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

@theNbodyShop
nbody.shop

Ferah Munshi

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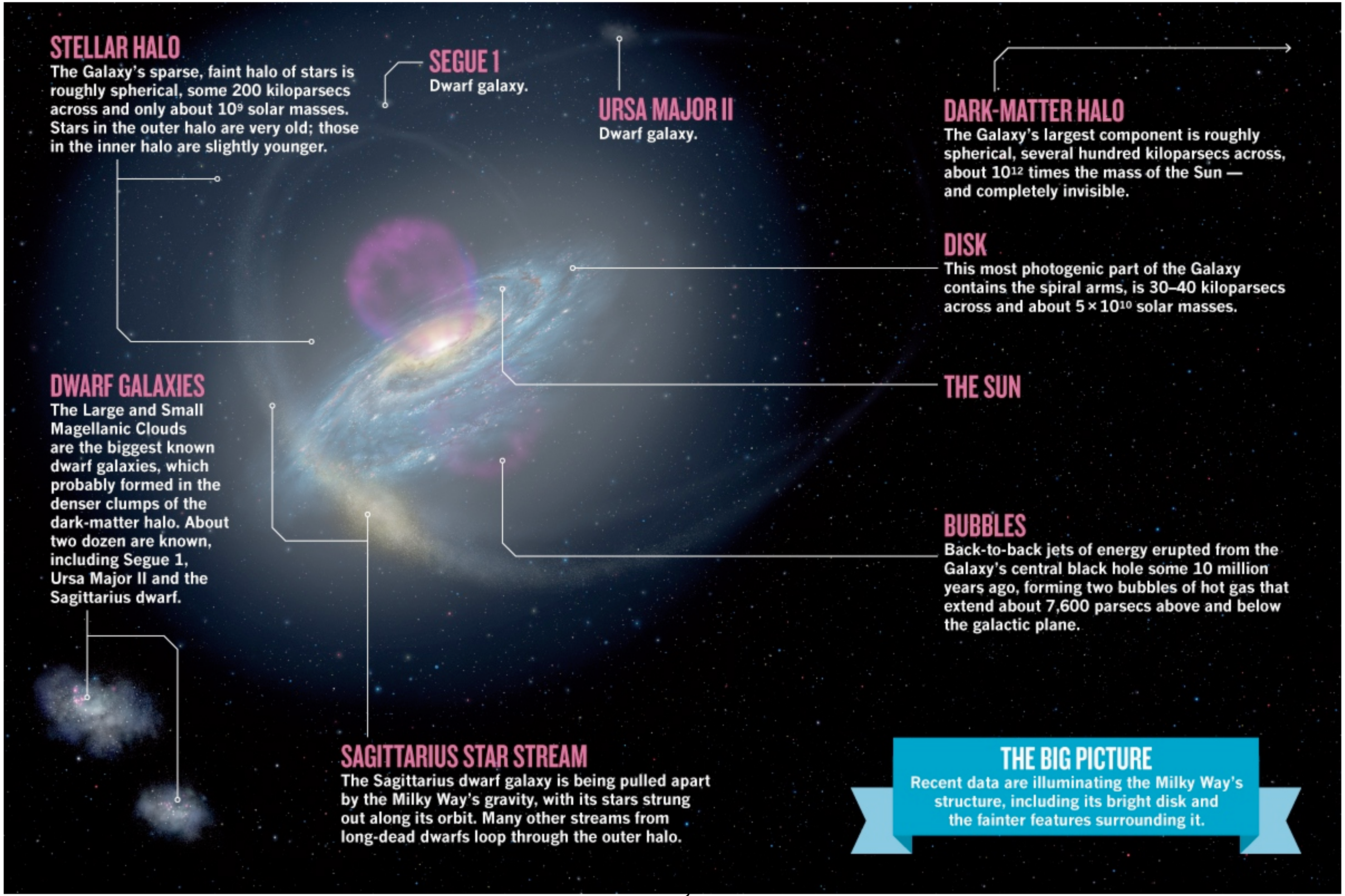
In collaboration with: Alyson Brooks (Rutgers), Jillian Bellovary (QCC/AMNH), Kelly Holley-Bockelmann (Vanderbilt), Charlotte Christensen (Grinnell), Michael Tremmel (Yale)+ UW N-body Shop

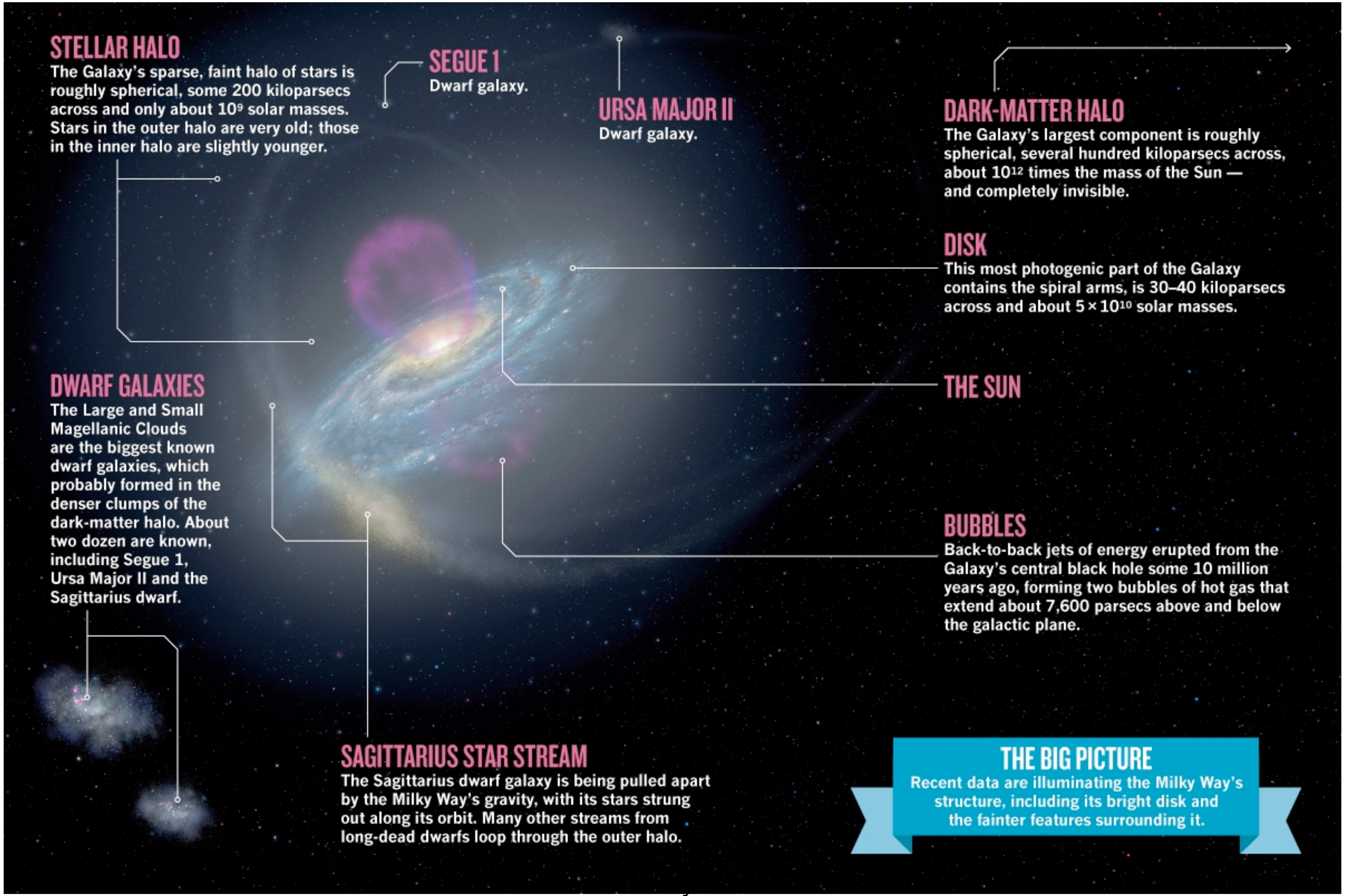
Student work highlighted: *Claire Riggs* (OU—>Rutgers), Elaad Applebaum (Rutgers—>data science), Jordan Van Nest (OU), *Alexi Musick* (OU), *Bianca Azartash-Namin* (OU), *Anna Engelhardt* (OU REU, Grinnell College)

