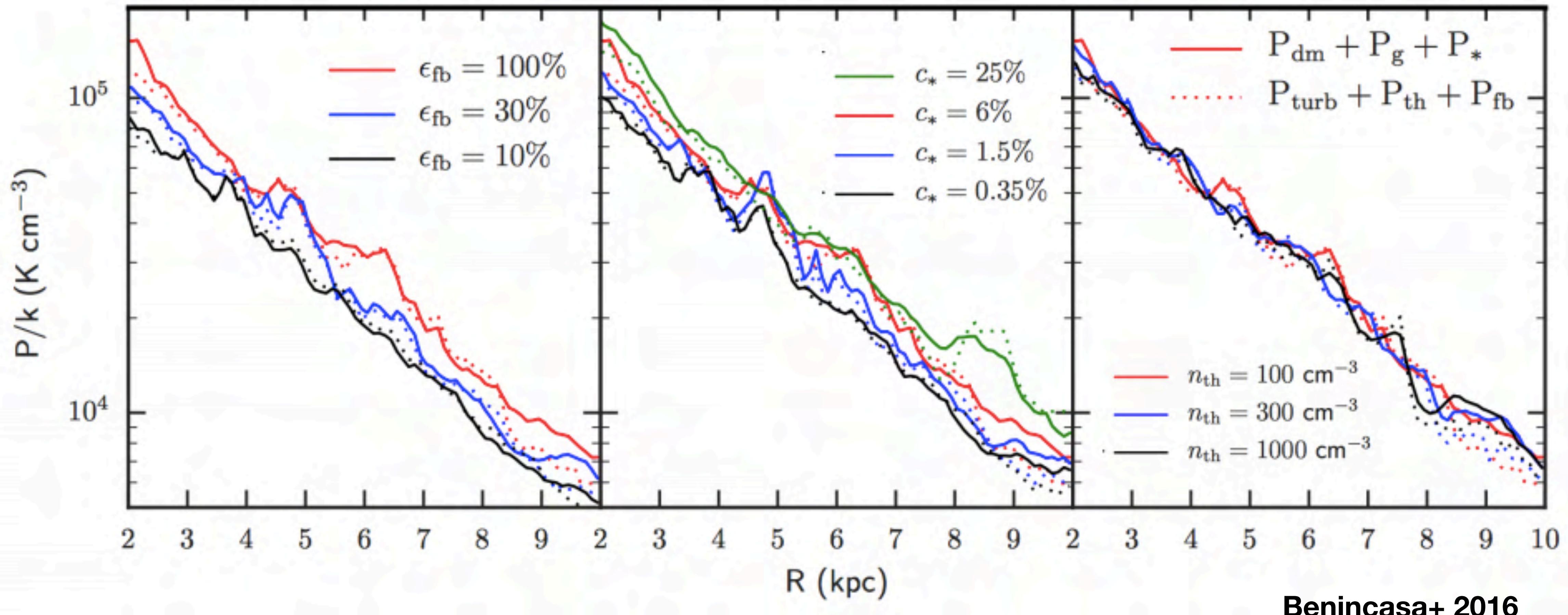


Any predictions you make depend on your star formation and feedback model



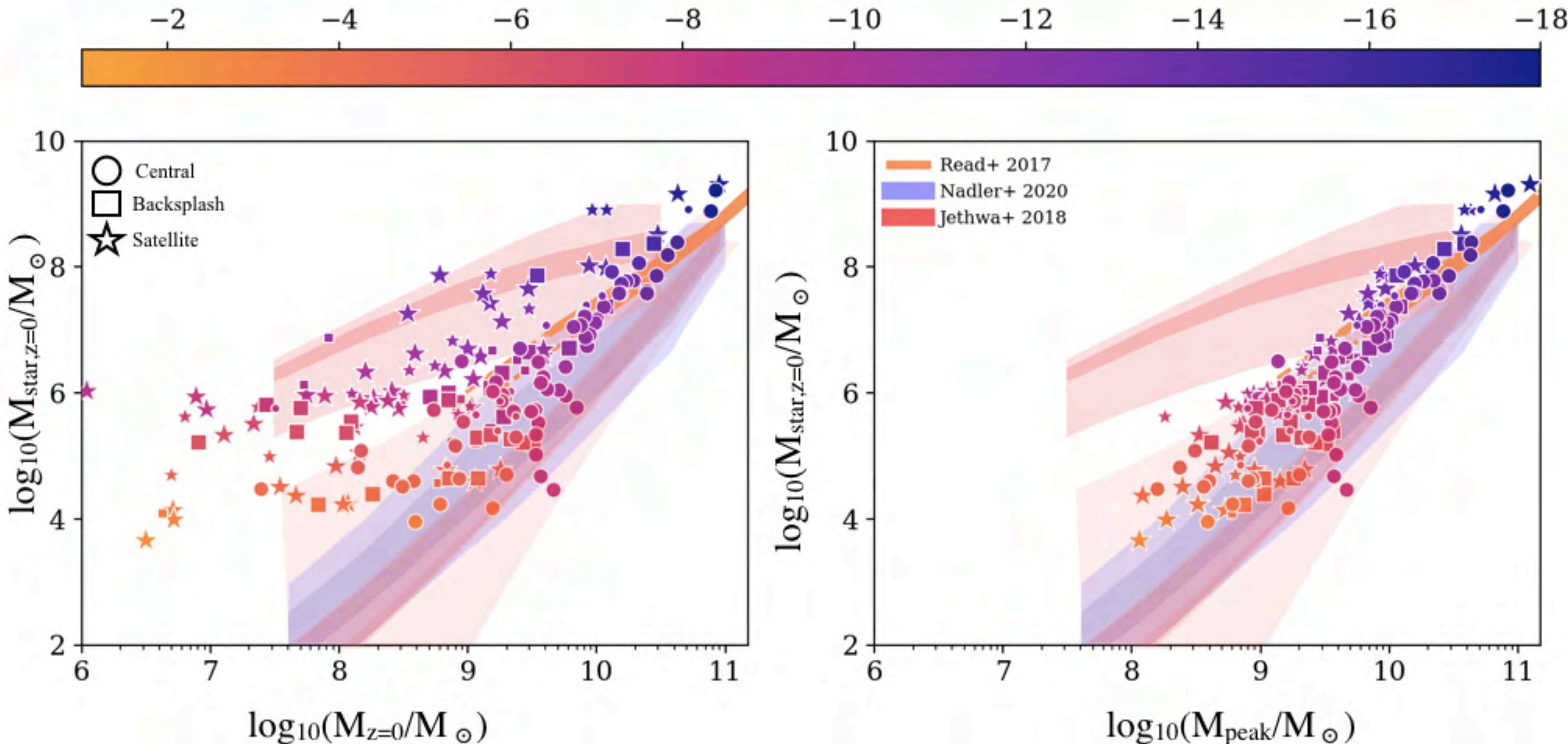
Munshi+ 2019, with former graduate student E. Applebaum

Why haven't we worried before?

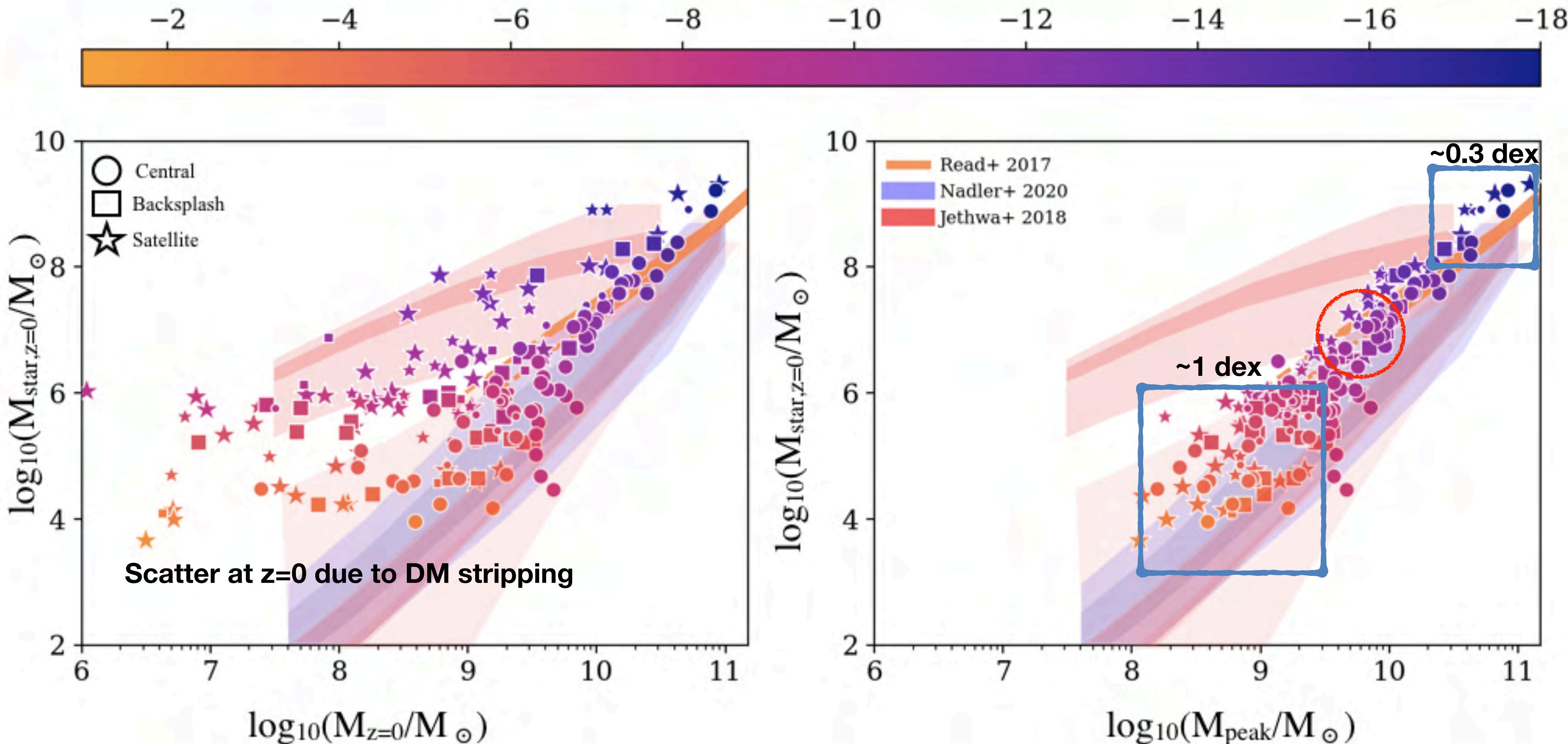


Star formation and feedback self-regulate at classical dwarf masses and above.