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



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

Dwarf galaxies are galaxies smaller than the Milky Way

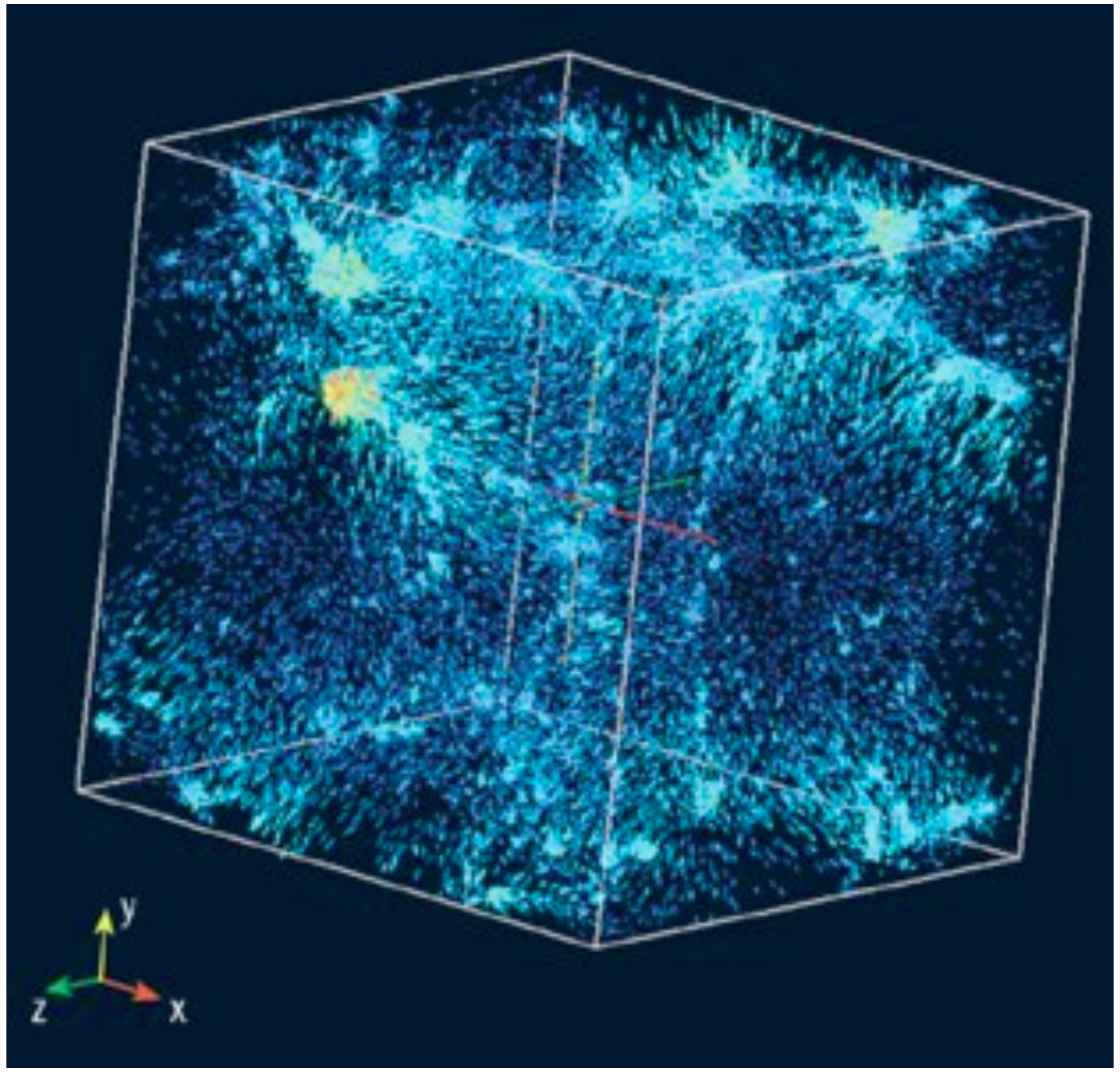


http://www.nature.com/news/galaxy-formation-the-new-milky-way-1.11517

I use galaxy simulations
to figure out how
(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?

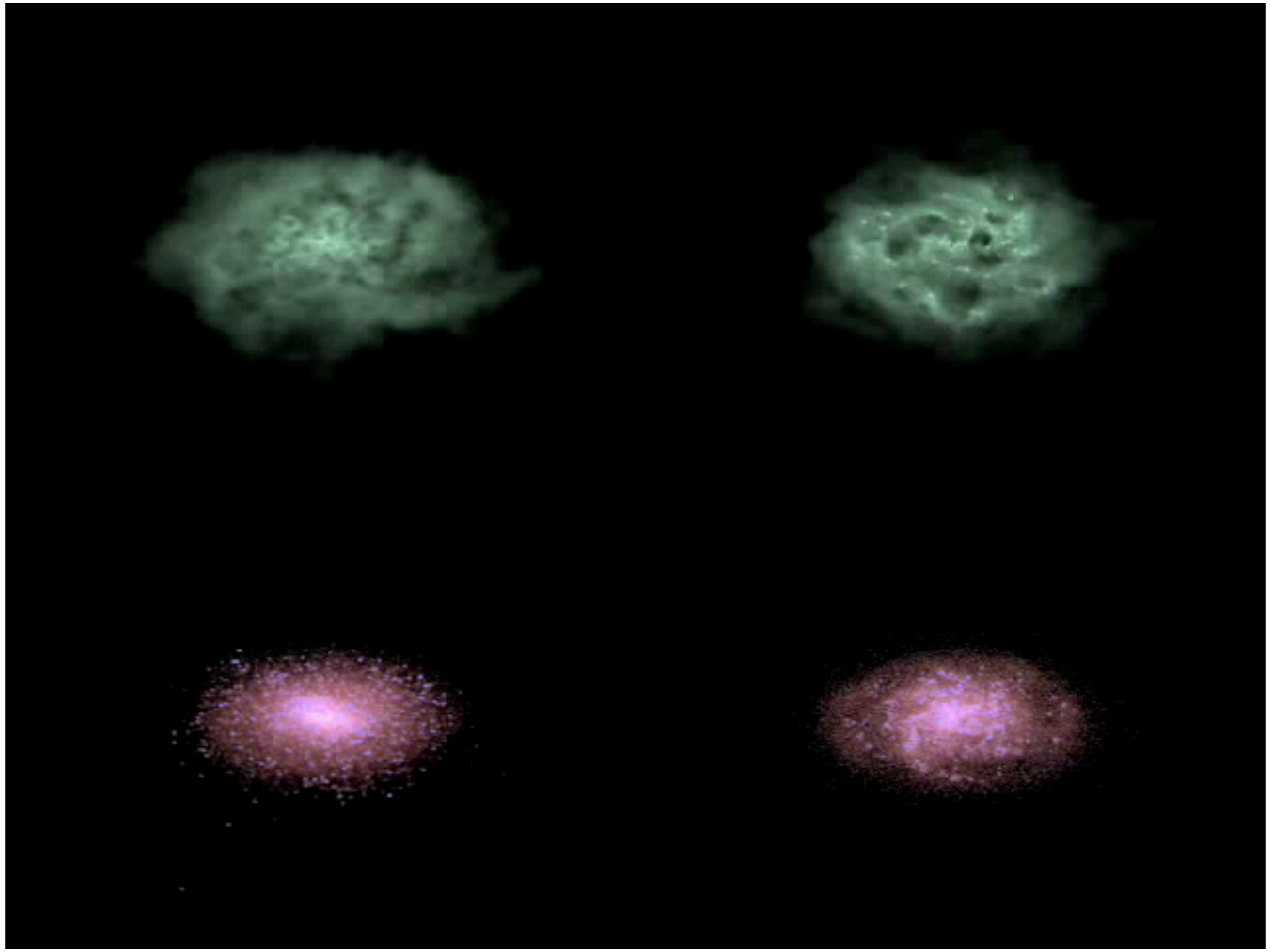


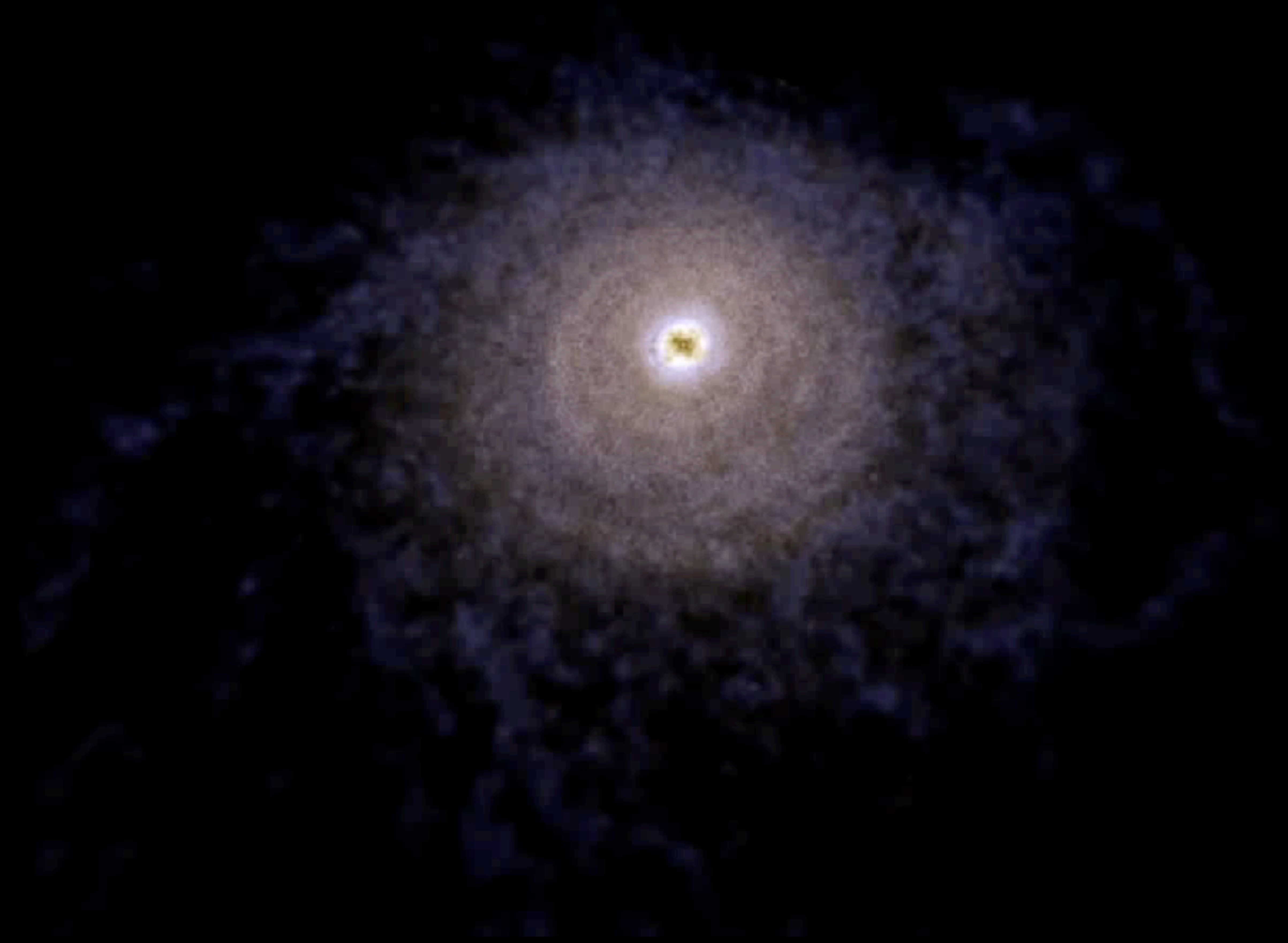
Modeling a dynamical system of particles, usually under the influence of physical forces, in this case: **gravity**

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

What is an N-body + SPH Simulation?

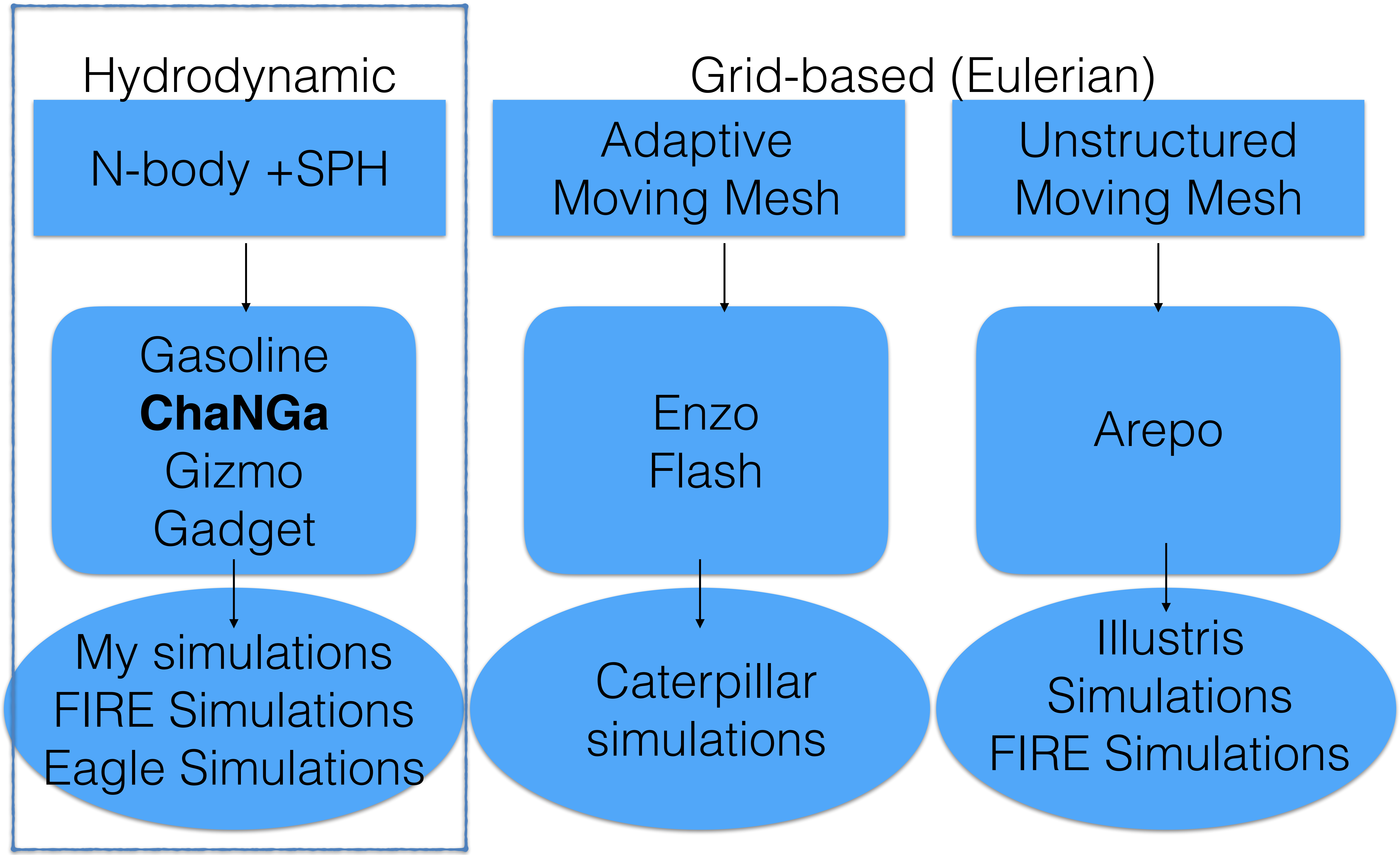
- SPH= “smoothed particle hydrodynamics”
- computational method used for simulating fluid flows- ie, gas
- Gas is divided into a set of discrete elements, referred to as “particles”
- “cosmological”= from early times all the way to present day





Video courtesy of A. Pontzen

Types of galaxy simulations



Pros & Cons of different simulation suites

	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

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

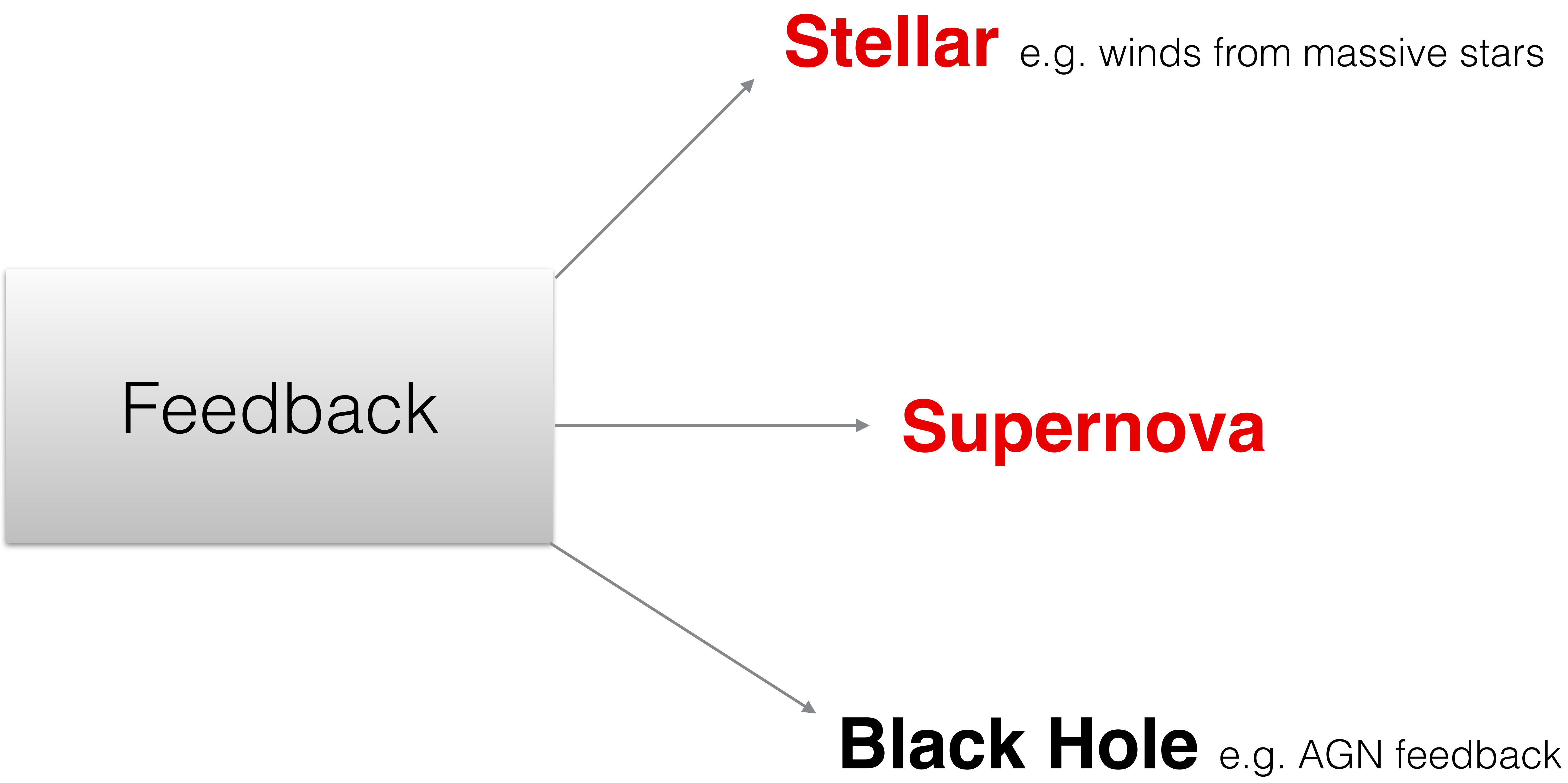
All feedback mechanisms have this in common:

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

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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Key Problems