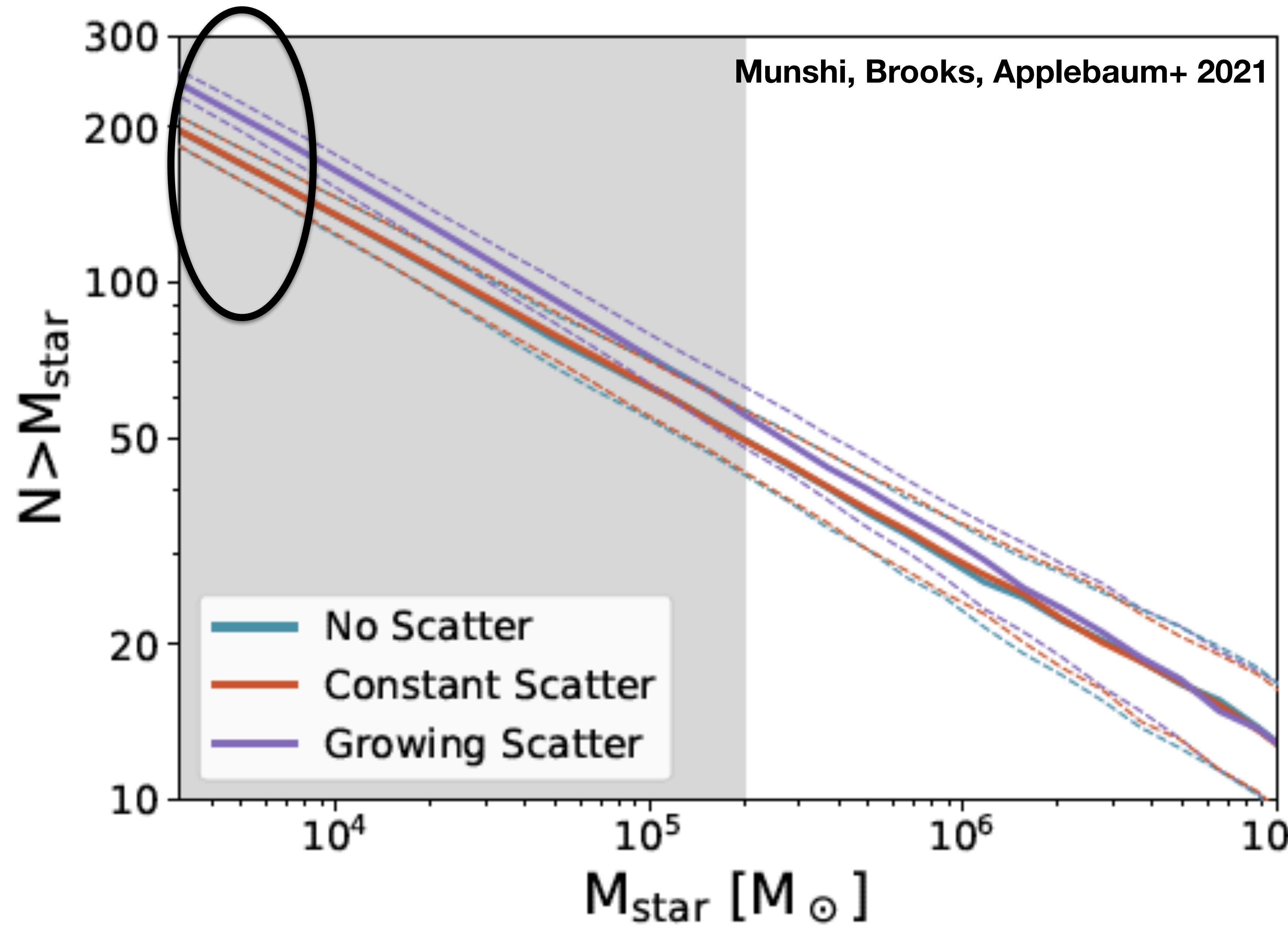
V-band magnitude



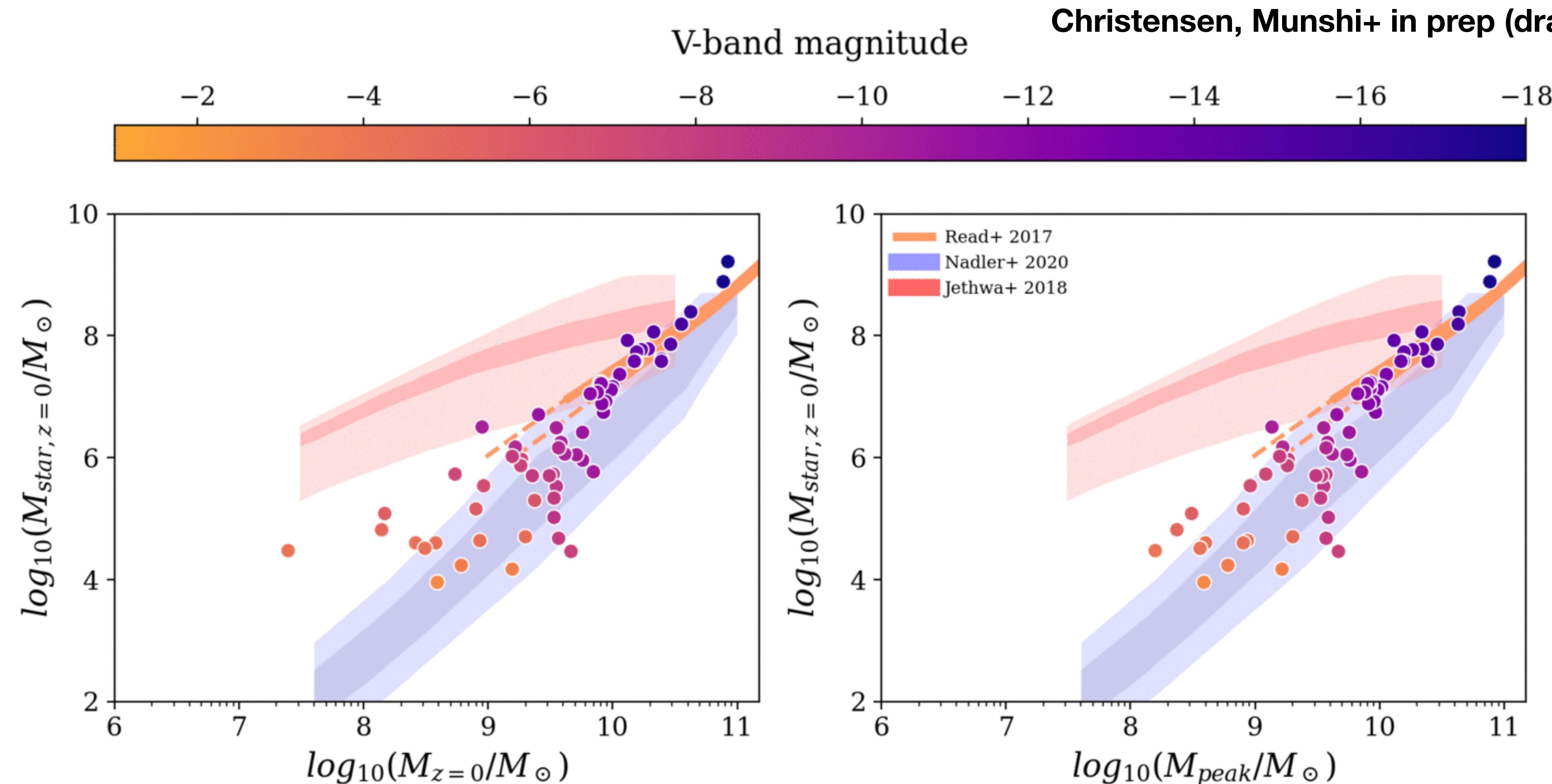
V-band magnitude



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



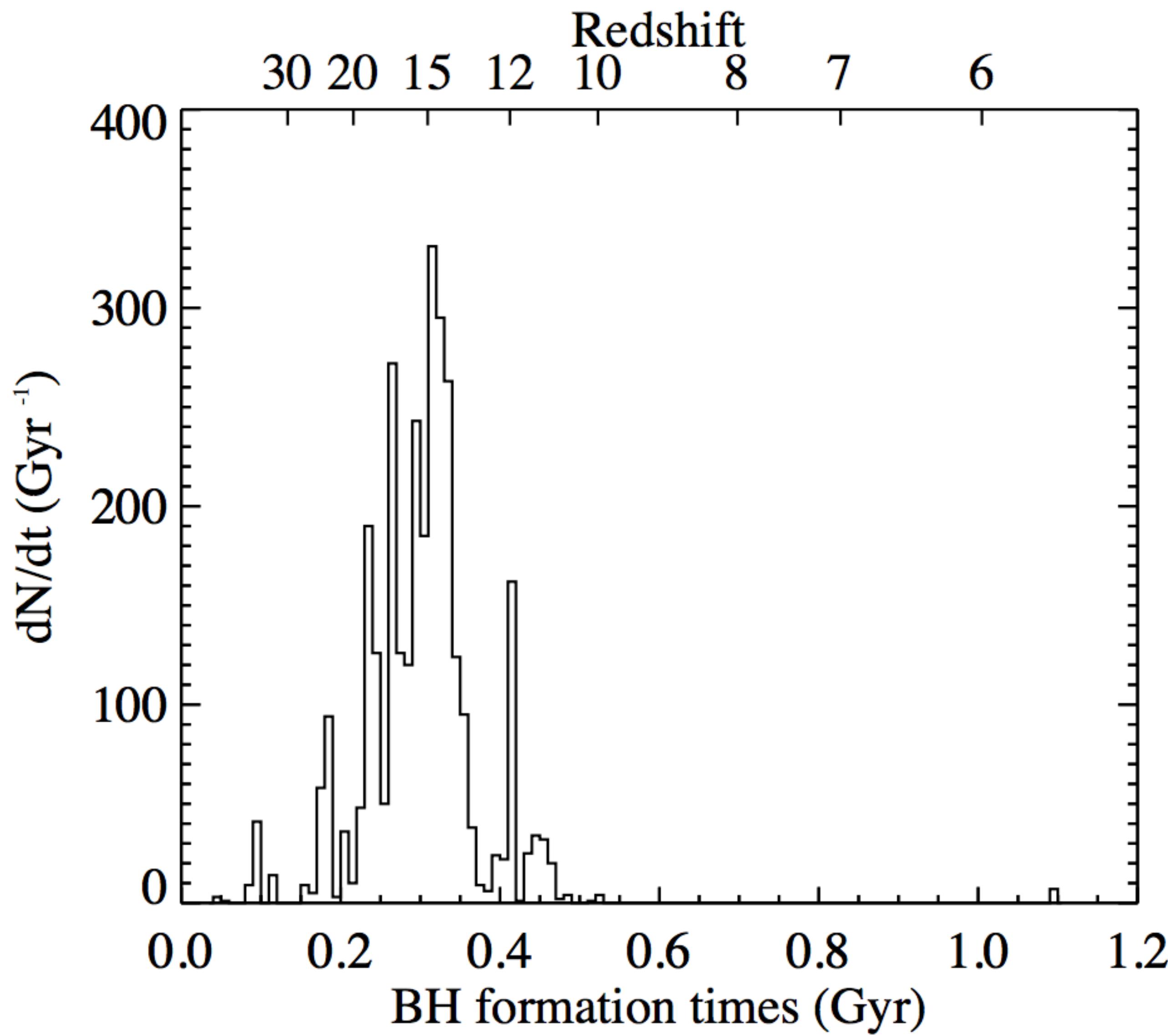
Upcoming: Effect of Environment



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

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

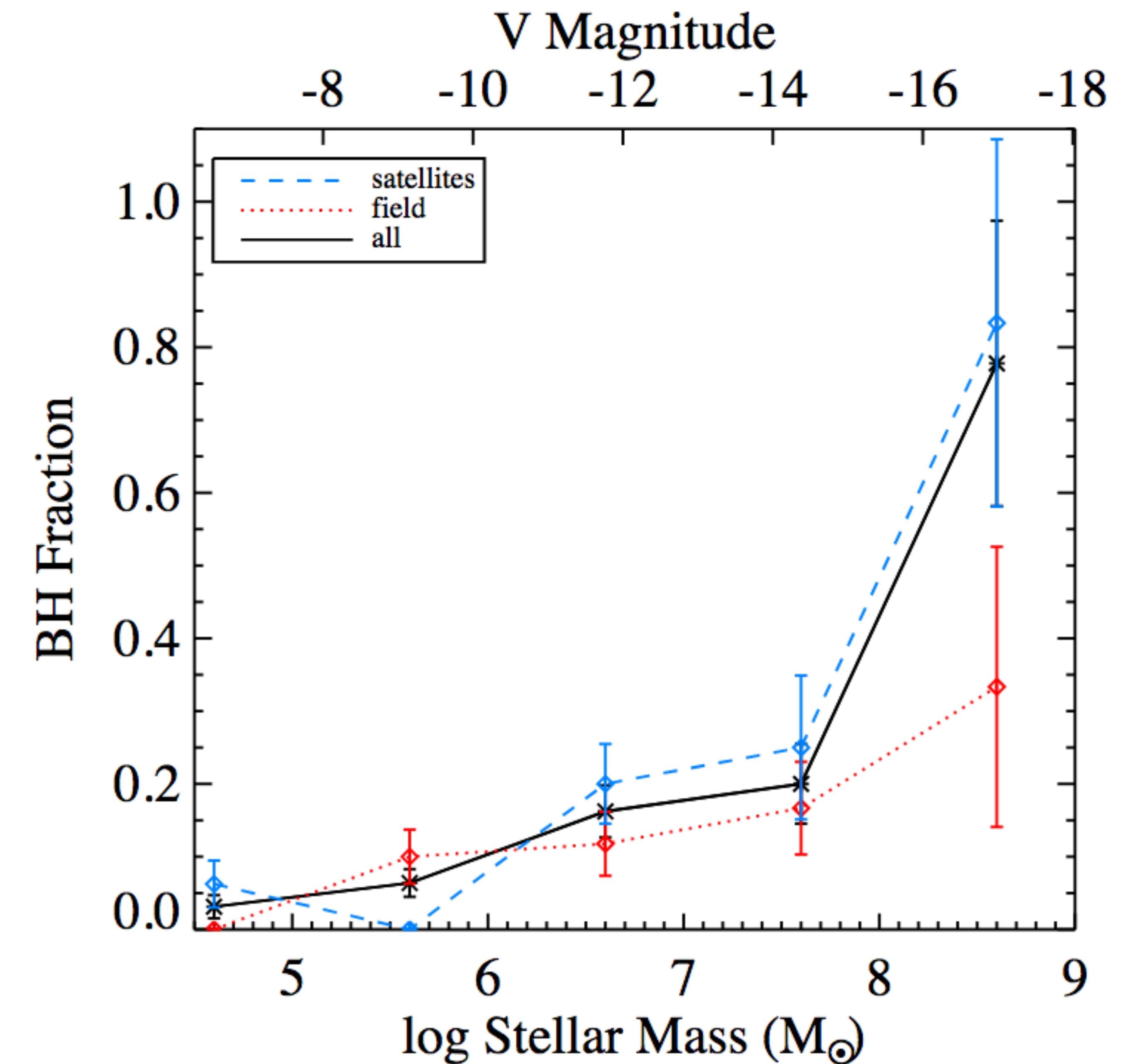
This is important as these predictions are 1. dependent on DM model and 2. detectable by LISA



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

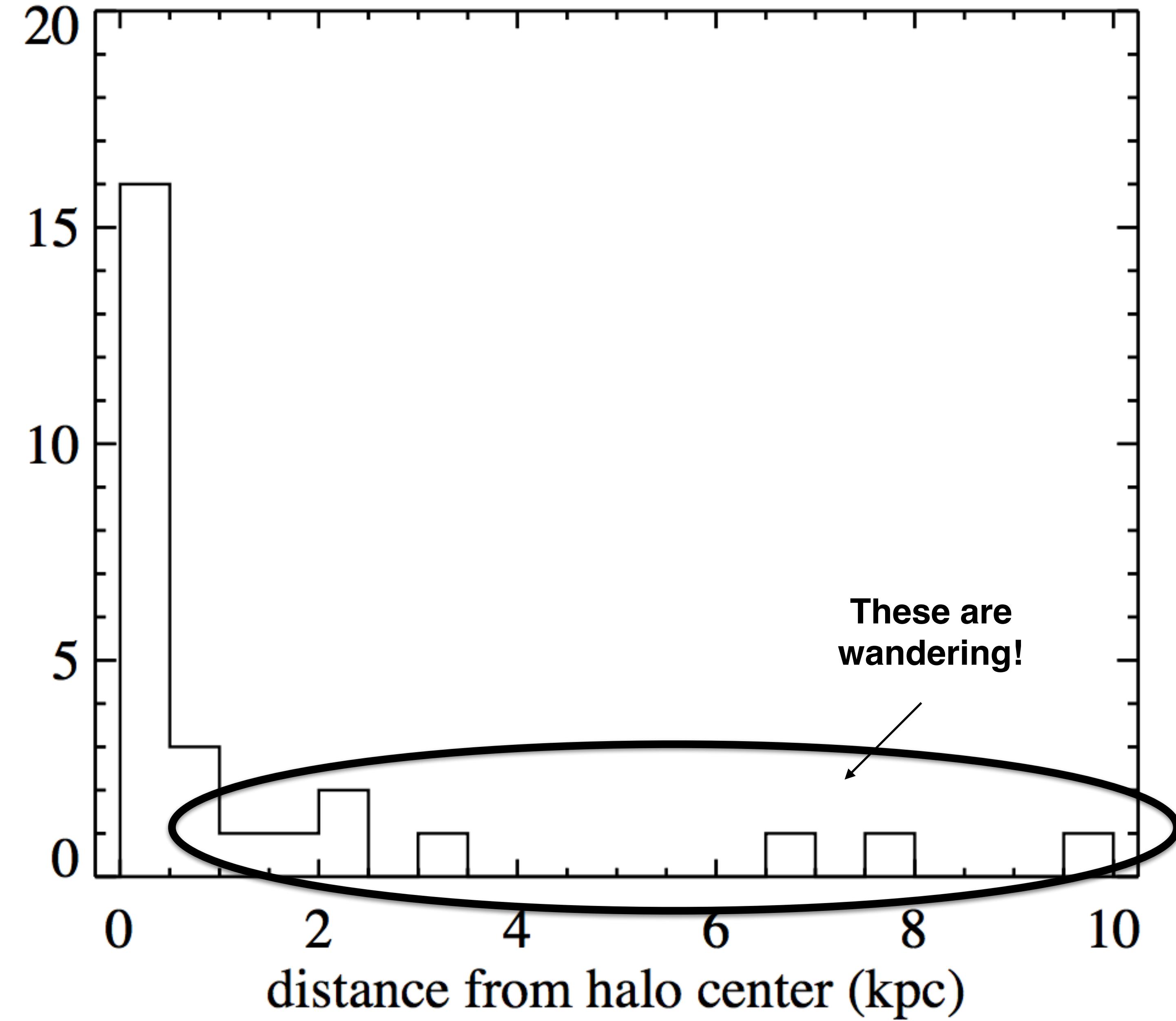
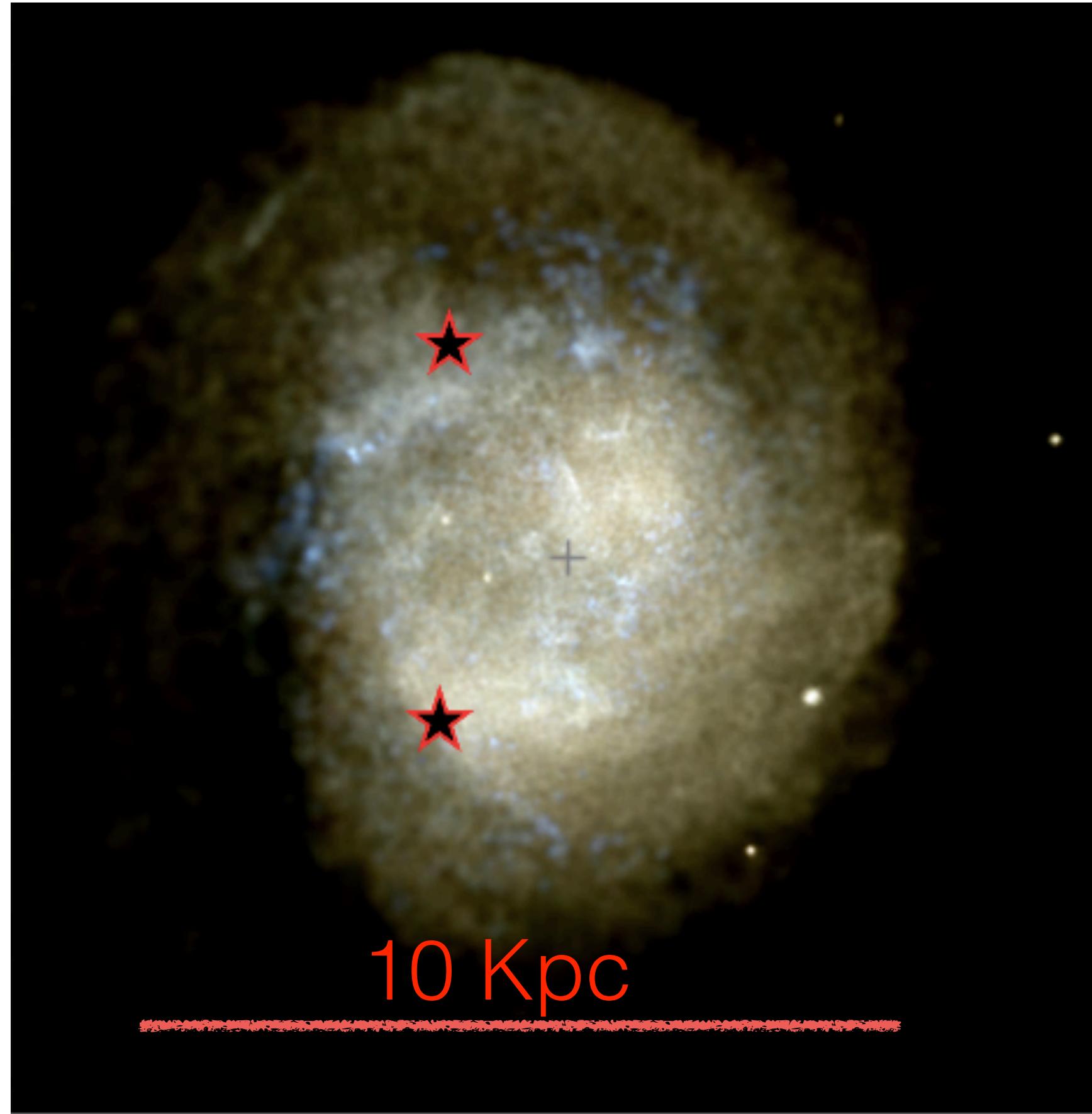
- MBHs form at high $-z$
- Truncation due to propagation of metals (need pristine gas)

Unlike more massive galaxies, not all dwarf galaxies host a massive black hole at the center

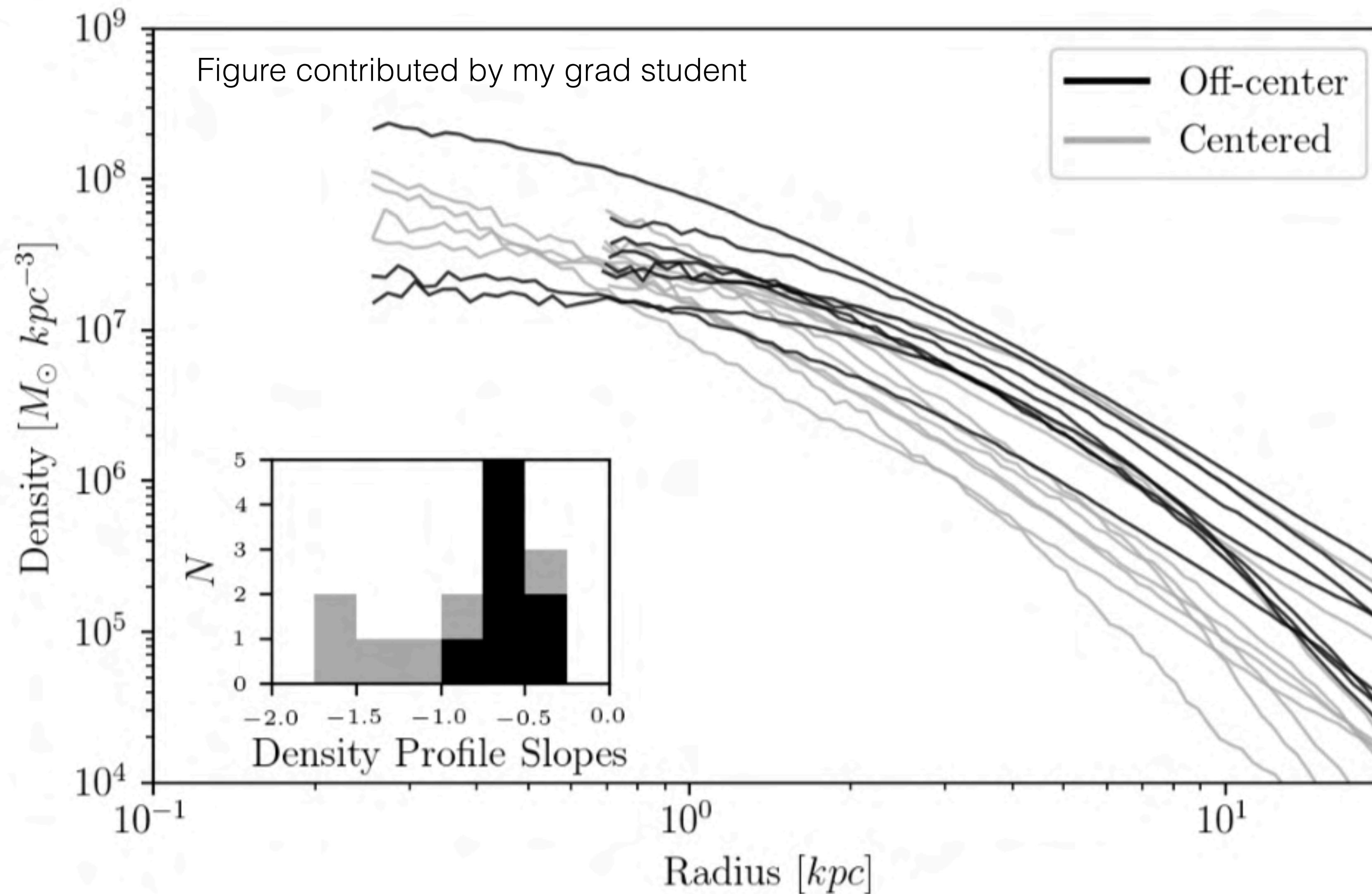


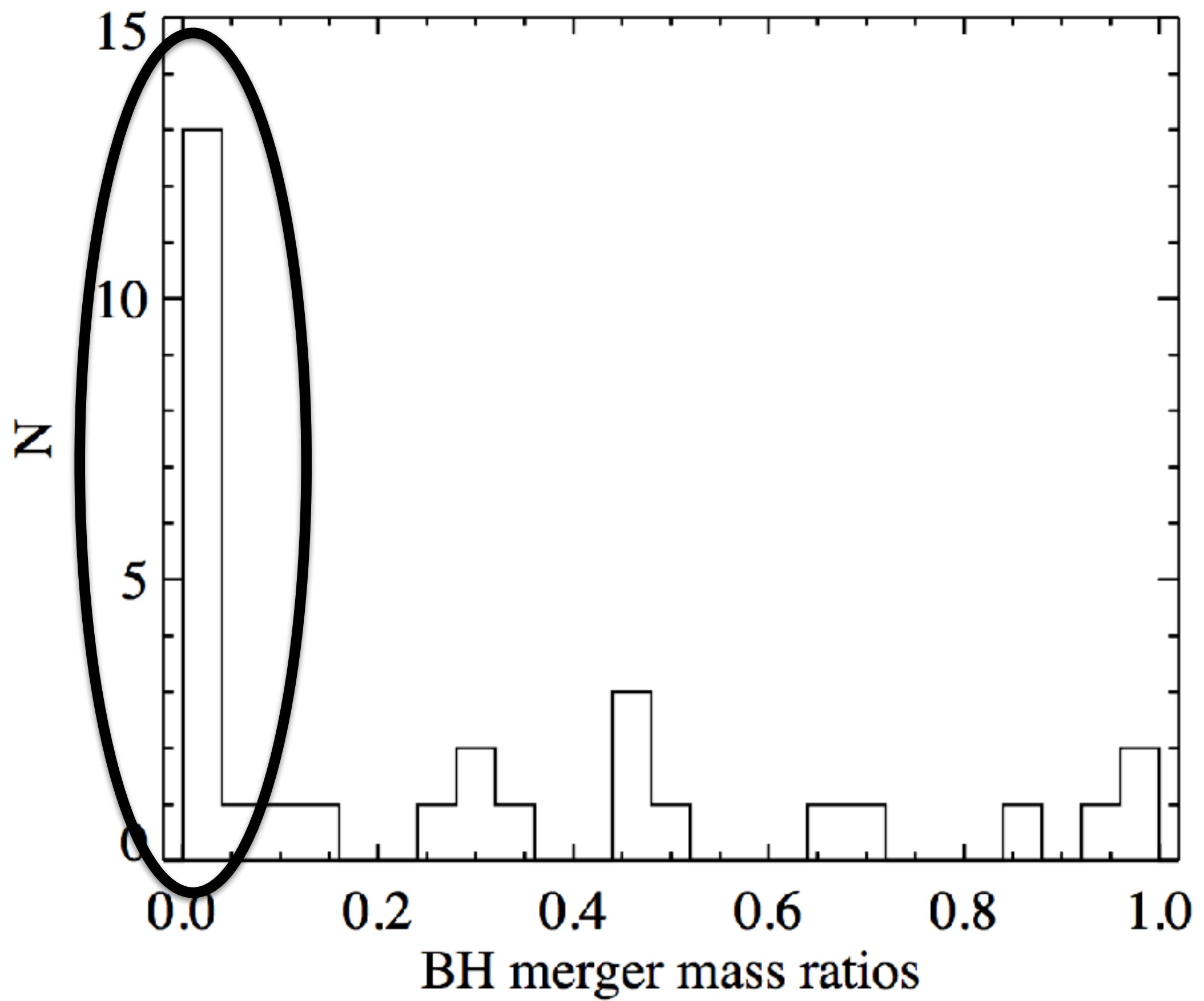
- No environmental difference in occupation fraction

They are not necessarily in the center of dwarf halos!