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

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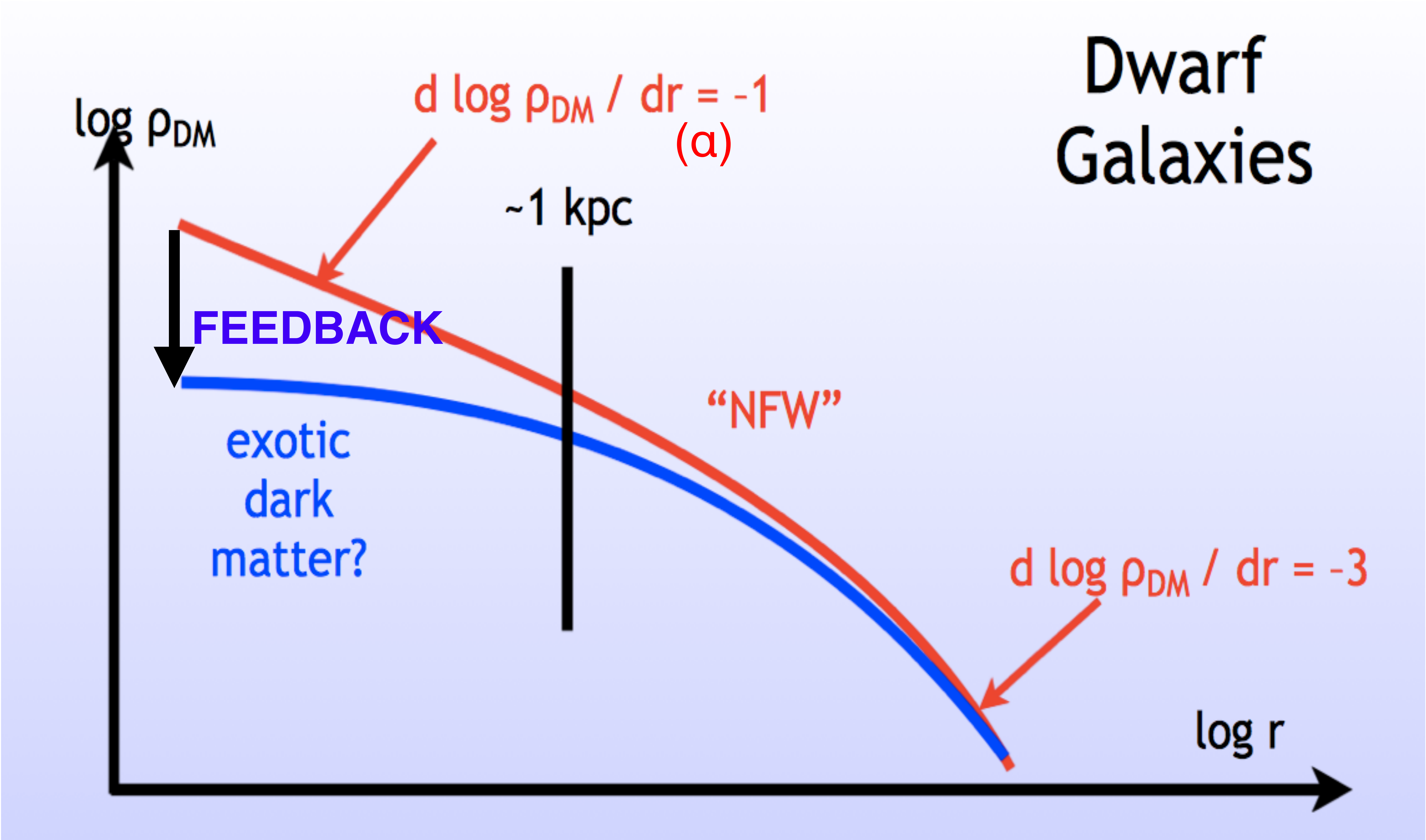
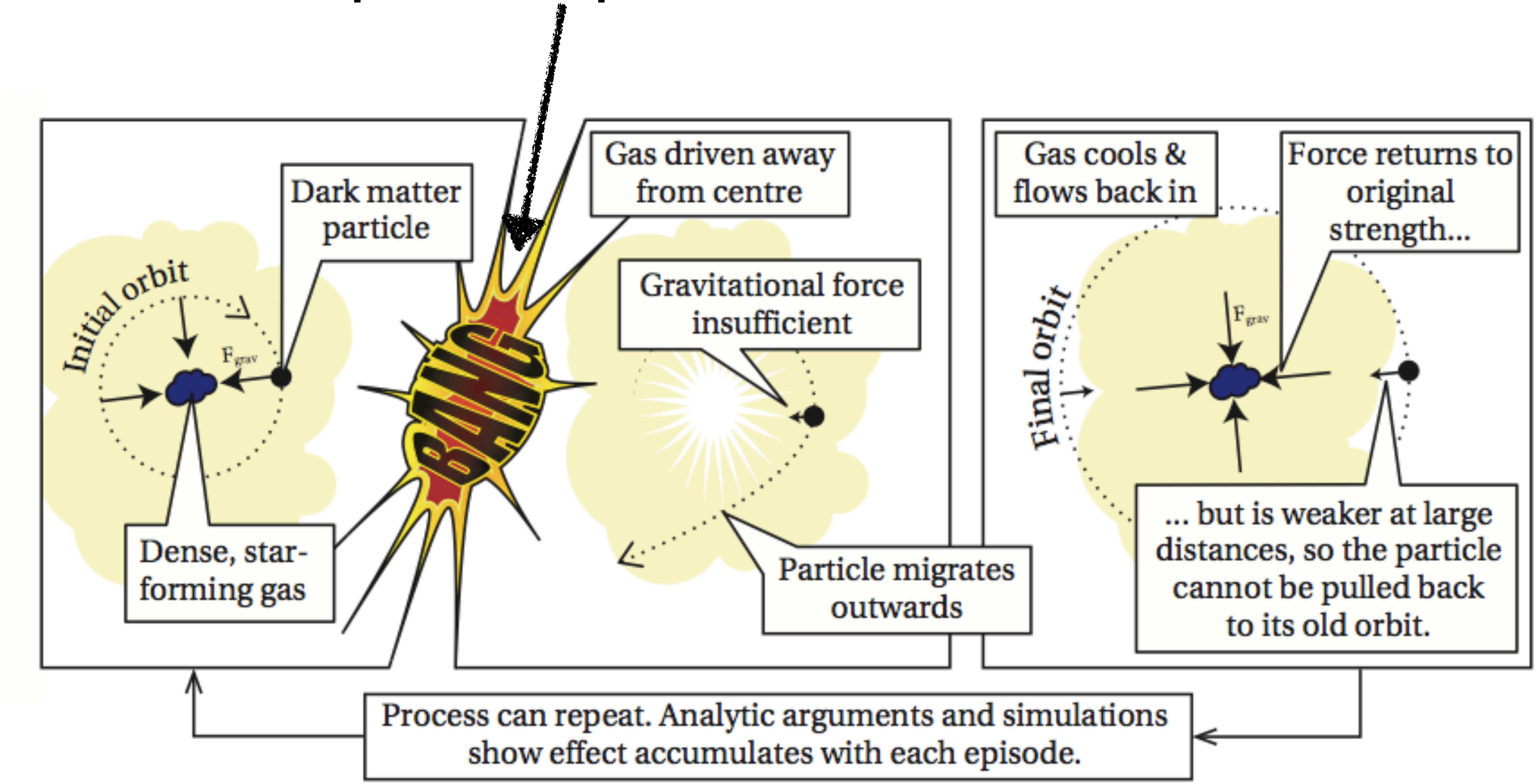