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





Most common MBH merger ratio is dwarf's
MBH + SMBH of the MW progenitor nearby

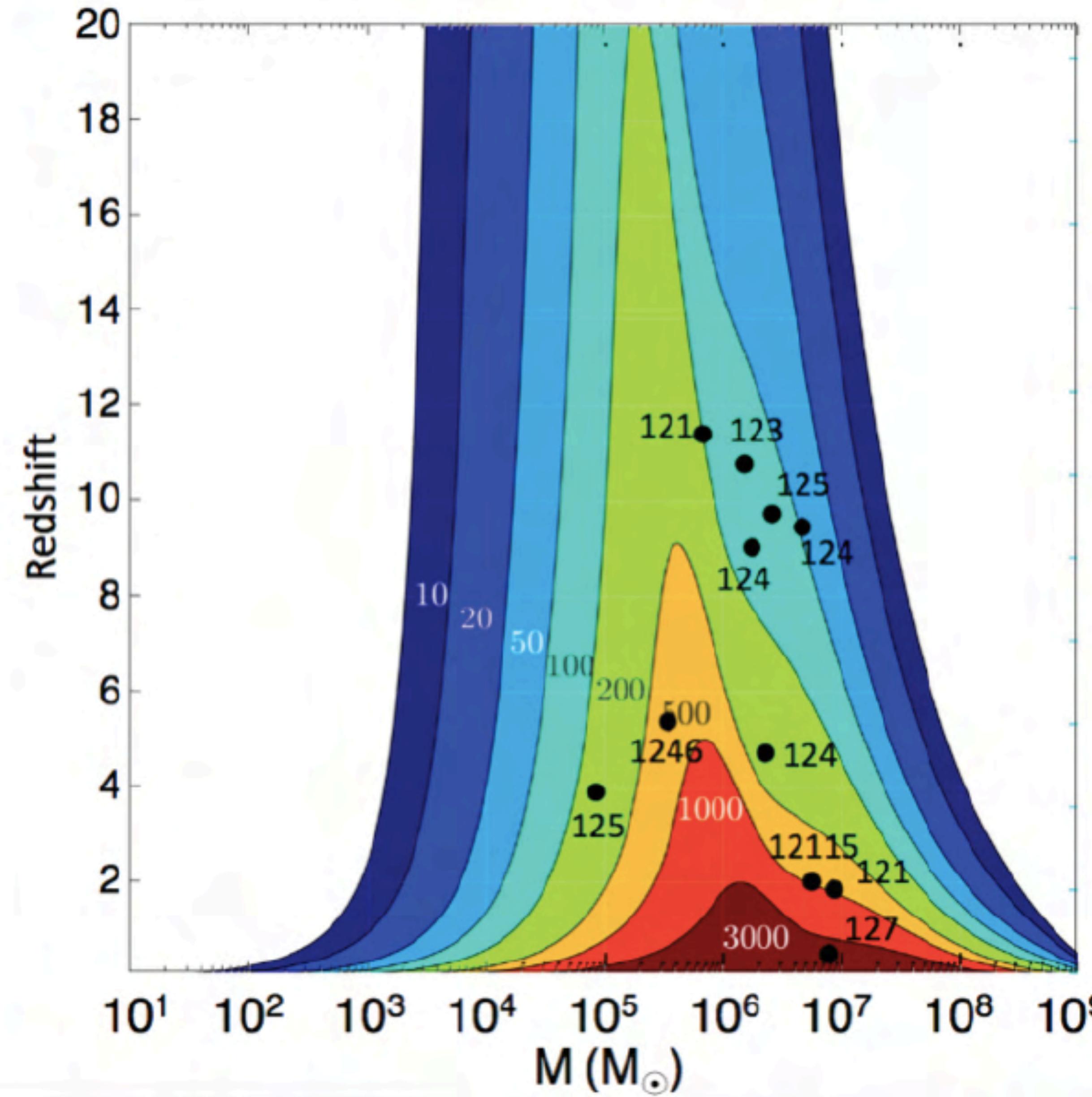
“wandering” off-center MBHs are due to
mergers (usually with a larger galaxy)

Core stalling should happen in nearly every *bright/classical* dwarf halo in SIDM →
testable prediction: more wandering BHs in SIDM?

This would be consistent with studies at higher masses e.g. DiCintio+ 2017

Can we find these wandering (I)MBHs at the large radii? TDEs?

Bellovary, Cleary, Munshi + 2018
Bellovary...+ Munshi + 2021



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.**

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

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

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

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

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

But the baryons are required in all DM models to reconcile the small scale “crisis”....

Key Problems #2

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

SIDM Dwarfs: Shapes as a smoking gun?

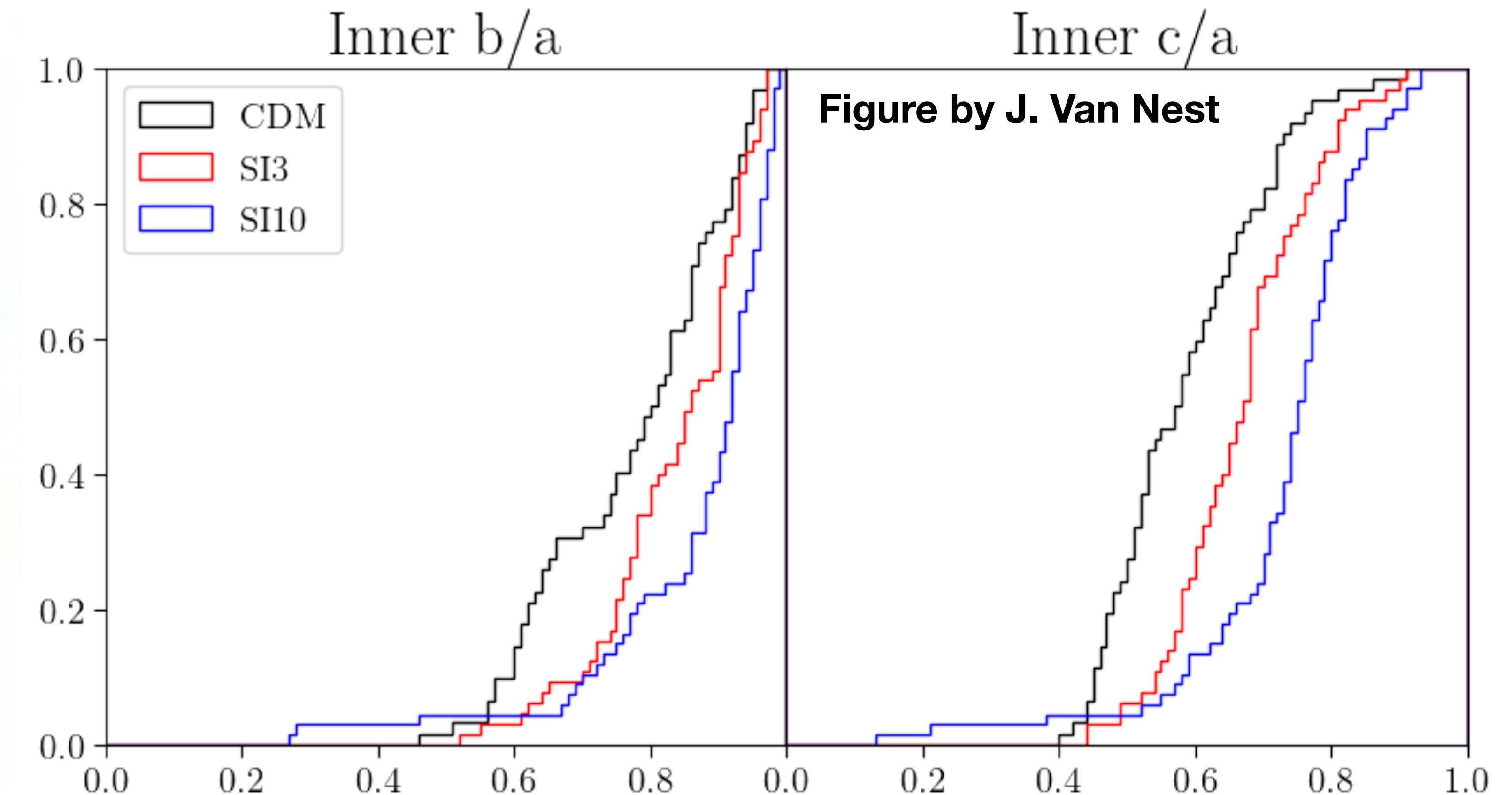
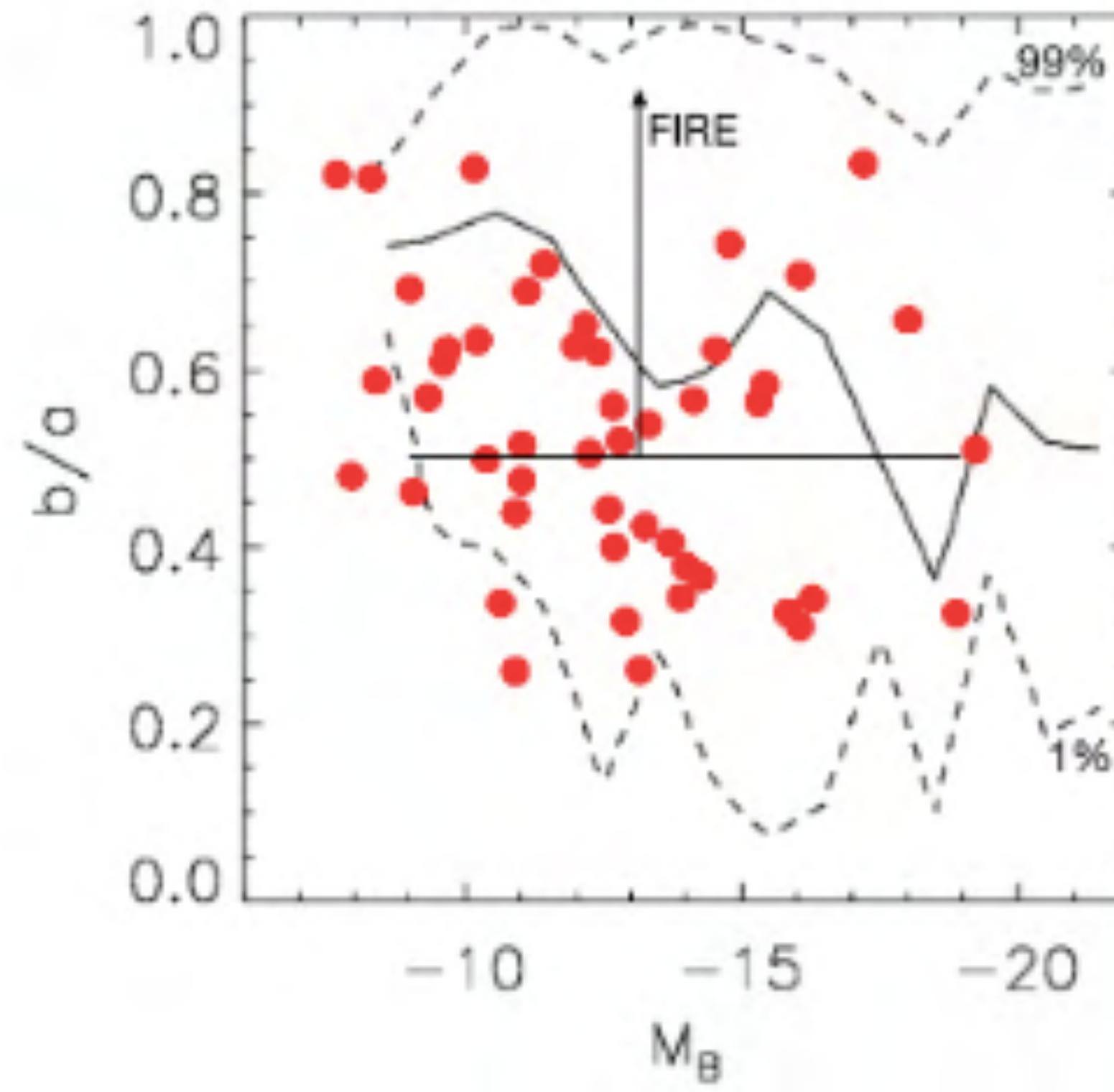


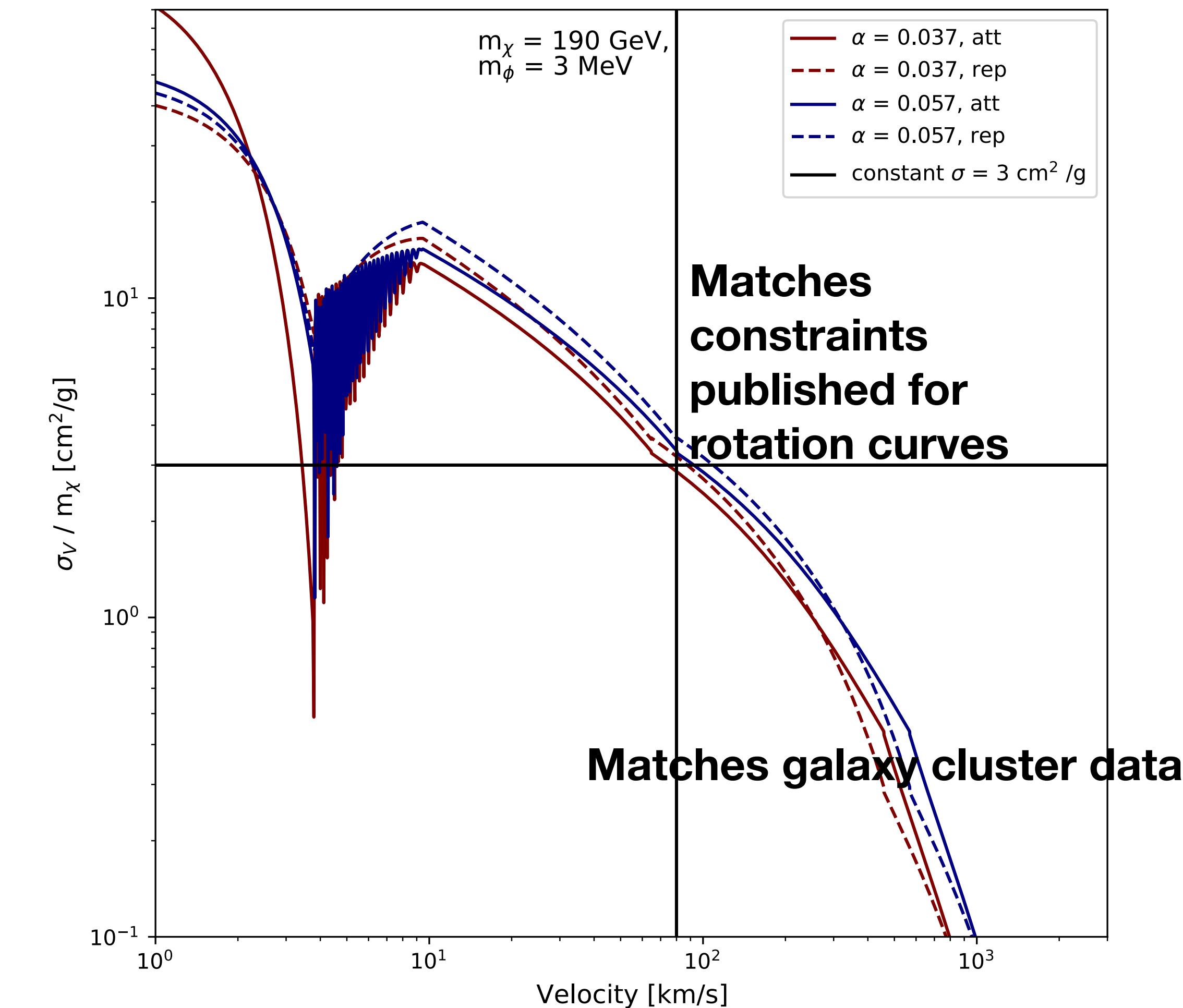
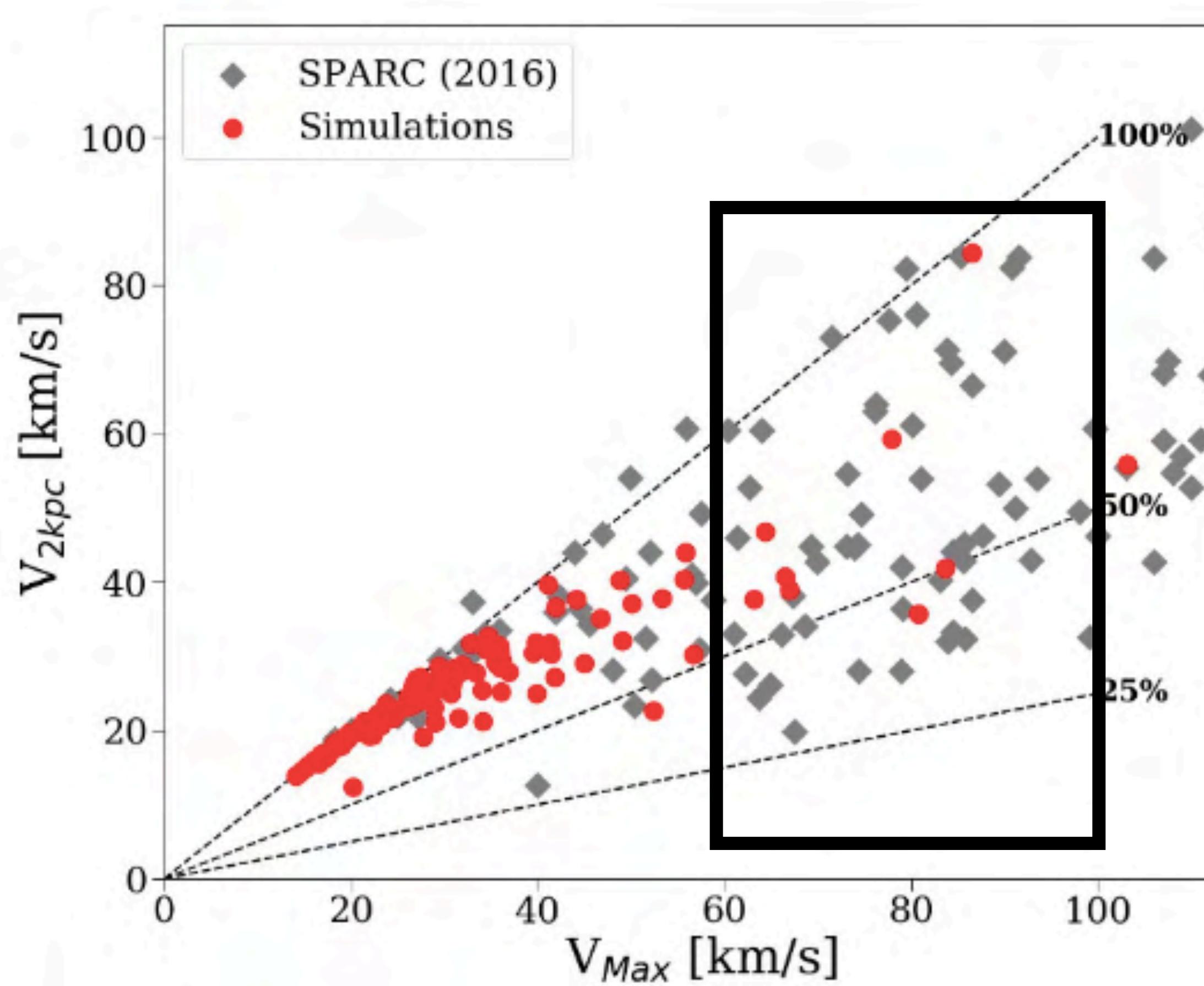
Figure by J. Van Nest

Funded NSF proposal to study SIDM in zooms

SIDM Dwarfs: smoking gun in rotation curves?

New velocity dependence based on latest literature

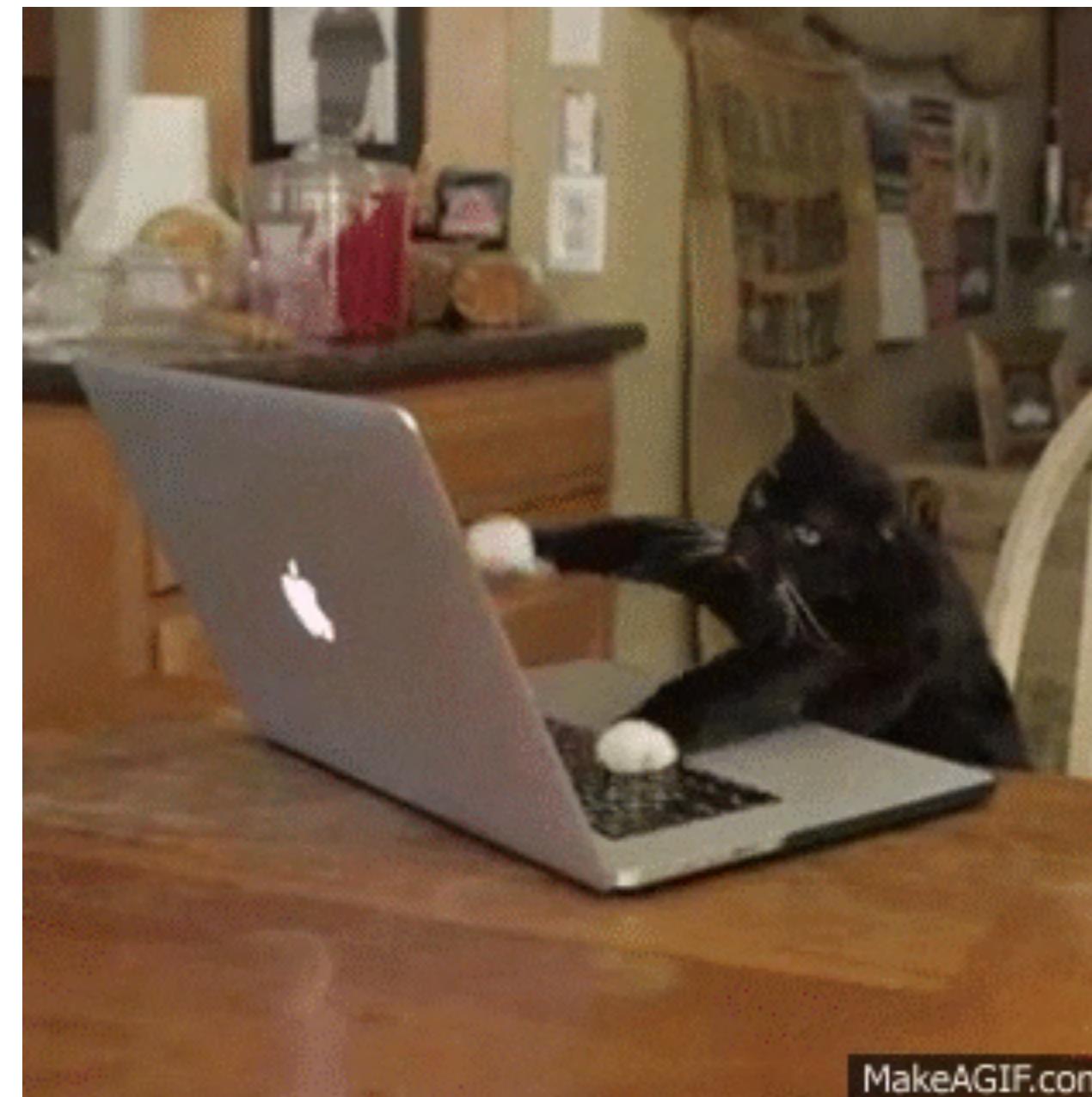
New CDM/SIDM dwarfs fill in parameter space



Funded NSF proposal to study SIDM in zooms

Key Problem #2

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



Working on it!



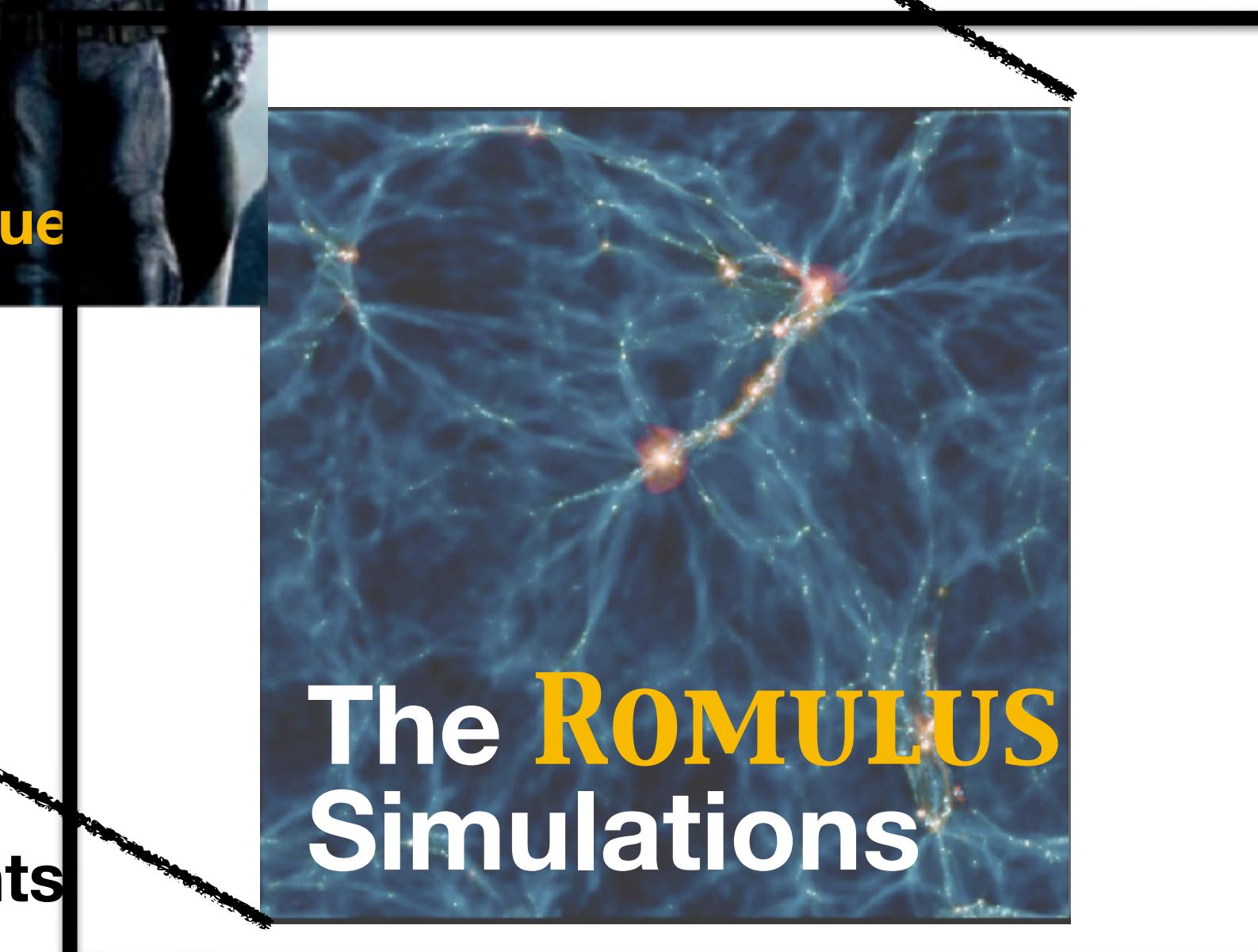
MARVELous Dwarfs

Ultra-faints in isolation

Ultra-faints in the vicinity of a MW



The ROMULUS
Simulations



Dwarfs (and UDGs) across environments

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

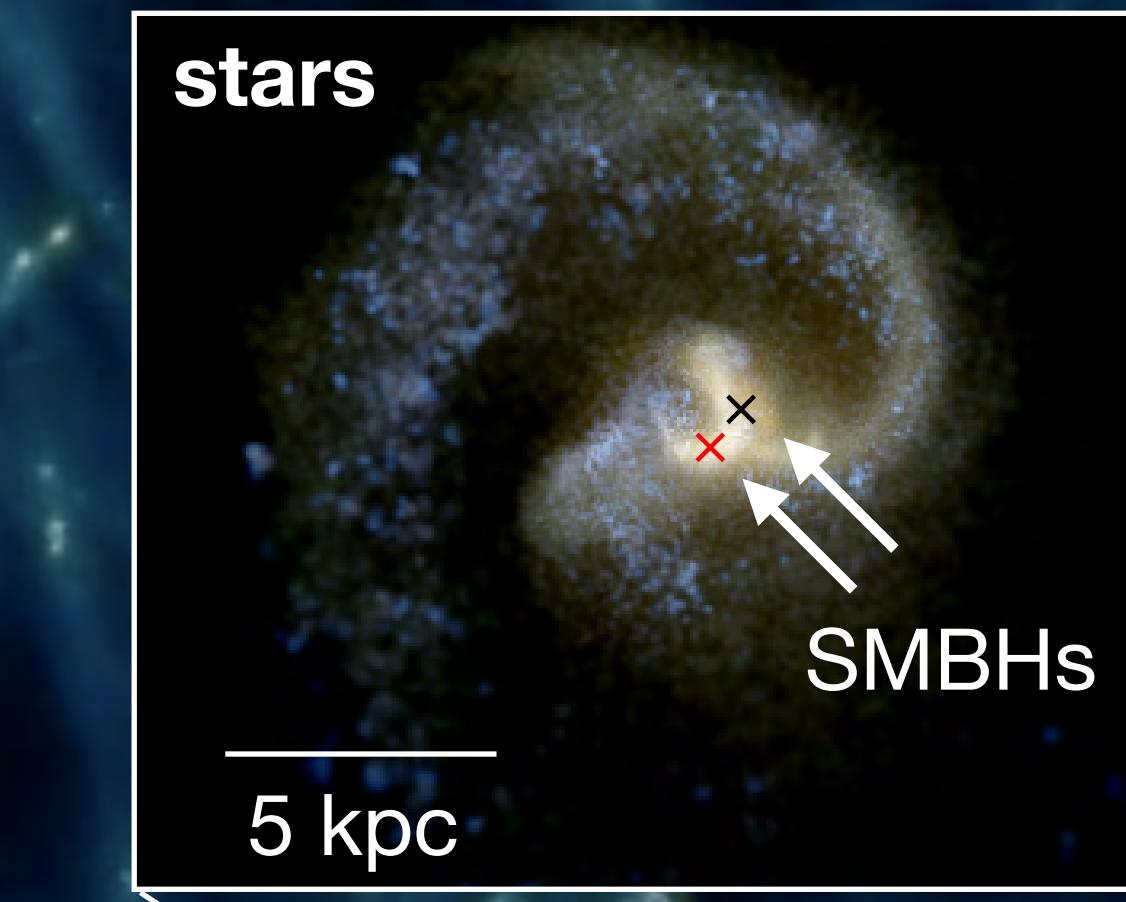
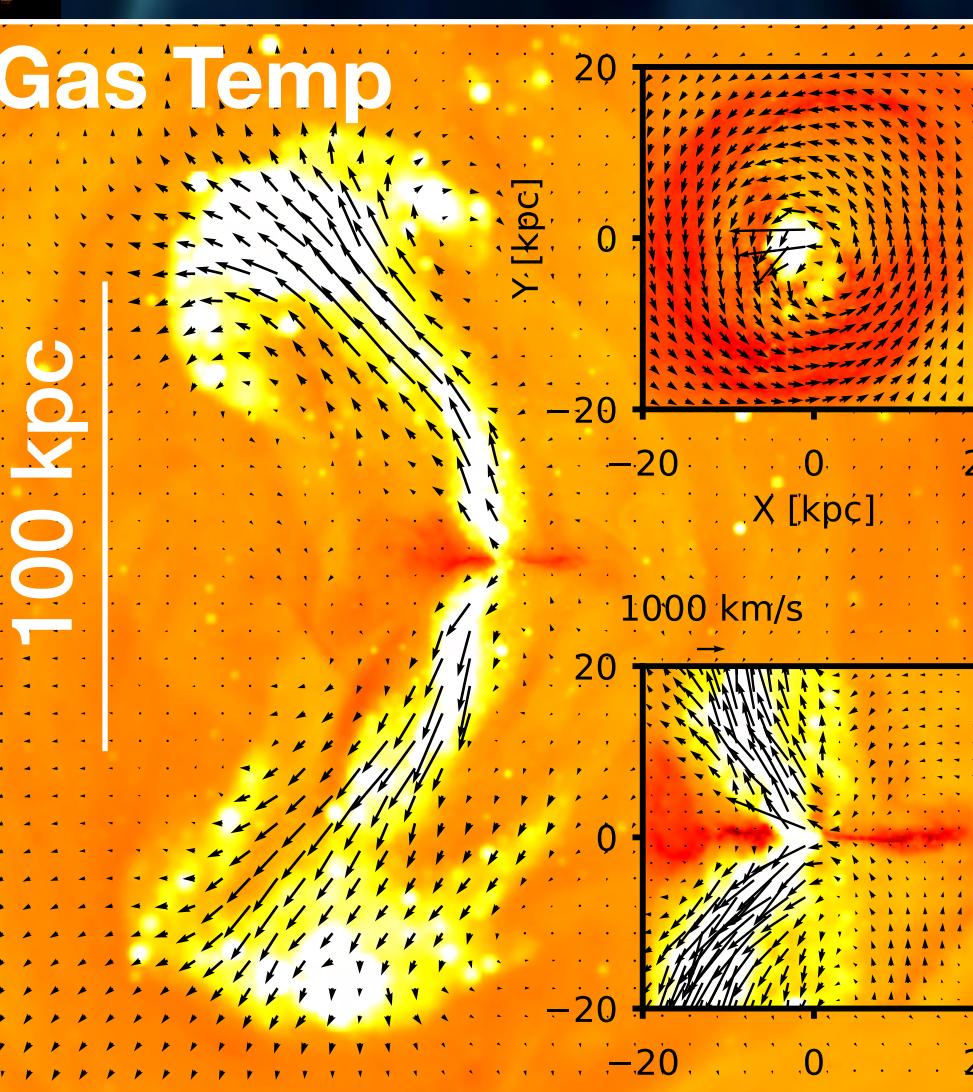
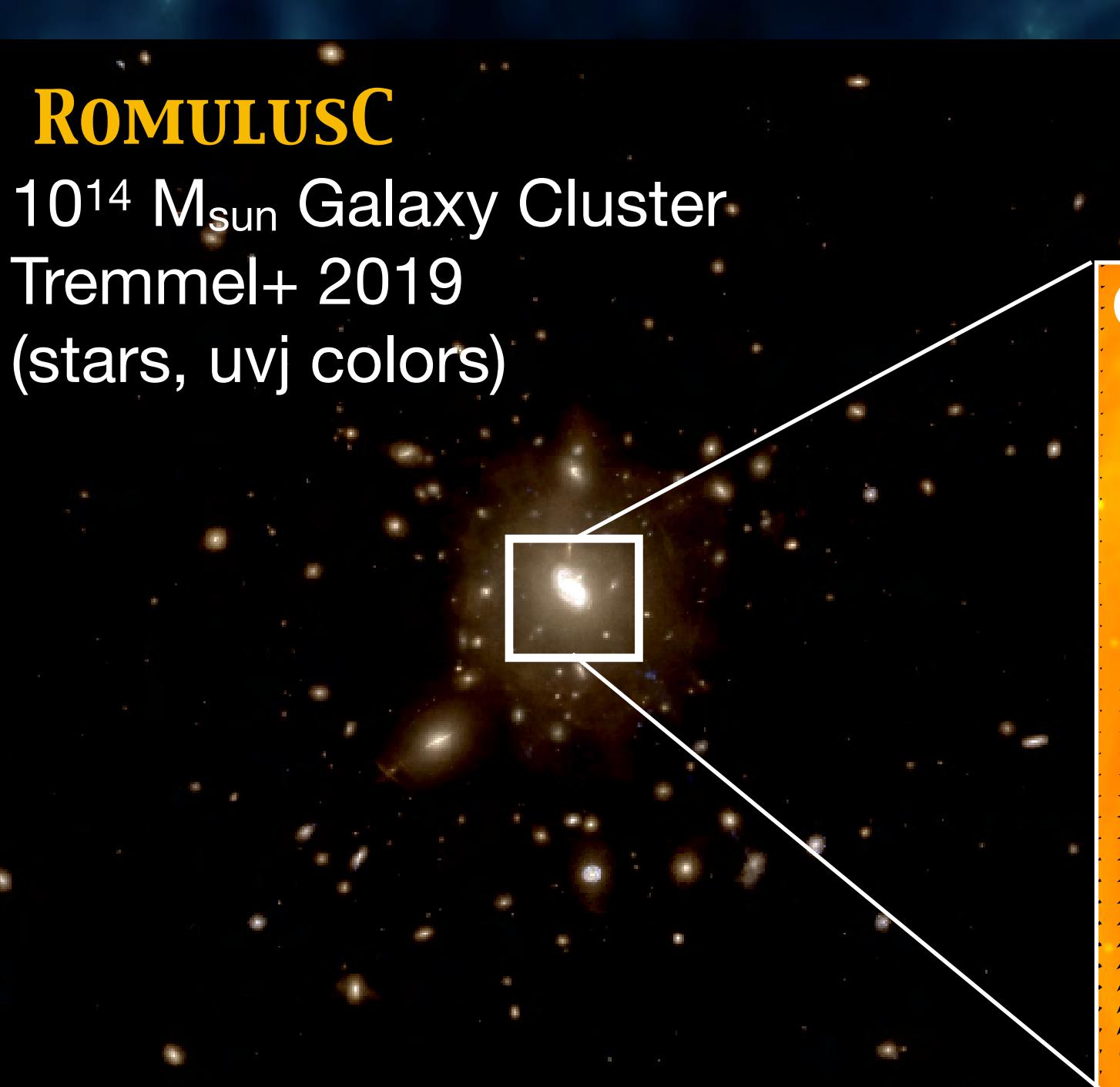
The ROMULUS Simulations

Certified organic, free-range, locally grown supermassive black holes

- ✓ Early Seeding in low mass halos
- ✓ Self-consistent and physically motivated dynamics, growth, and feedback
- ✓ Naturally produces large-scale outflows
- ✓ **No unnecessary additives or assumptions**

ROMULUS25

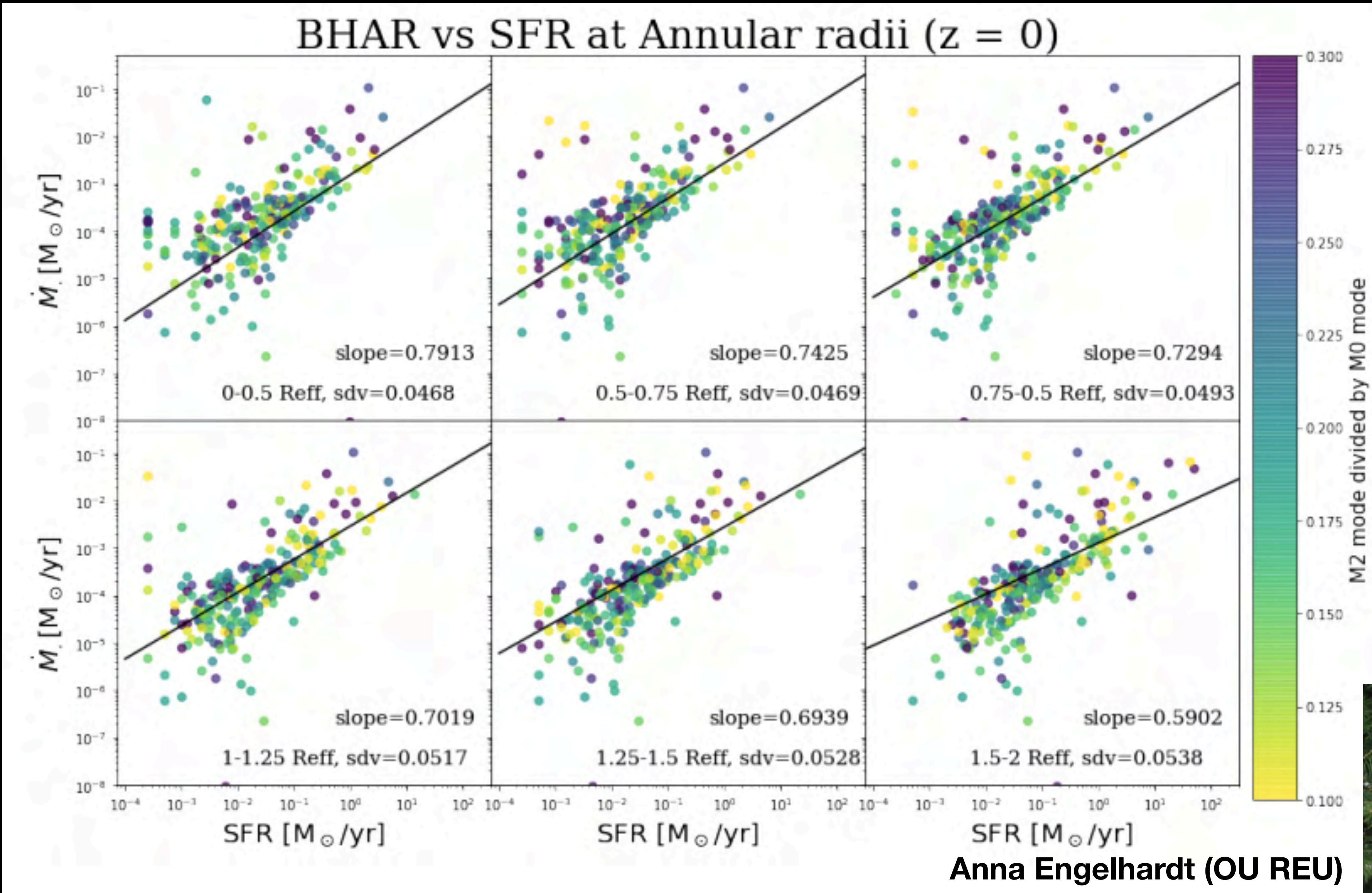
25 Mpc Volume
Tremmel+ 2017
(gas temp)



Resolution:
250 pc (grav)
70 pc (hydro)
 $\sim 1 \times 10^5 \text{ M}_{\odot}$

CHANGA

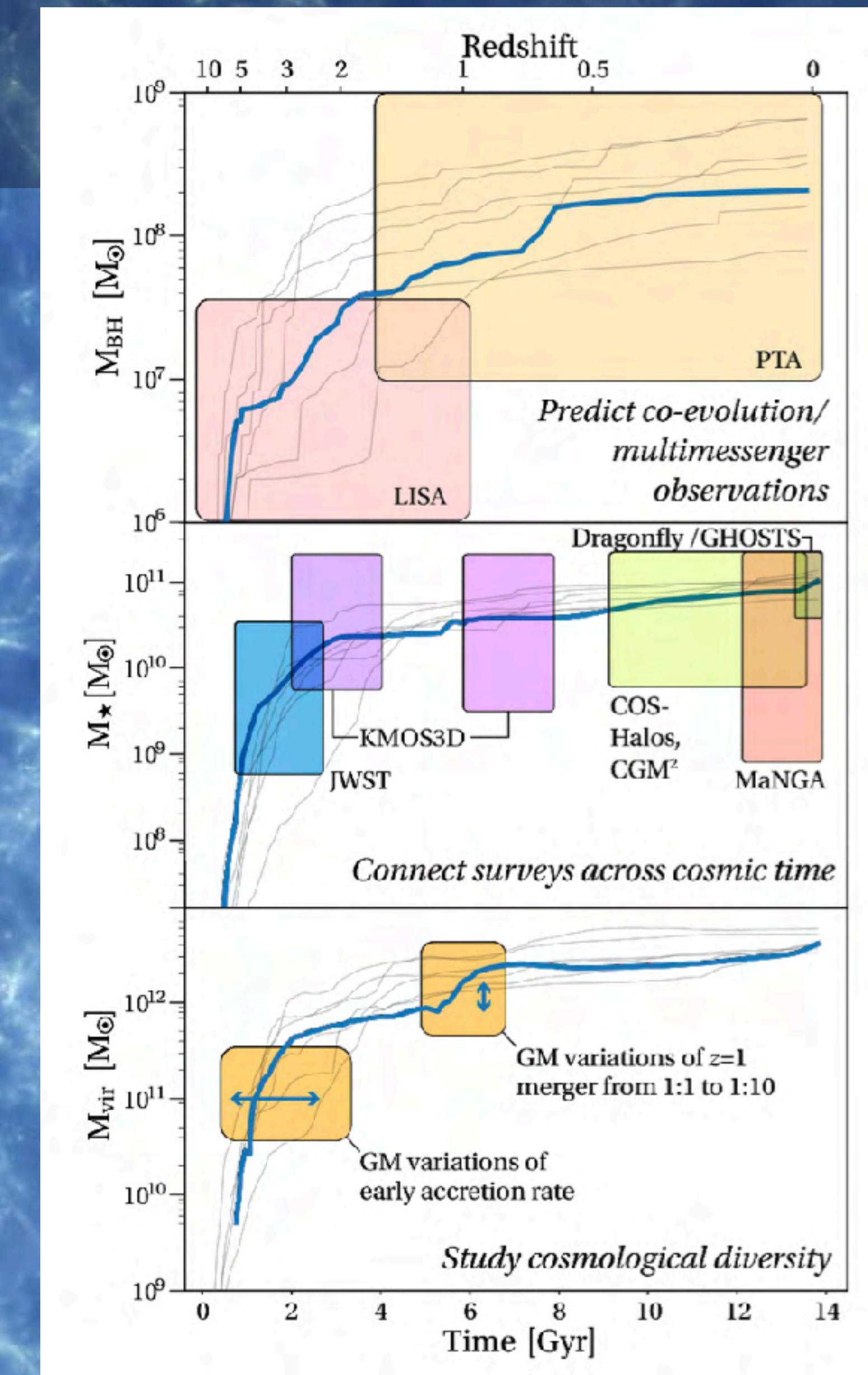
What role do galaxy bars play in SMBH accretion rate?