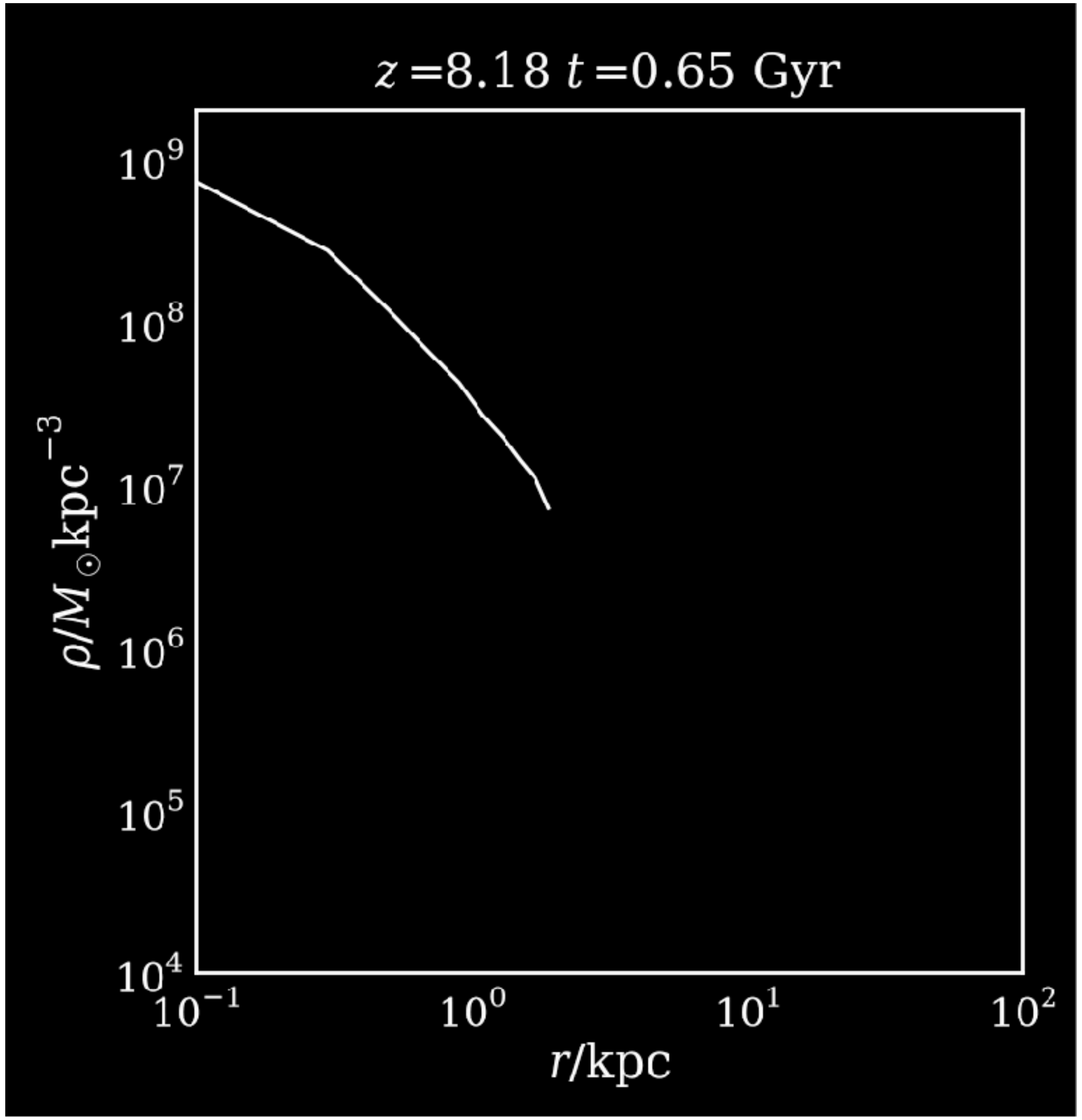
Figure courtesy of F. Governato

Supernova explosion/feedback

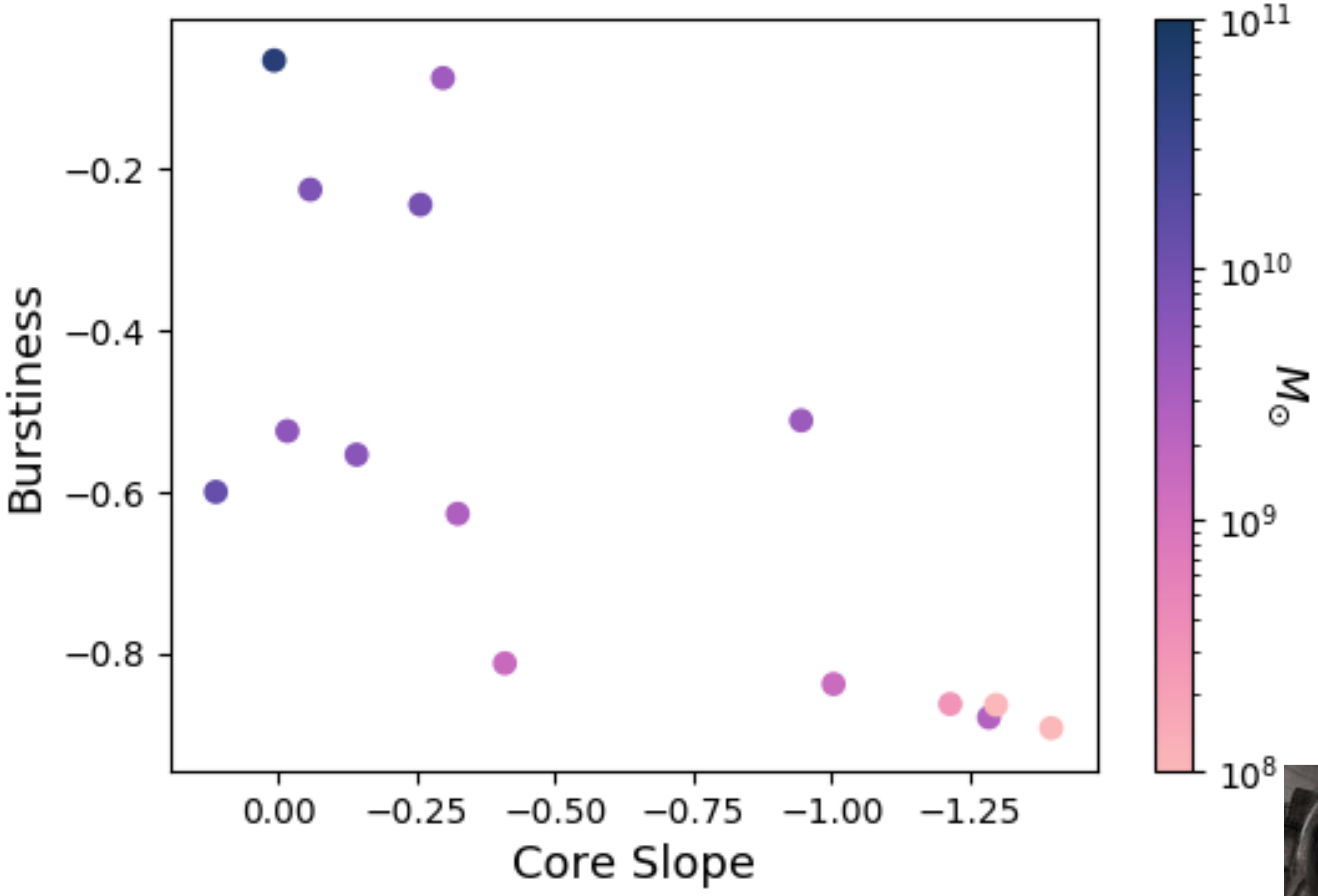


Pontzen & Governato 2012 & 2014

Repeated feedback events => flattening of DM core



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

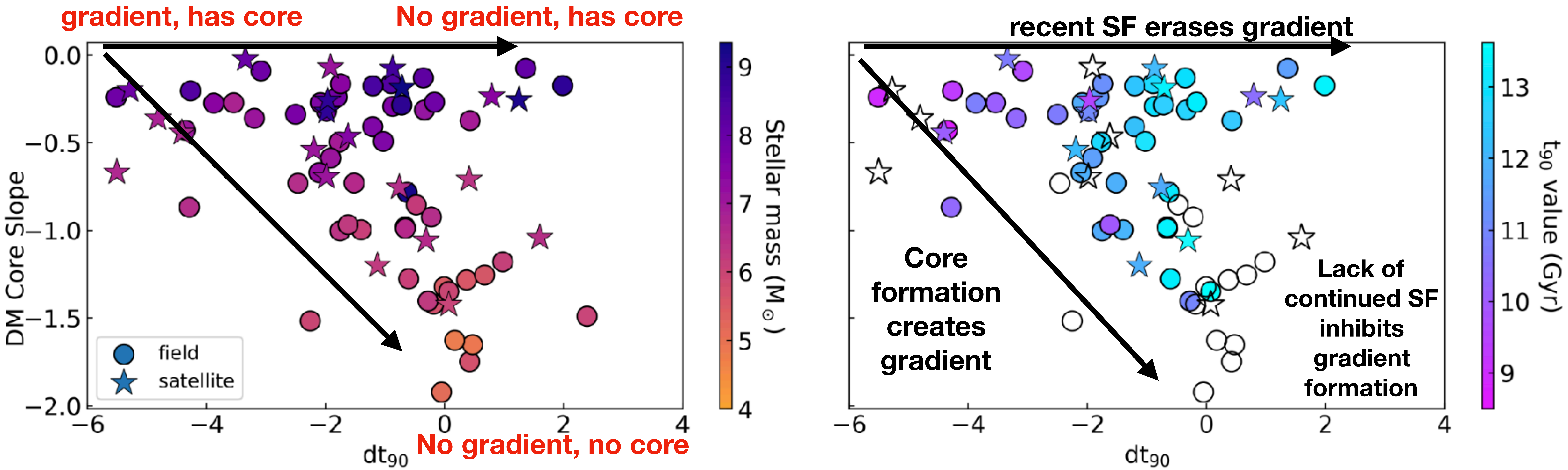


cored

cuspy

Preliminary results from OU undergraduates Alexi Musick & Bianca Azartash-Namin

Relation to Age Gradients in Dwarfs?



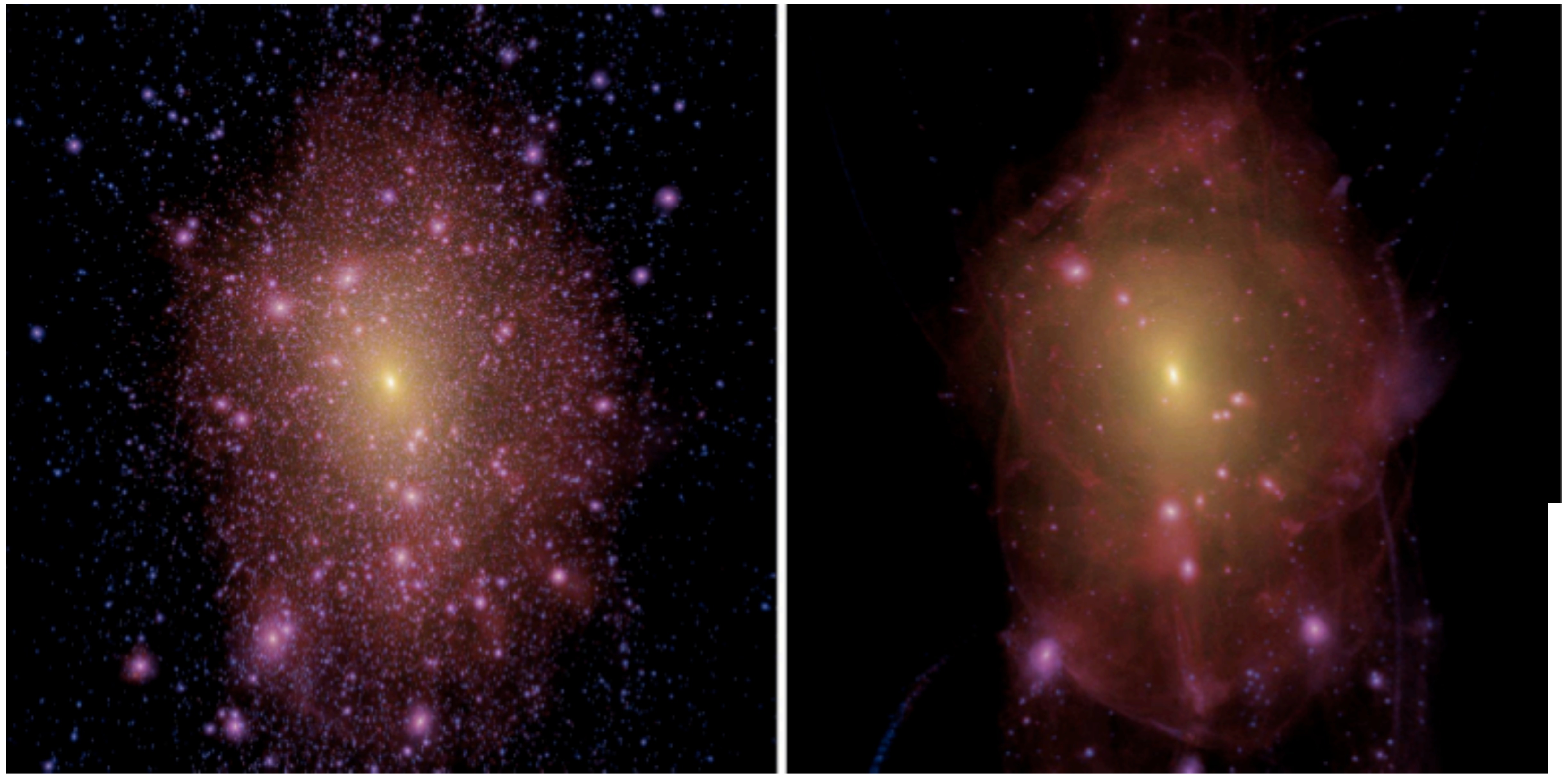
Core formation is the result of continued bursty SF. This drives age gradients in dwarf galaxies. However, dwarfs with **recent** SF can have their age gradients erased, despite having a core.

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

This is going into an HST proposal shortly!

Riggs (former OU undergrad), Munshi & Brooks, in-prep

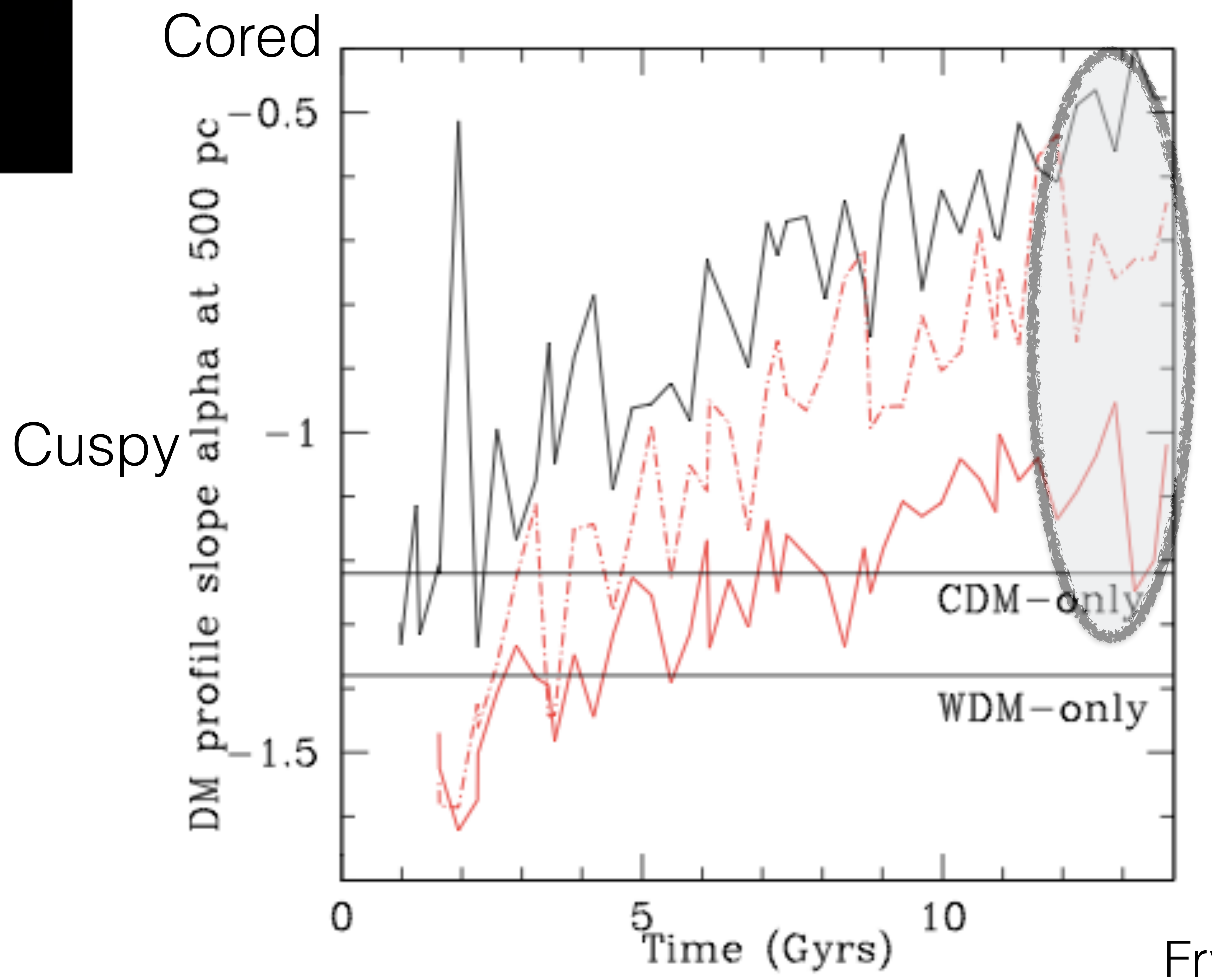
Lovell et al. 2011



CDM

WDM

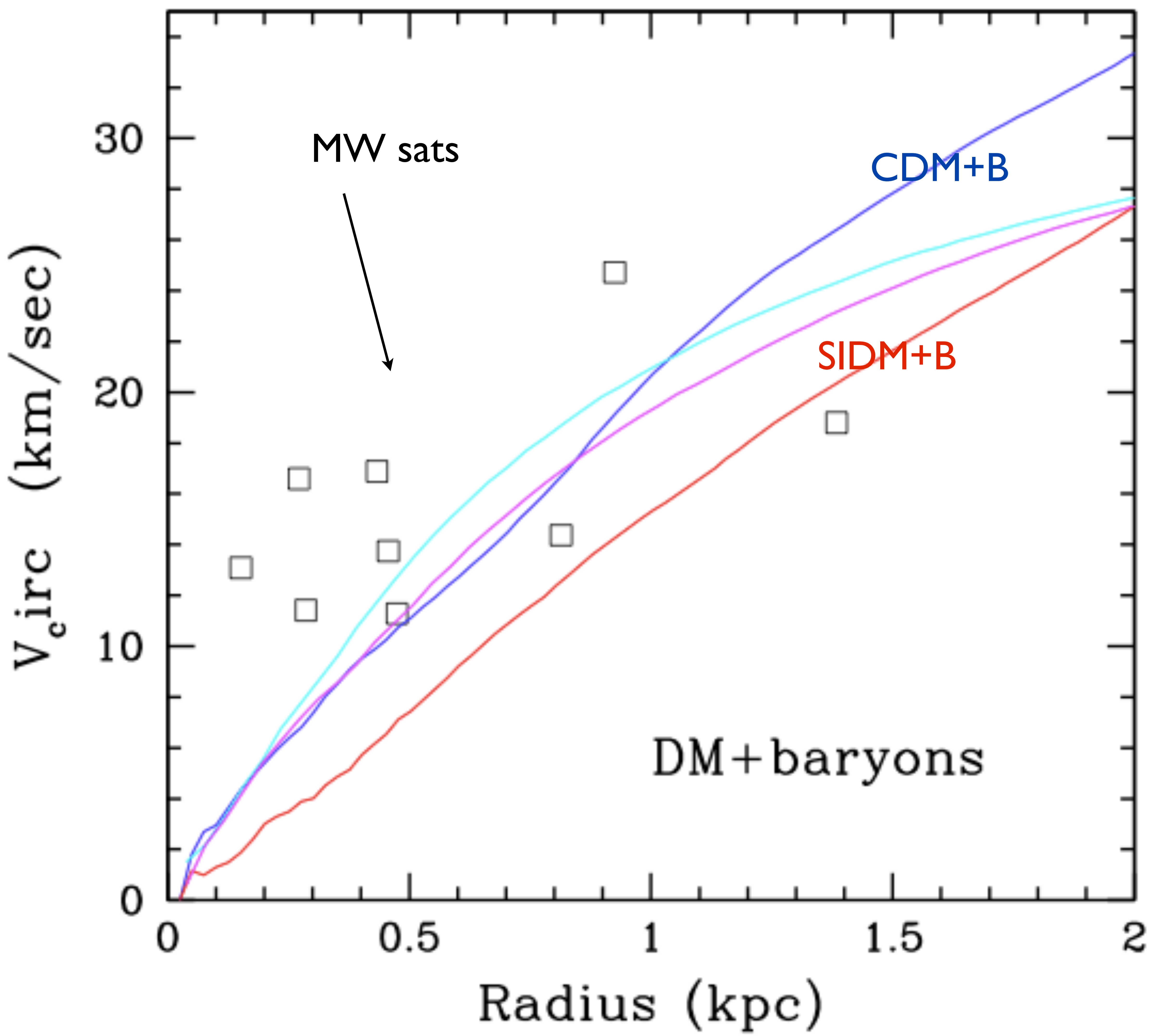
2keV WDM



Warm dark matter (WDM) with baryons creates cores

Fry + 2015