Research Synergy with Wayne State Physics & Astronomy: Unique implementation for BH seeding and feedback in both zooms and volumes-predictions for feedback, galaxy co-evolution!

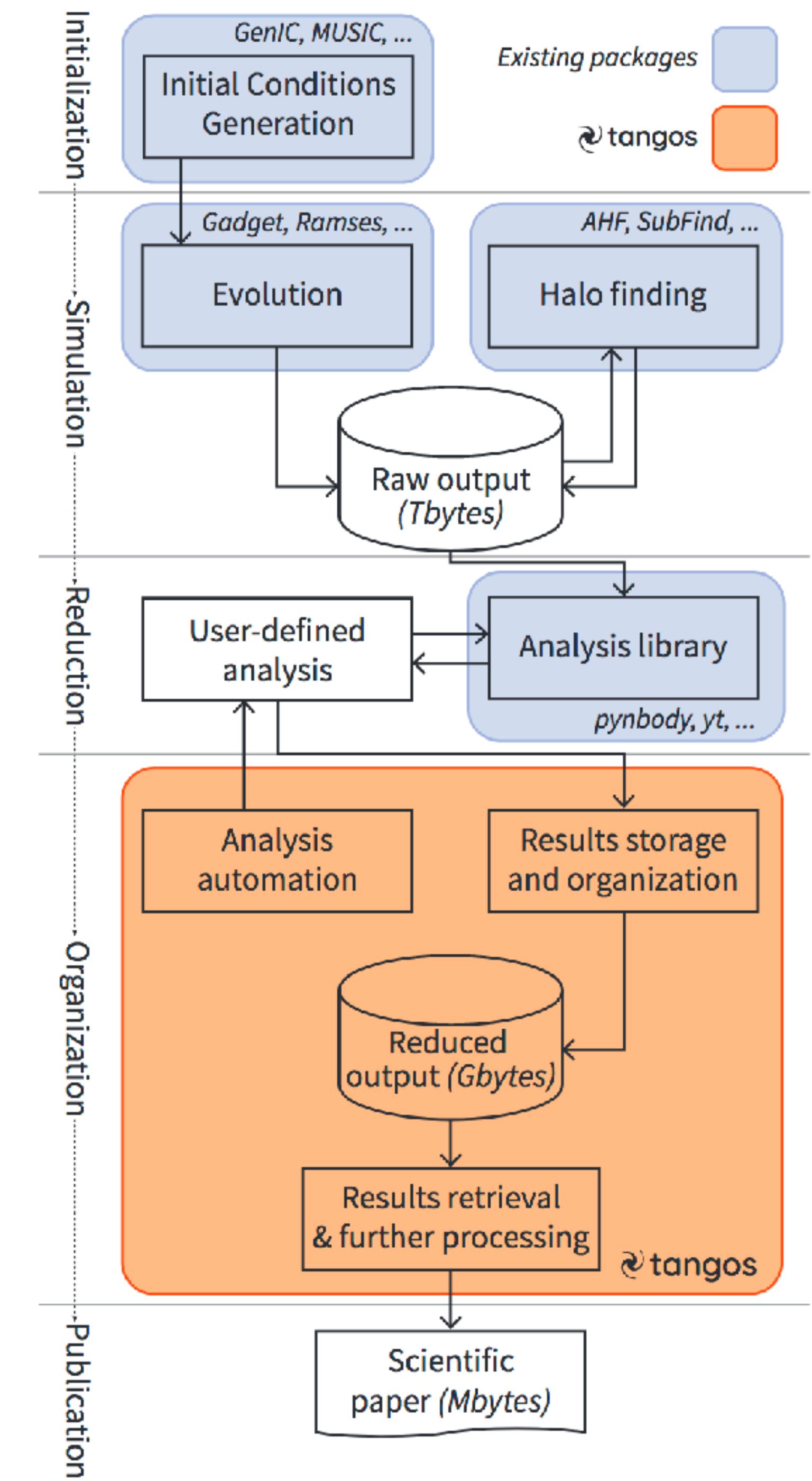


Cosmological simulations connect high redshift to low redshift and can give self-consistent predictions for SMBH growth and merger rates, as well as host galaxy properties (including DM distributions, assembly)!



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.

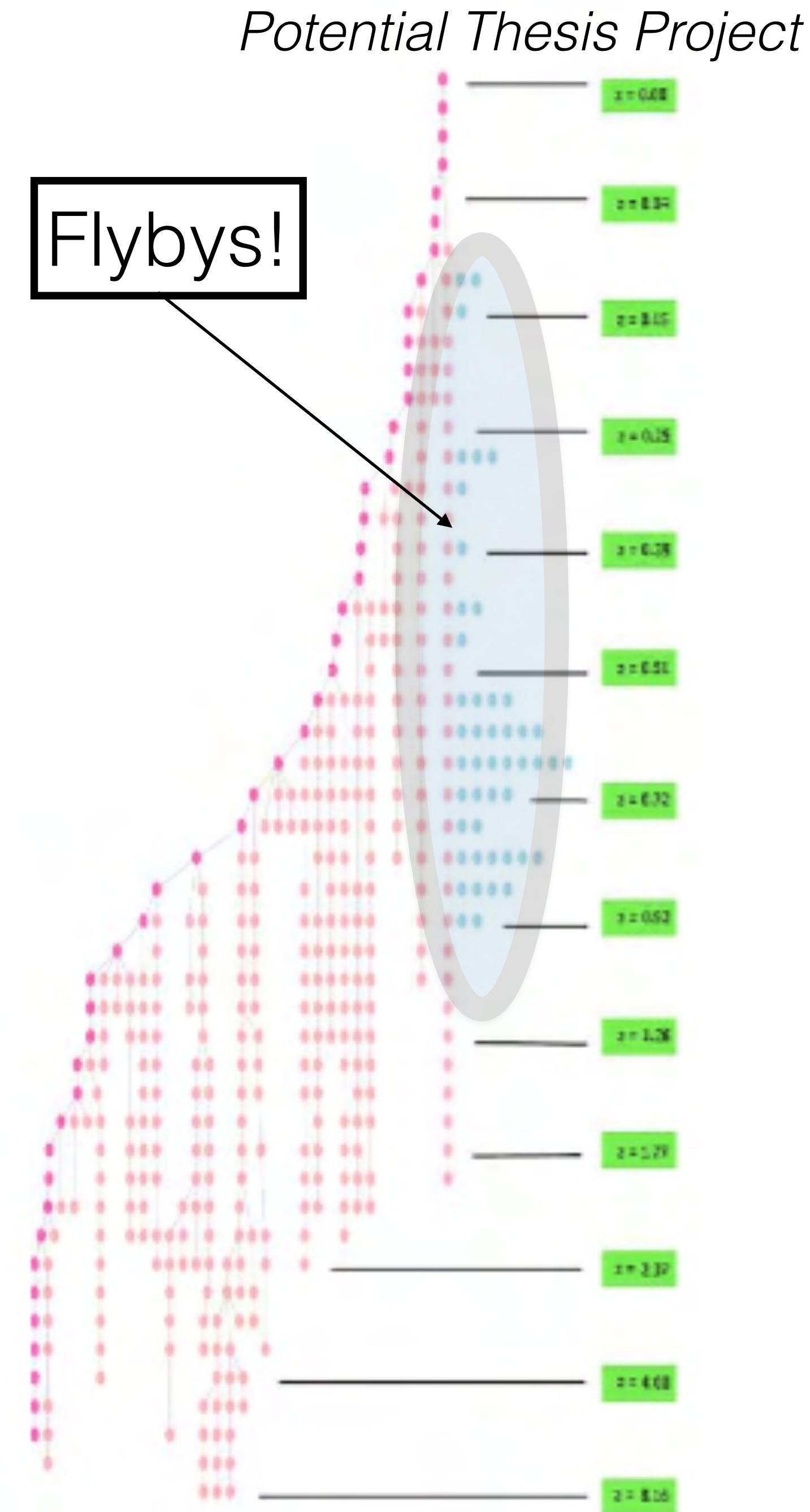


Leveraging “Big Data” techniques

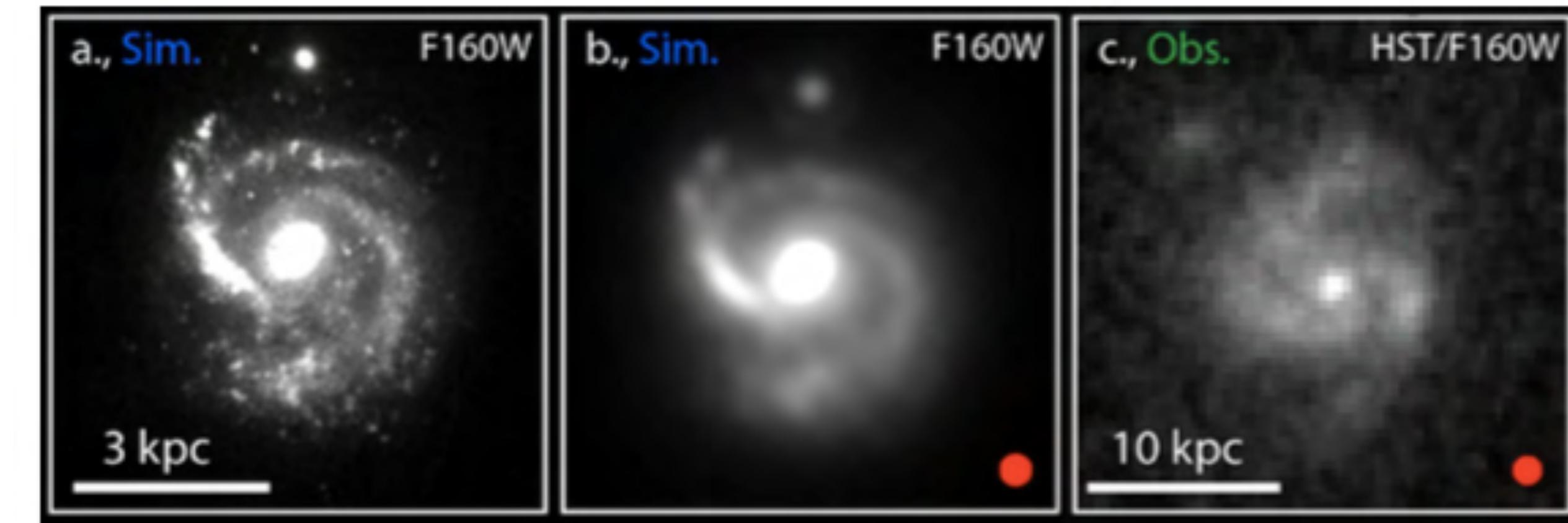
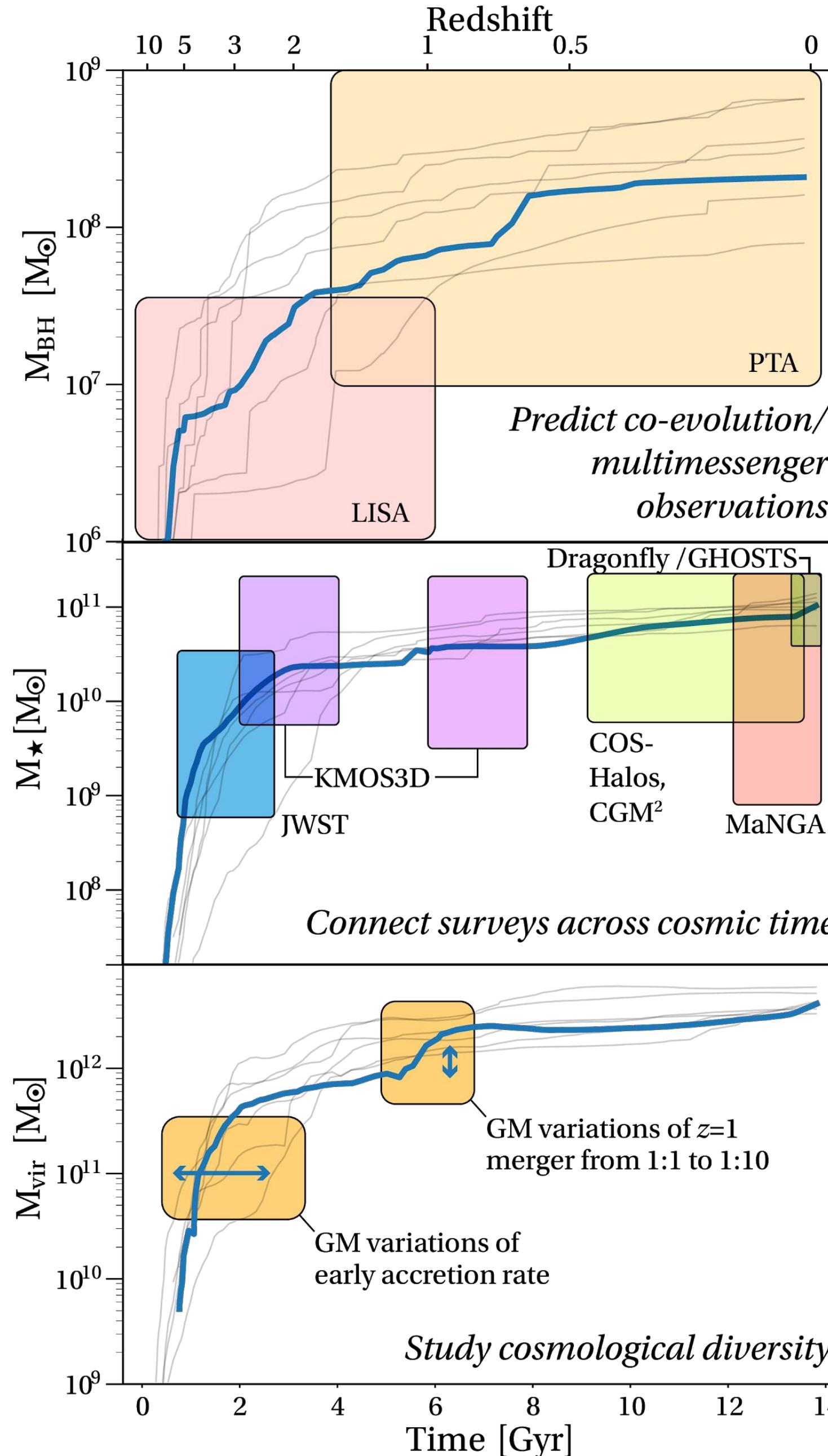
Machine Learning on Simulation Outputs-
Decision Tree Machine Learning: Romulus25 studies can leverage machine learning techniques since the sample of galaxies is enormous.

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



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.

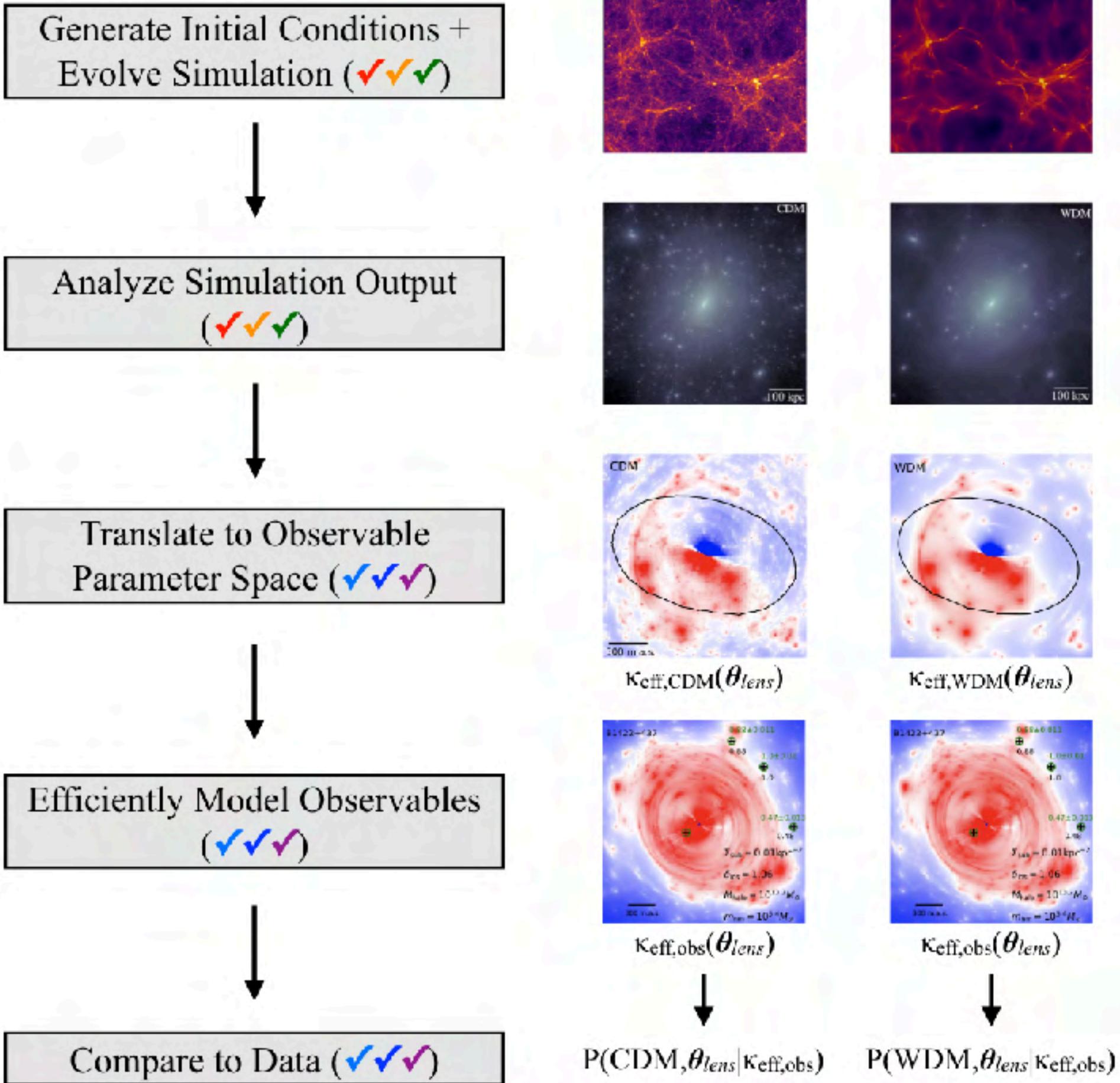
In the context of DM: a larger sample of UFDs, wandering BHs in dwarfs **in the environment of a MW** —> more robust constraints for Rubin, Roman, JWST

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 galaxy formation 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, Chikasaw and Patowatomi Peoples.



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

**Bonus Content
begins here**

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

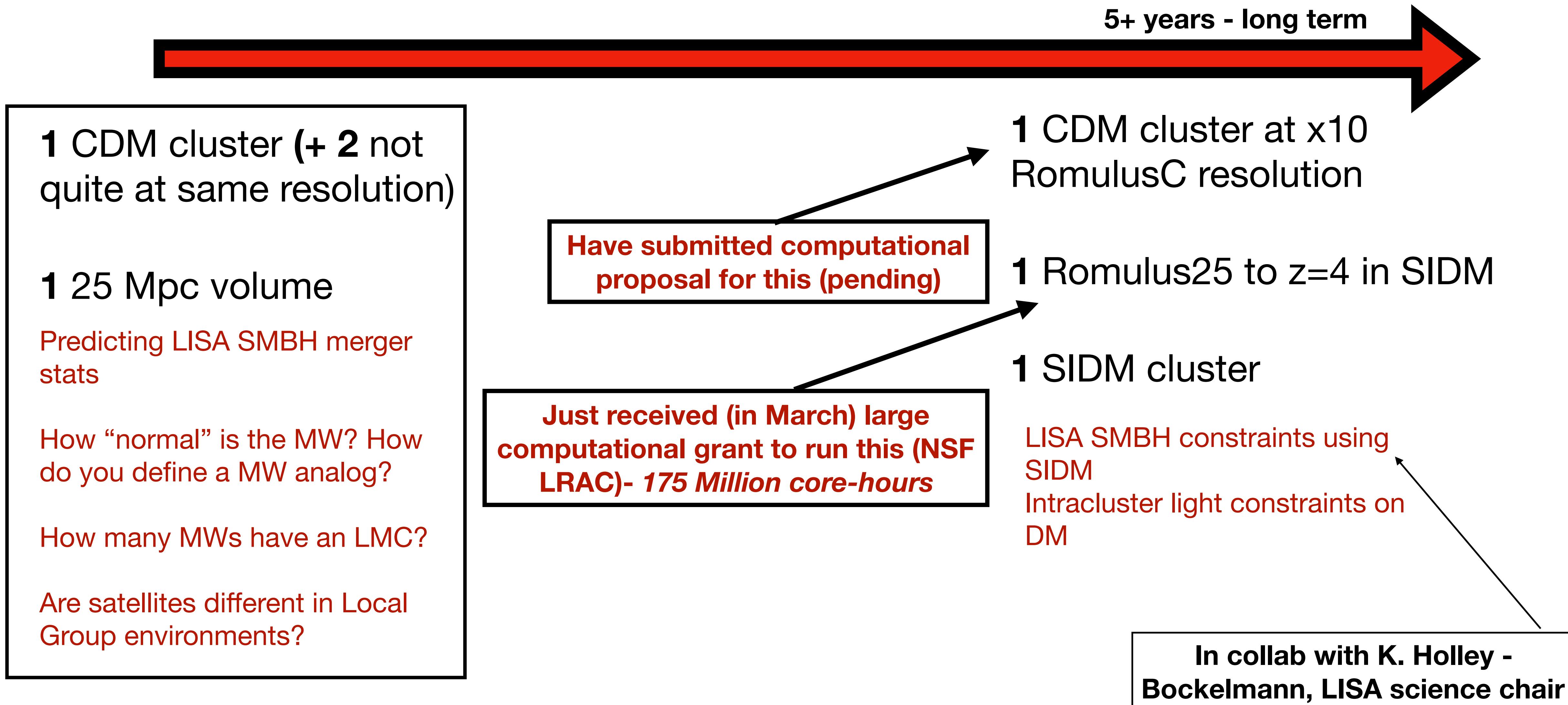
Have current computational grant to run
these MWs (NSF LRAC)- *currently
running*

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

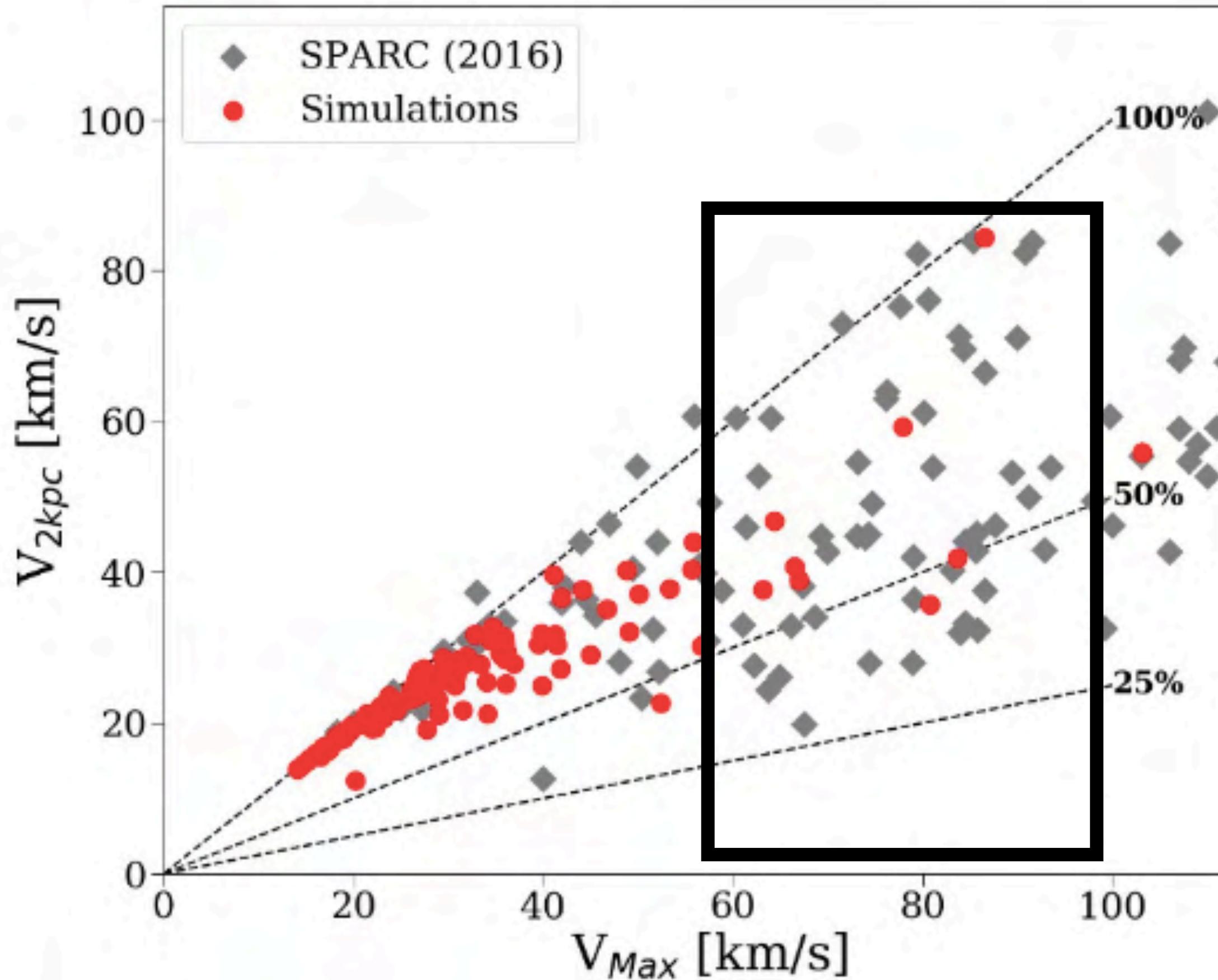
2 MW mass galaxies in SIDM
(+satellites)

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

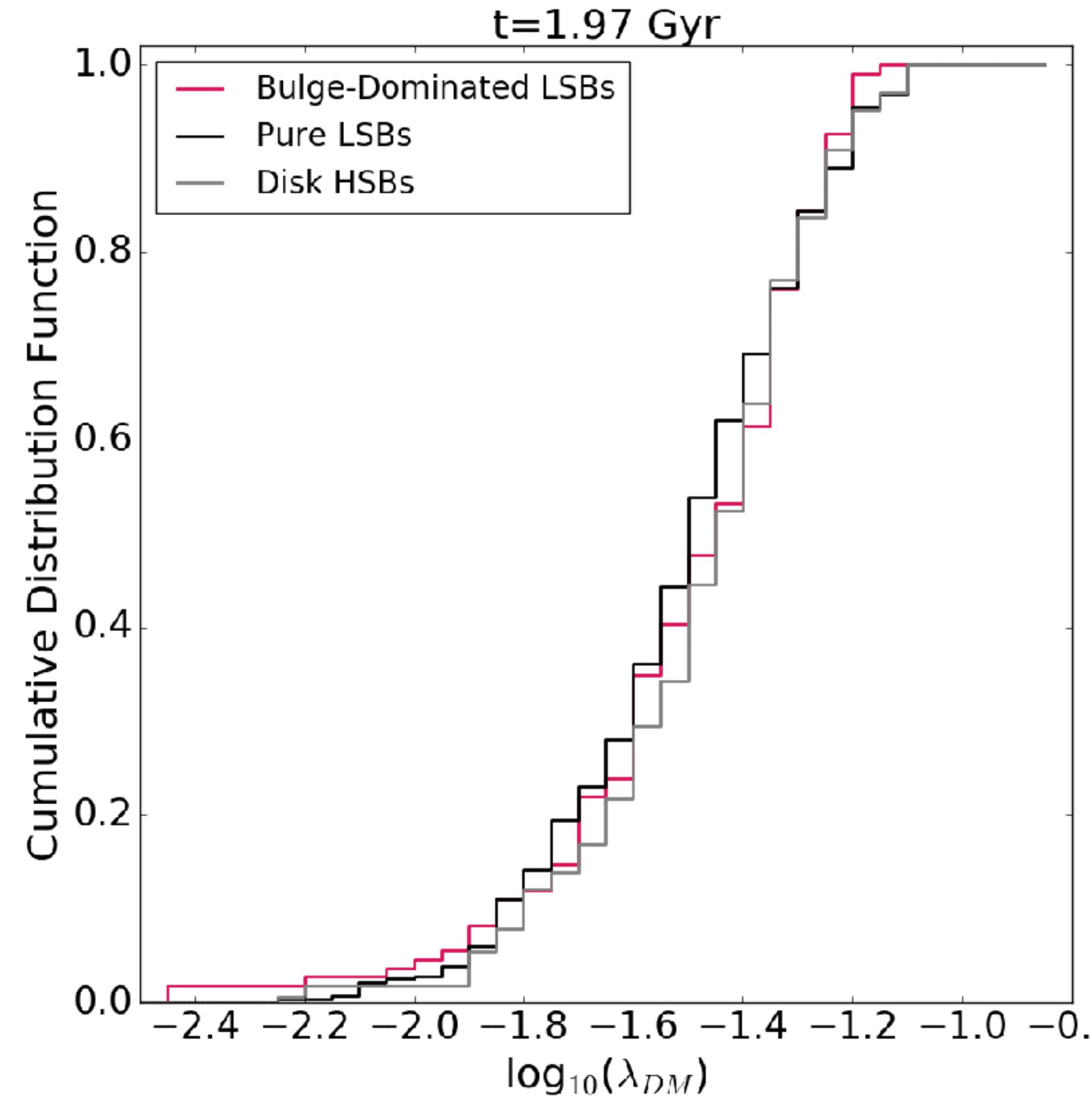
New CDM/SIDM dwarfs fill in parameter space

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

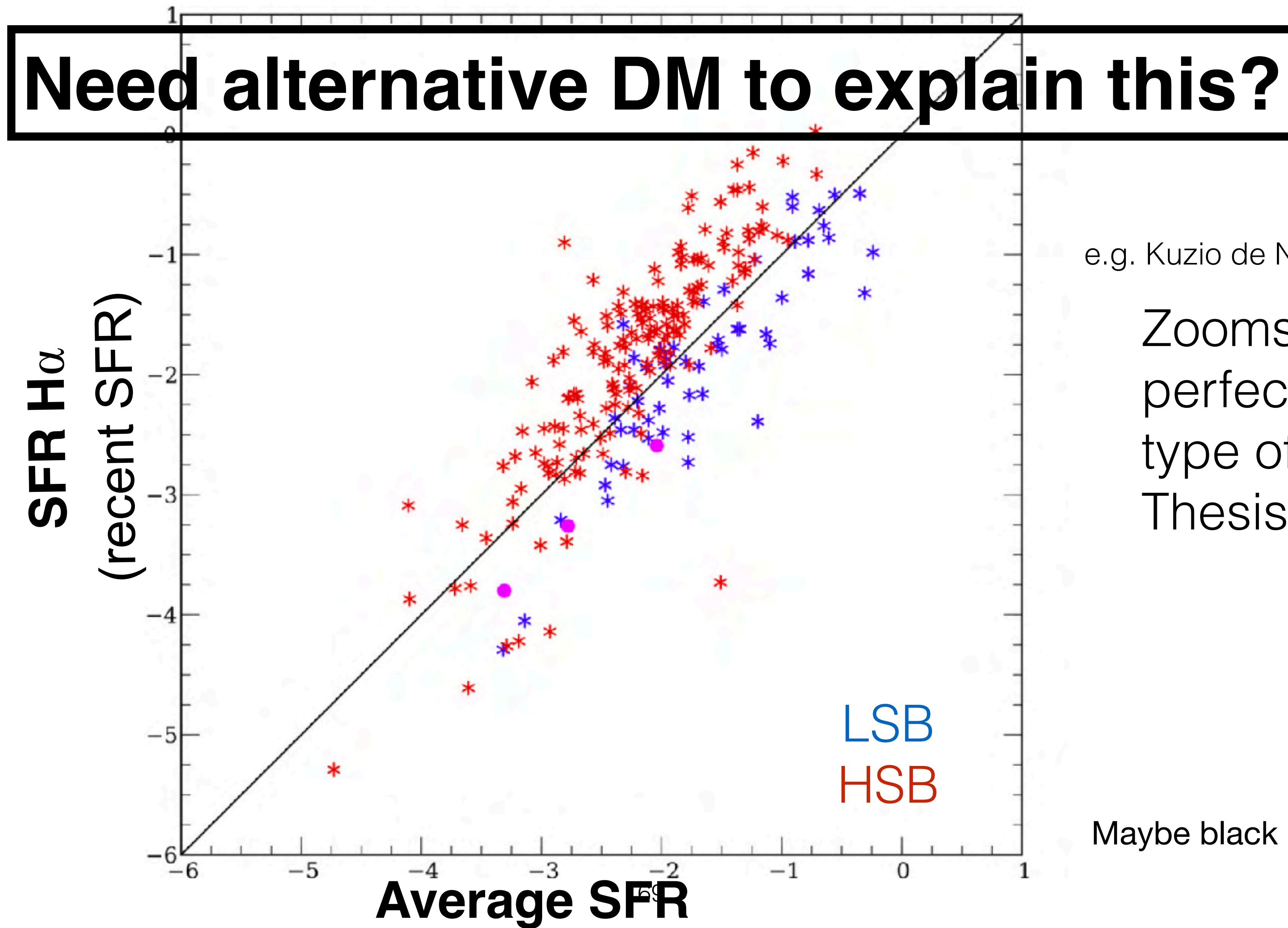
- Massive LSBs have cored profiles, but do not have bursty SFHs
- Romulus cannot resolve core-formation ==> need zooms!



In collaboration with A.
Wright (JHU/STScI)

e.g. Malin 1

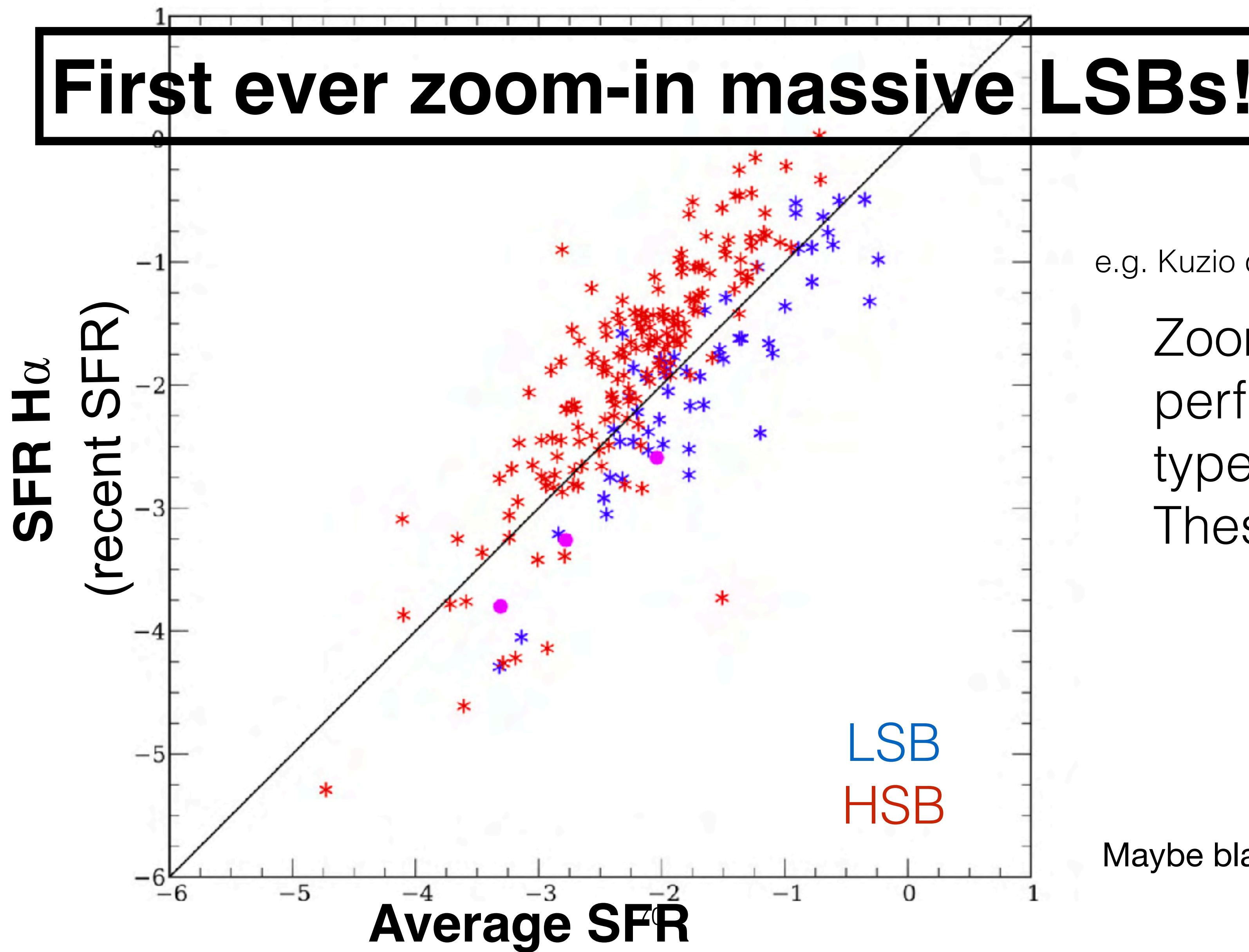
LSB zoom-in simulations



e.g. Kuzio de Naray + (2010)

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

LSB zoom-in simulations



e.g. Kuzio de Naray + (2010)