With baryons, SIDM and CDM are indistinguishable



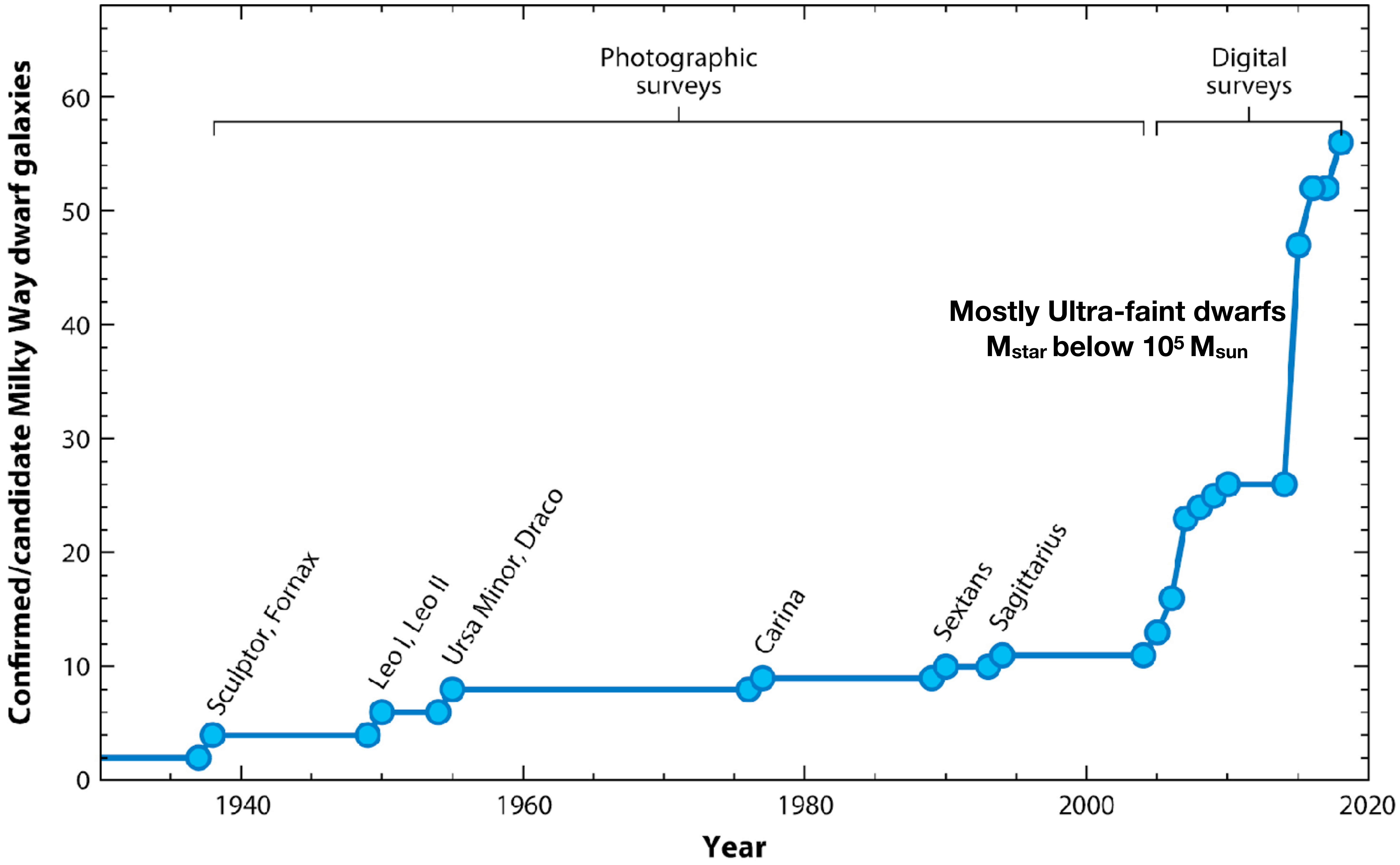
Fry+ (2015)

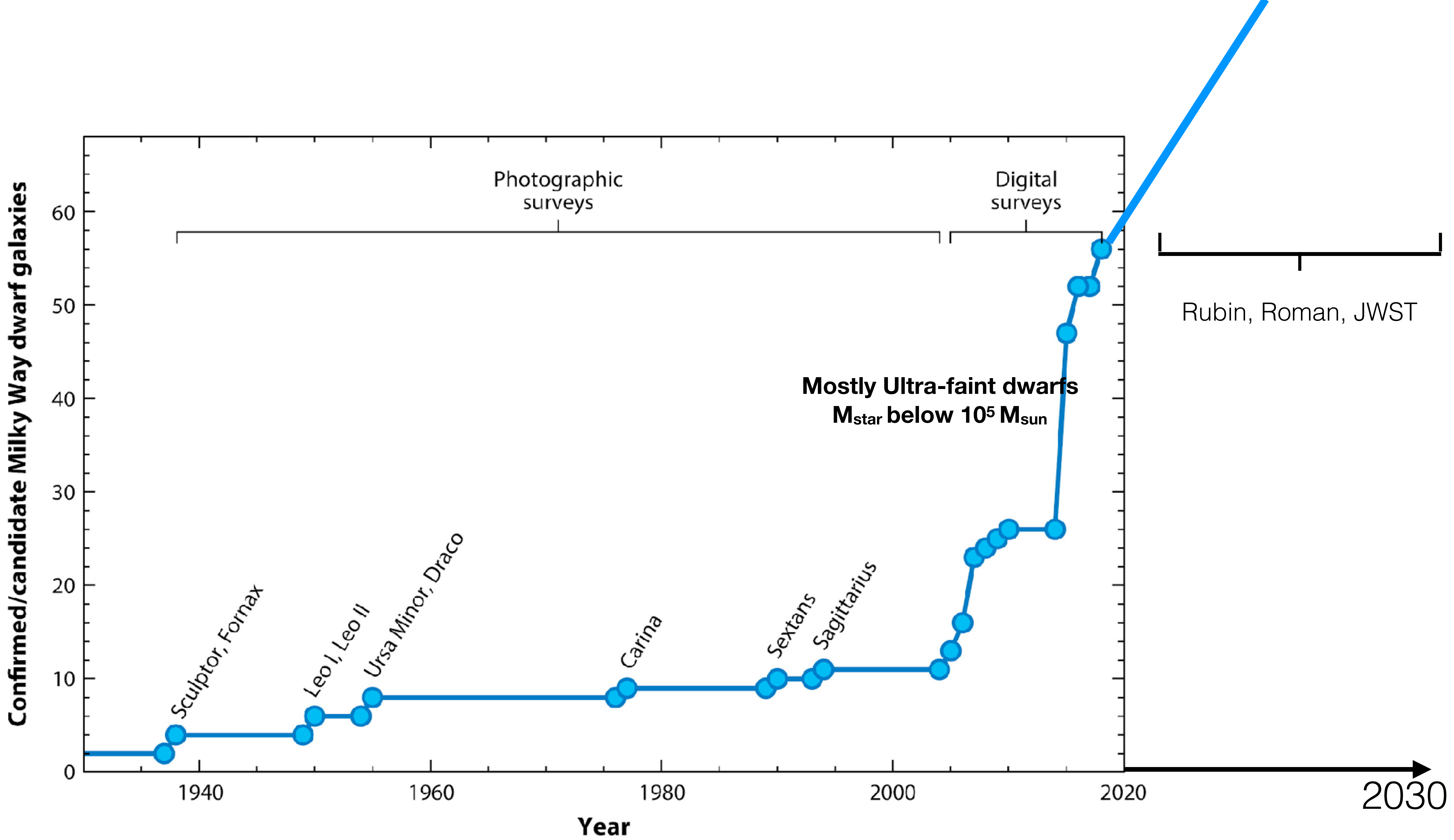
Key Problems

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





Confirmed/candidate Milky Way dwarf galaxies
Year
0
10
20
30
40
50
60
1940
1960
1980
2000
2020
2030
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