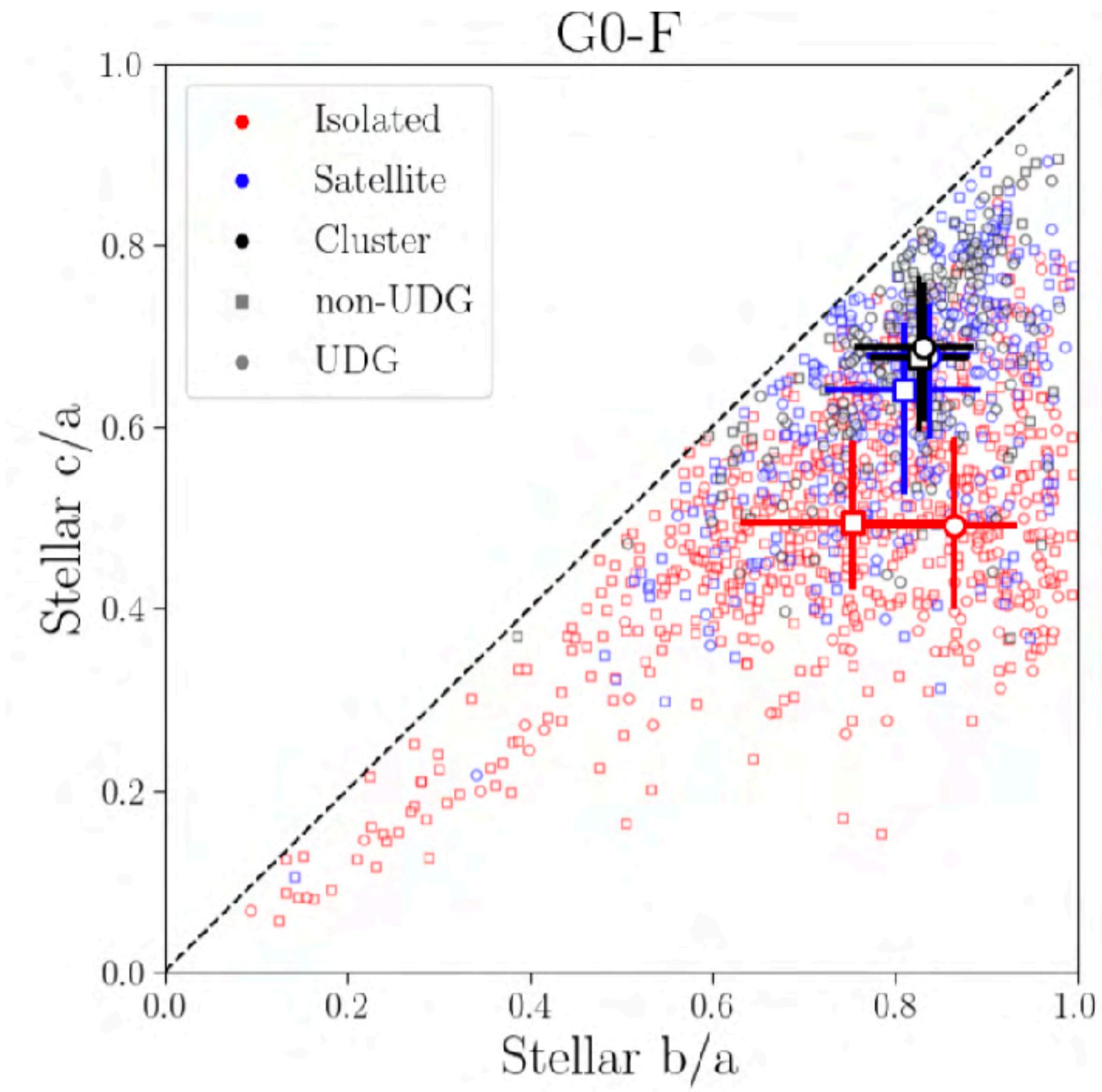
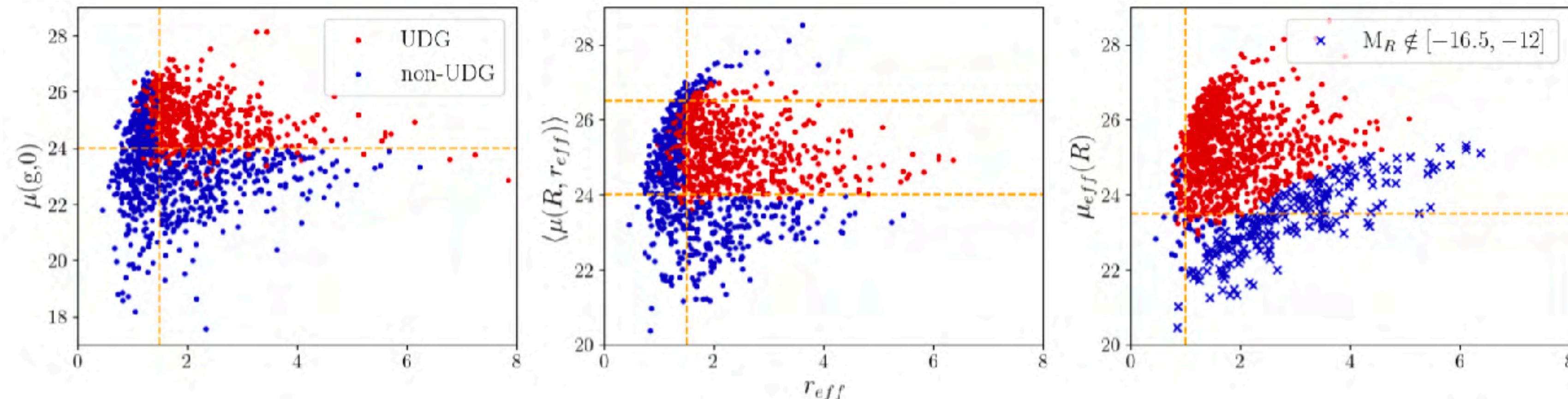
Zooms are
perfect for this
type of study!
Thesis project!

Maybe black holes?

The Low Surface Brightness Universe: UDGs

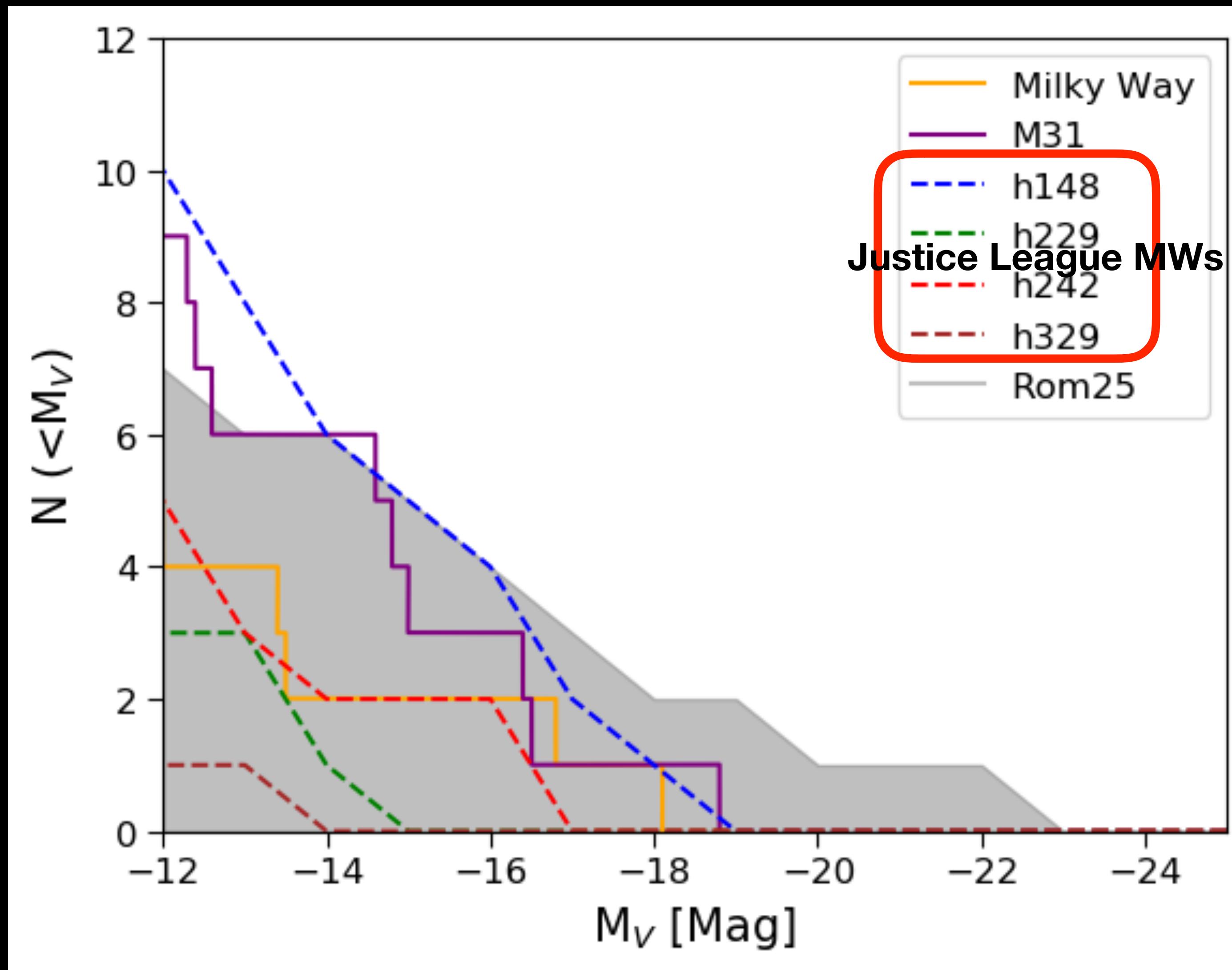
How do they form? Are they really a distinct population? What do their DM halos look like?

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

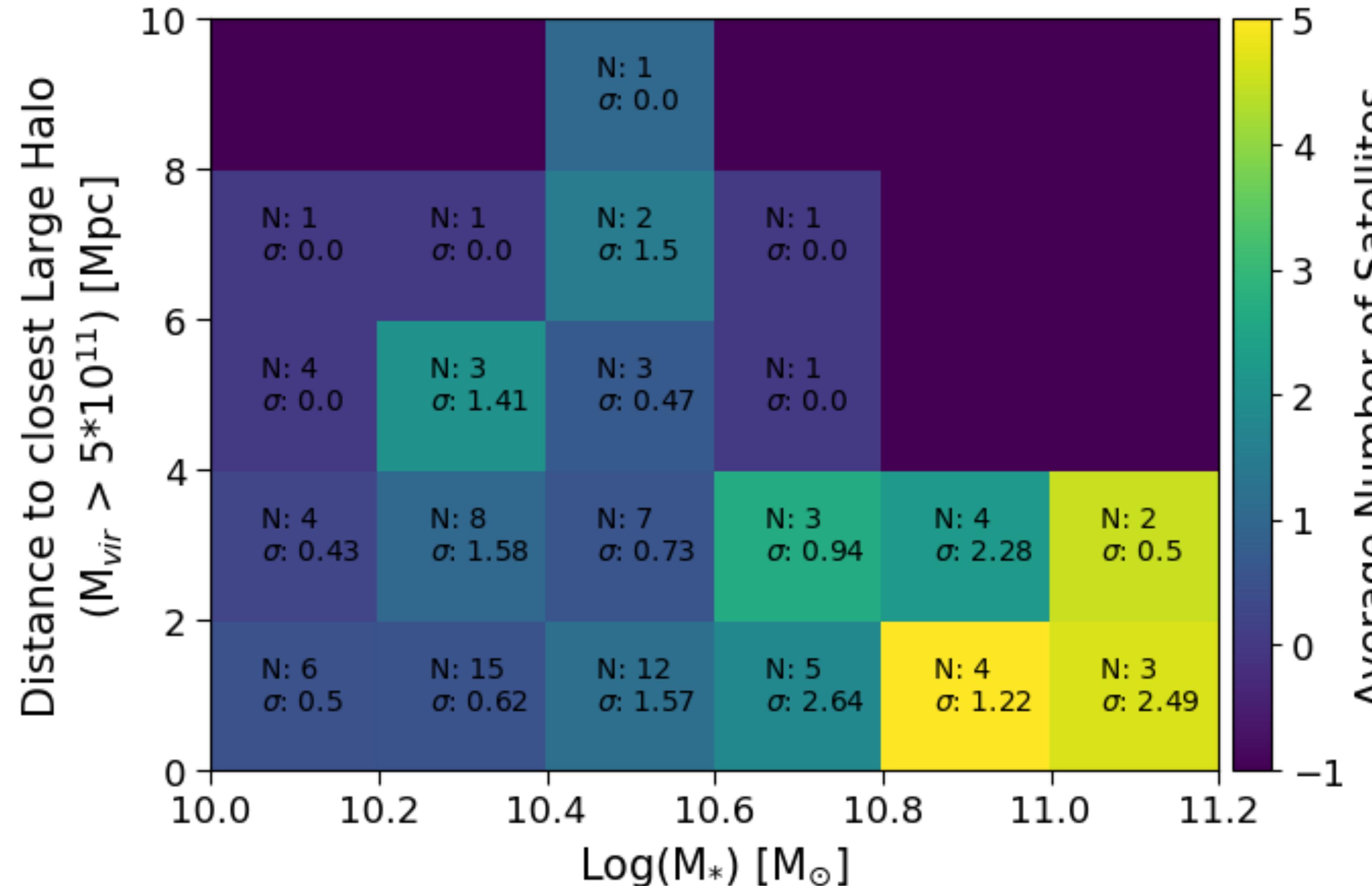


My current graduate student Jordan Van Nest has had his first paper accepted on this work.

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

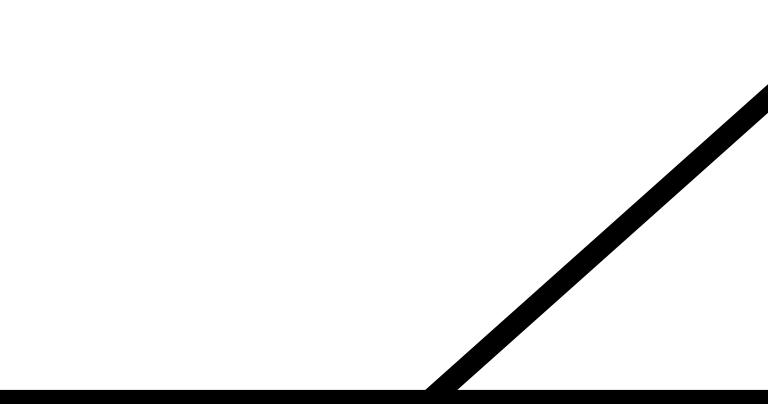
Different star formation/feedback methods

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

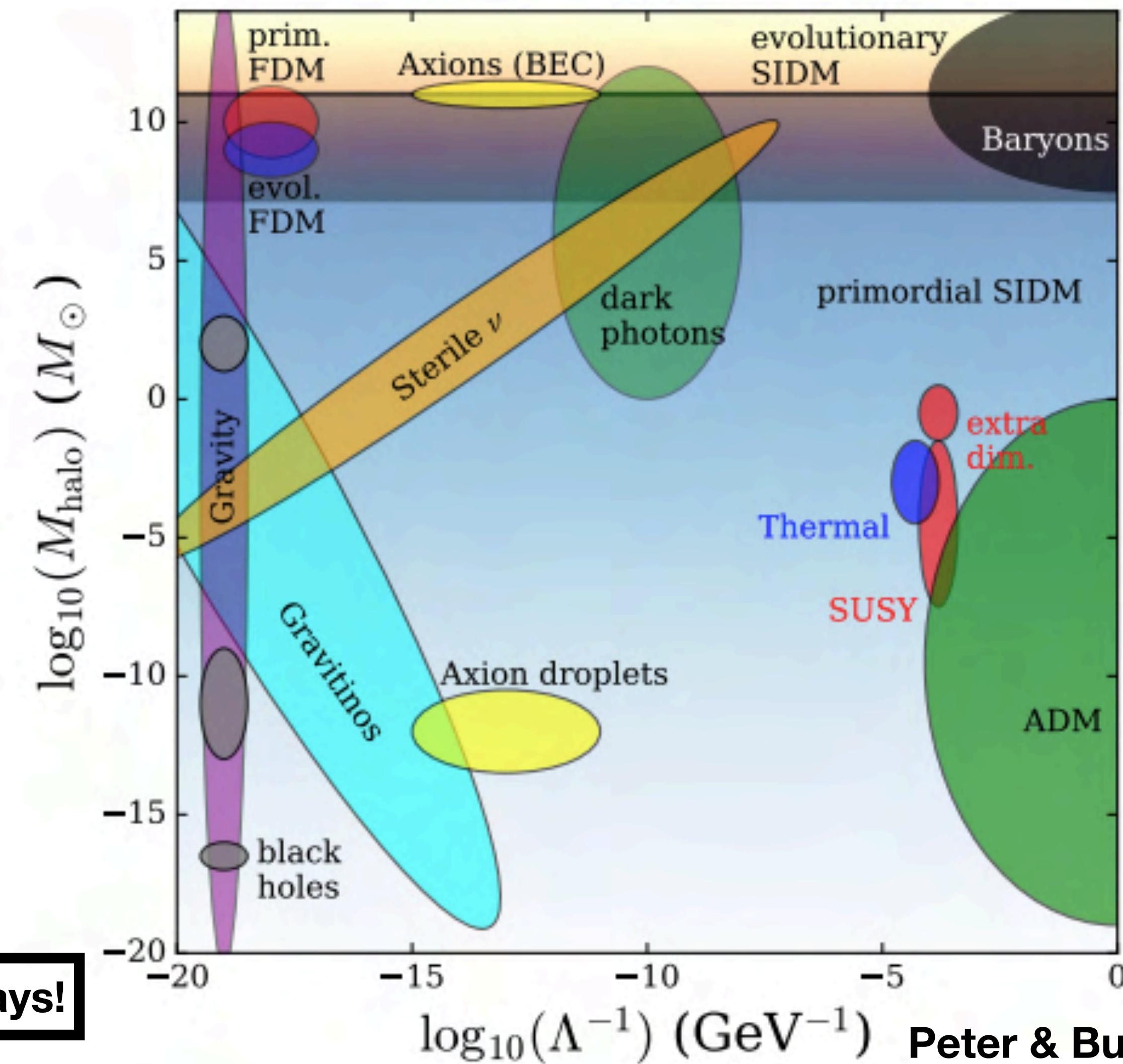
Radiative transfer being developed- can contribute

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



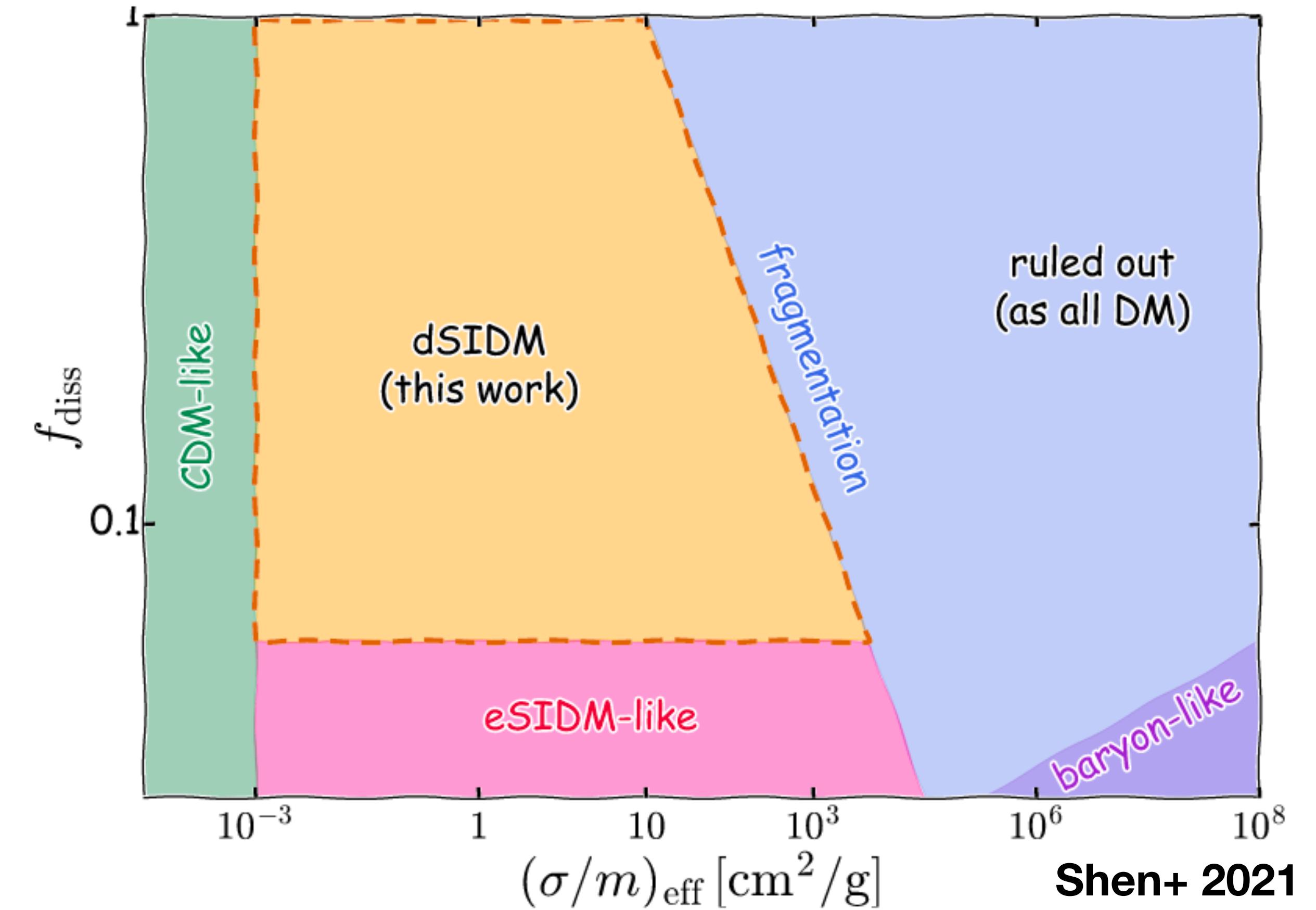
Complementary to dept and research in gamma rays!



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)
- Thesis project: implement DM self-annihilation at high z



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

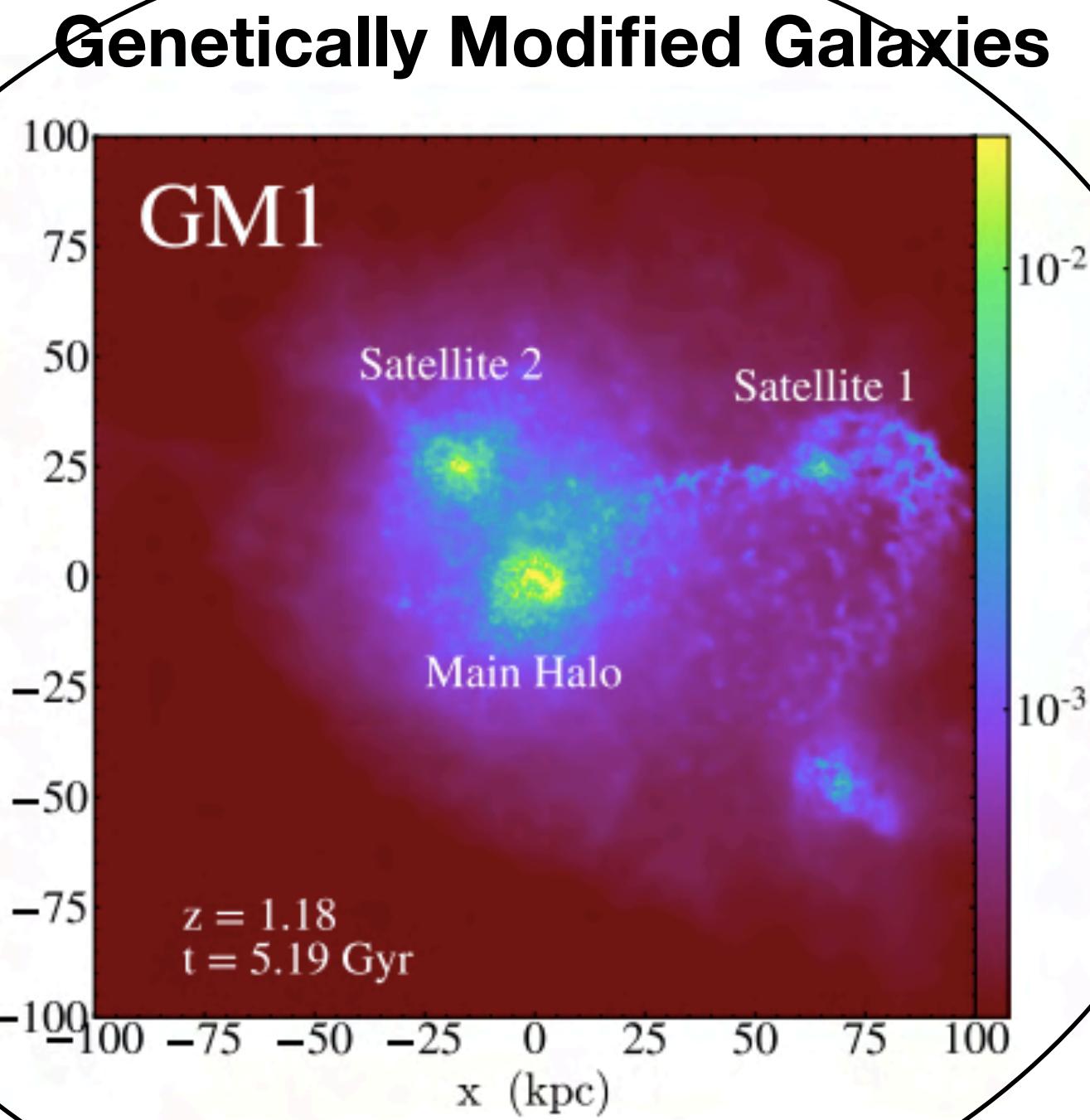
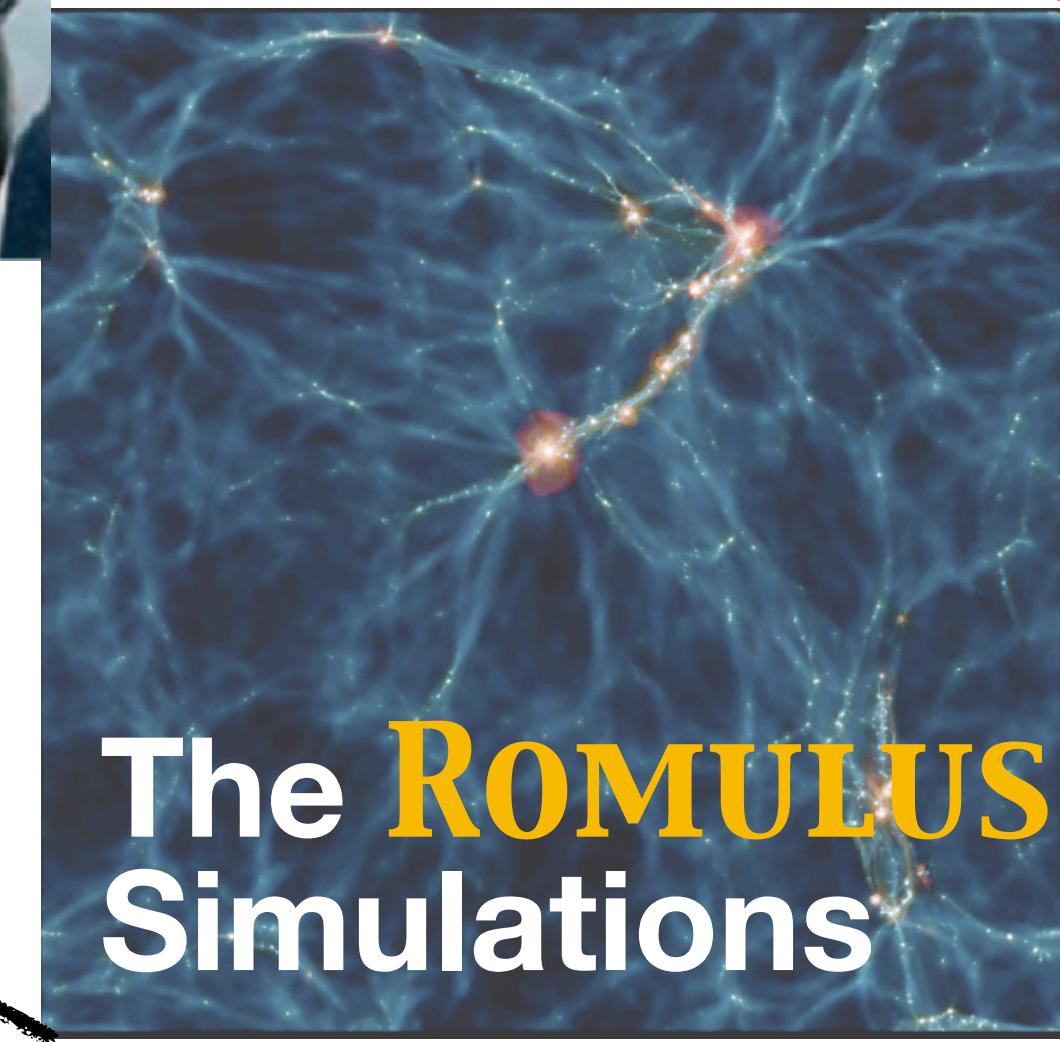
1. Enhance Dept's inclusion and equity goals
2. Broaden department's visibility both within the university and community
3. Grow diversity of both the graduate and undergraduate students in the Dept



Dwarfs in isolation

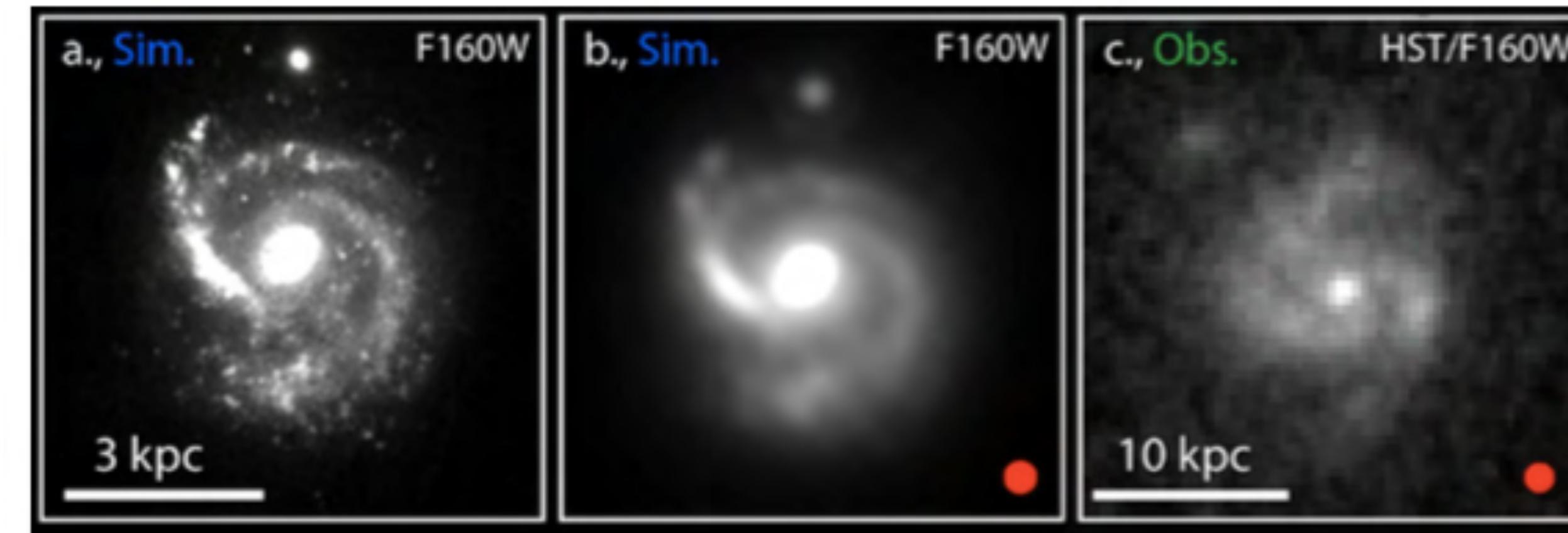
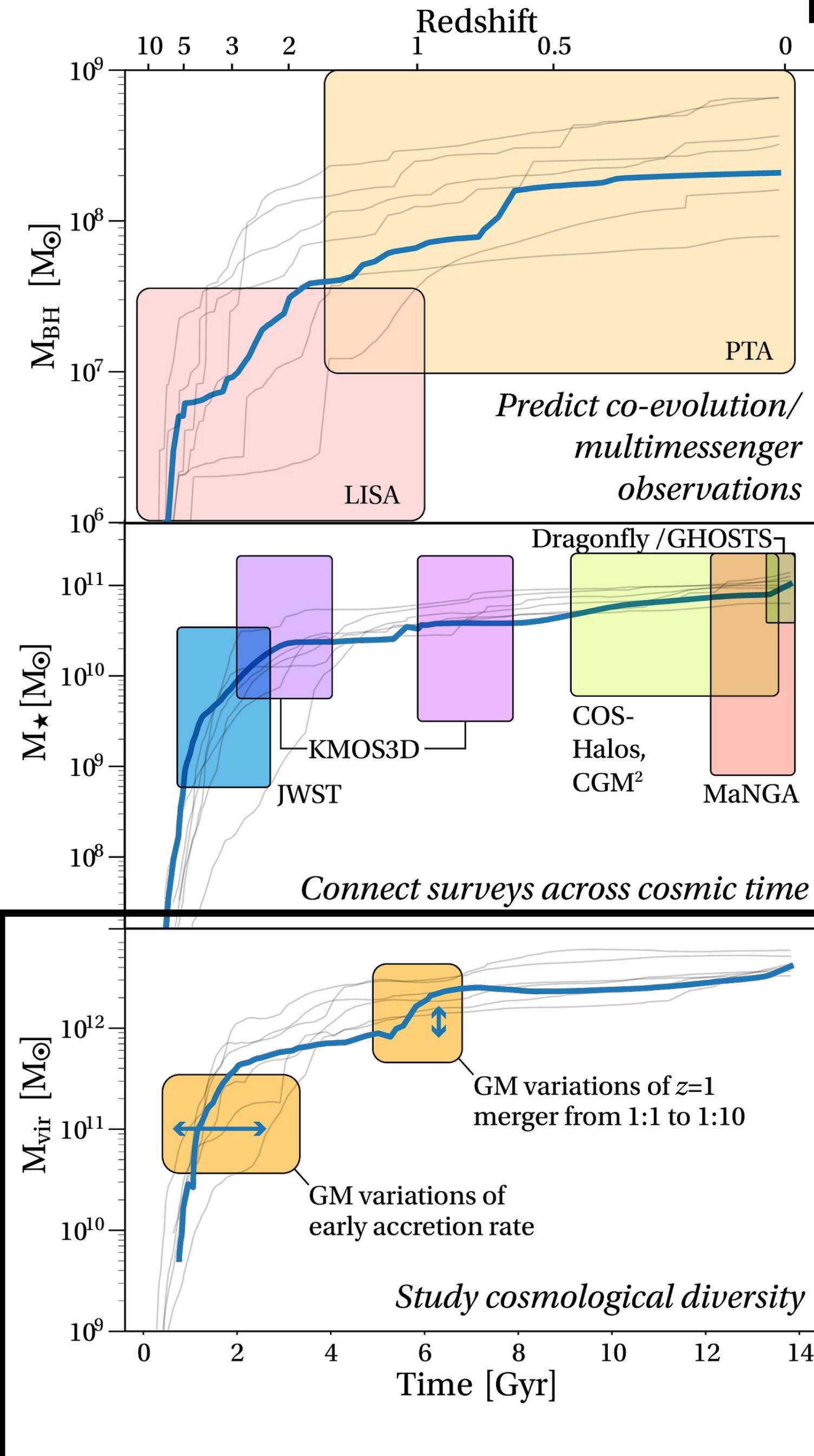


Dwarfs (and UDGs) across environments



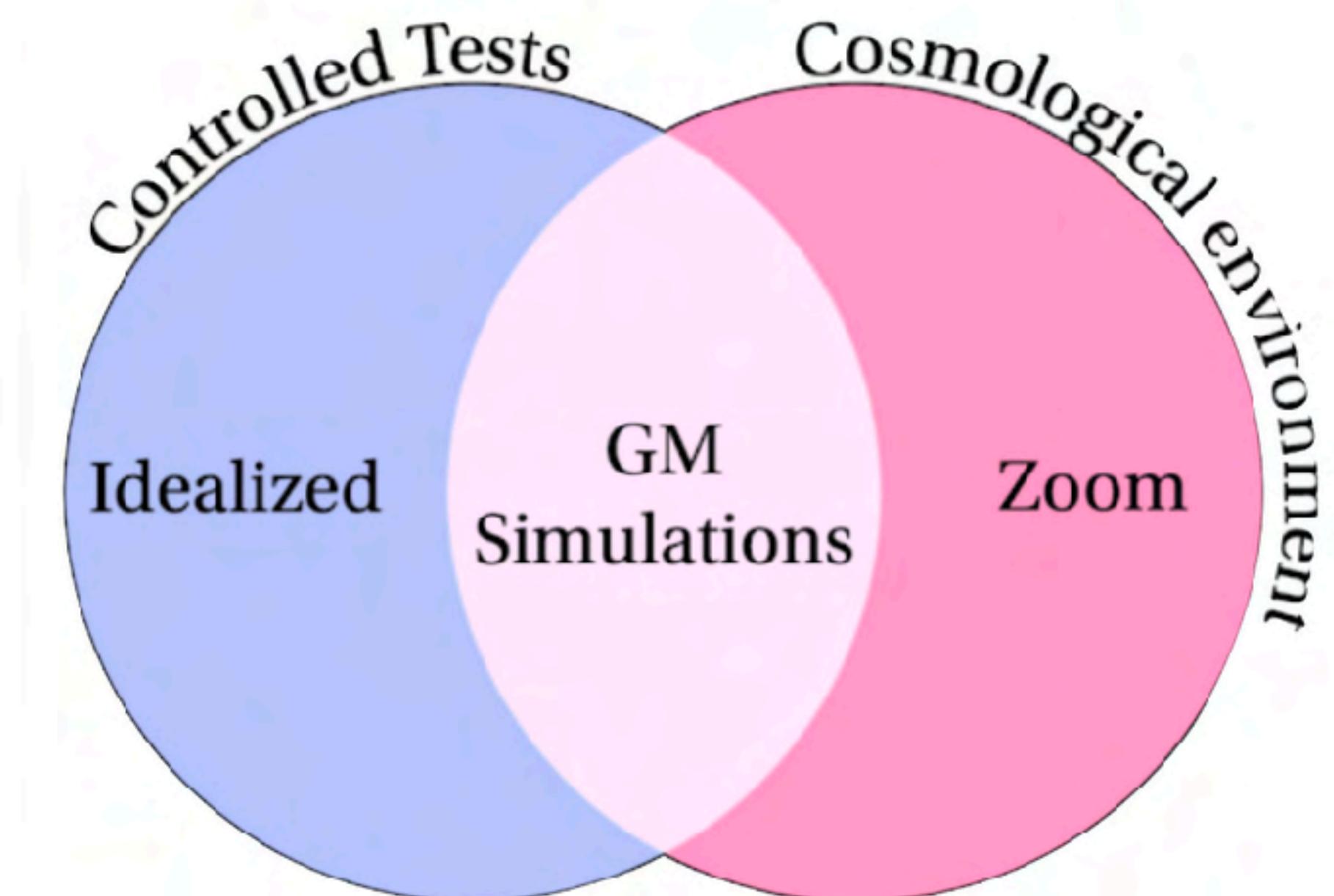
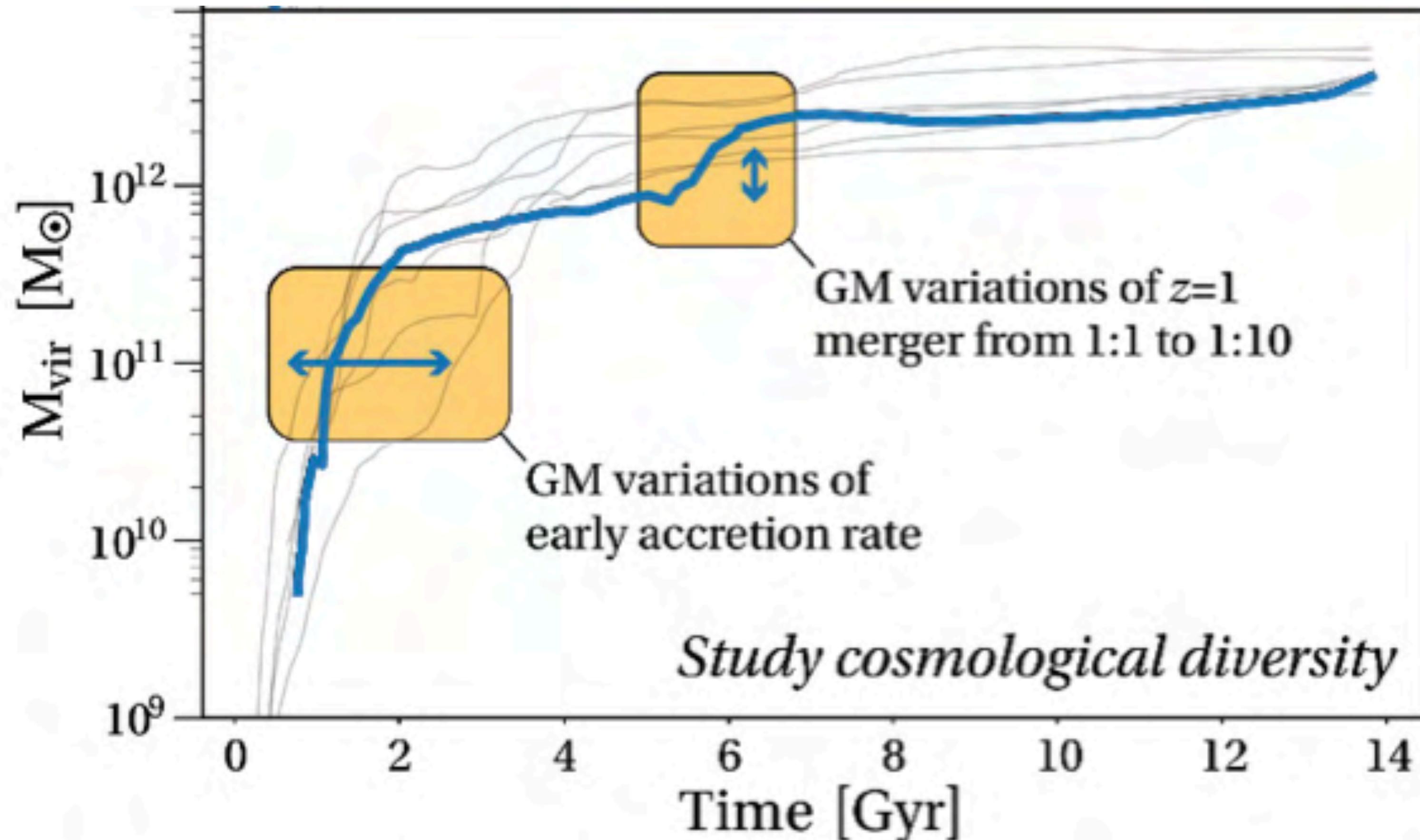
Current Data Sets

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



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