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

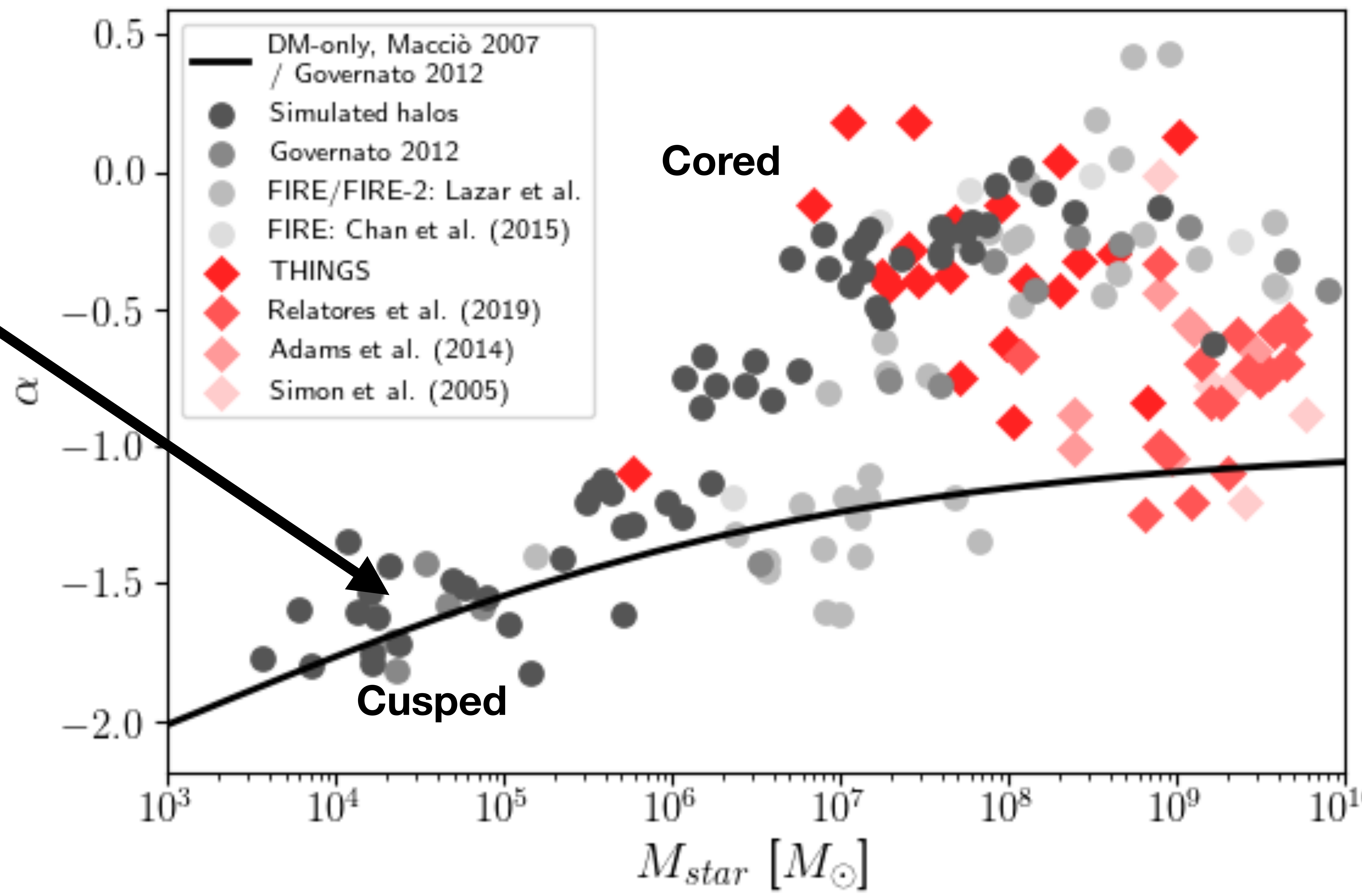


Figure from my grad student, J. Van Nest

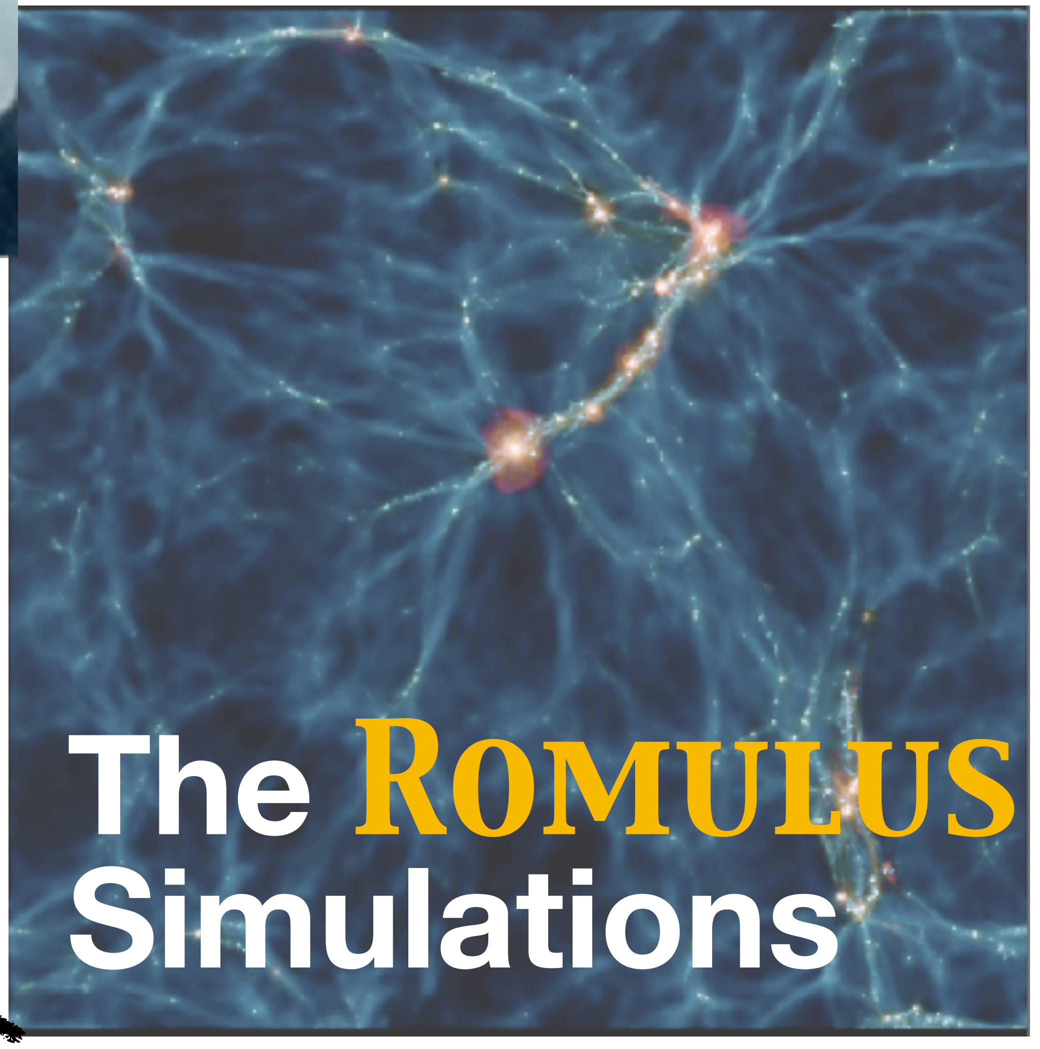
It is commonly assumed that ultra-faint dwarfs are “simple” systems

- 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

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

Ultra-faints in isolation

Ultra-faints in the vicinity of a MW



Dwarfs (and UDGs) across environments

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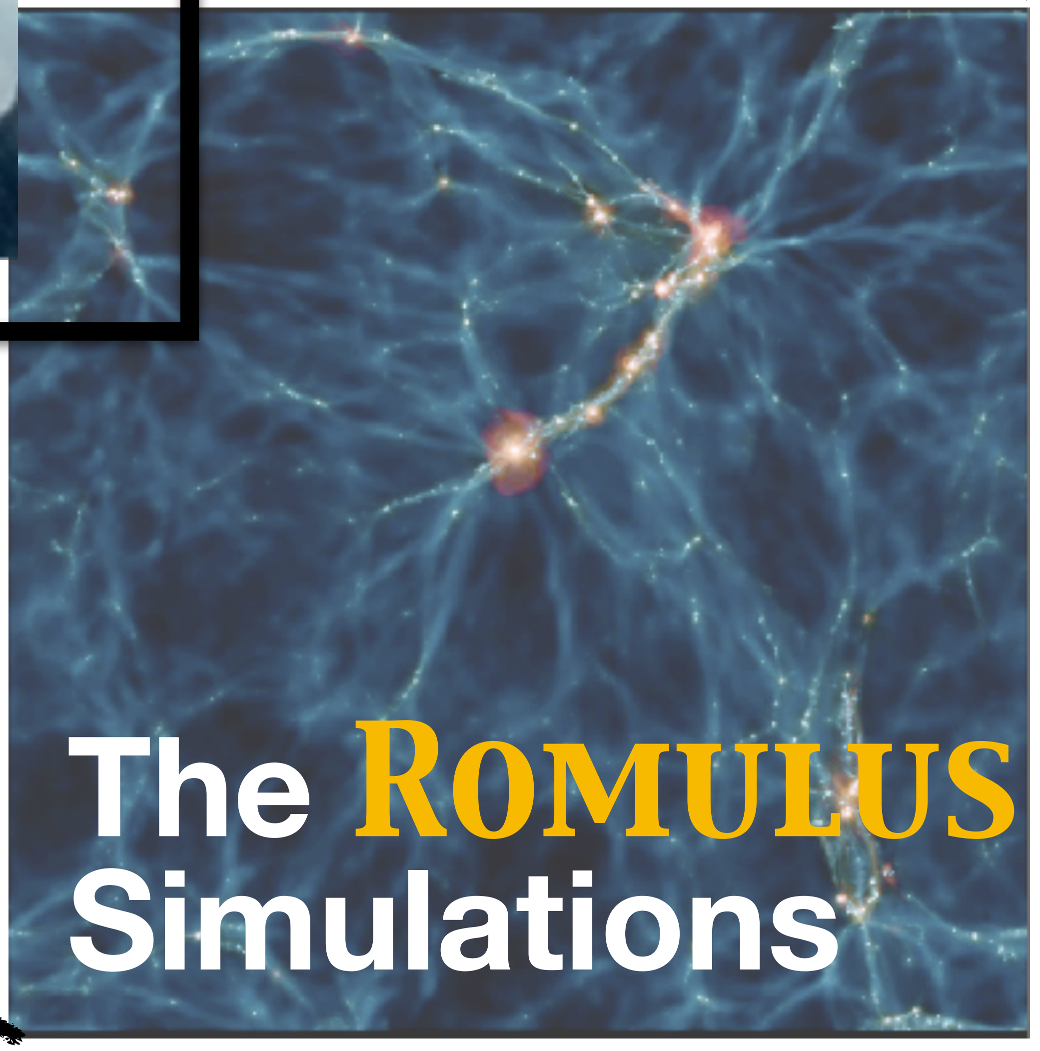
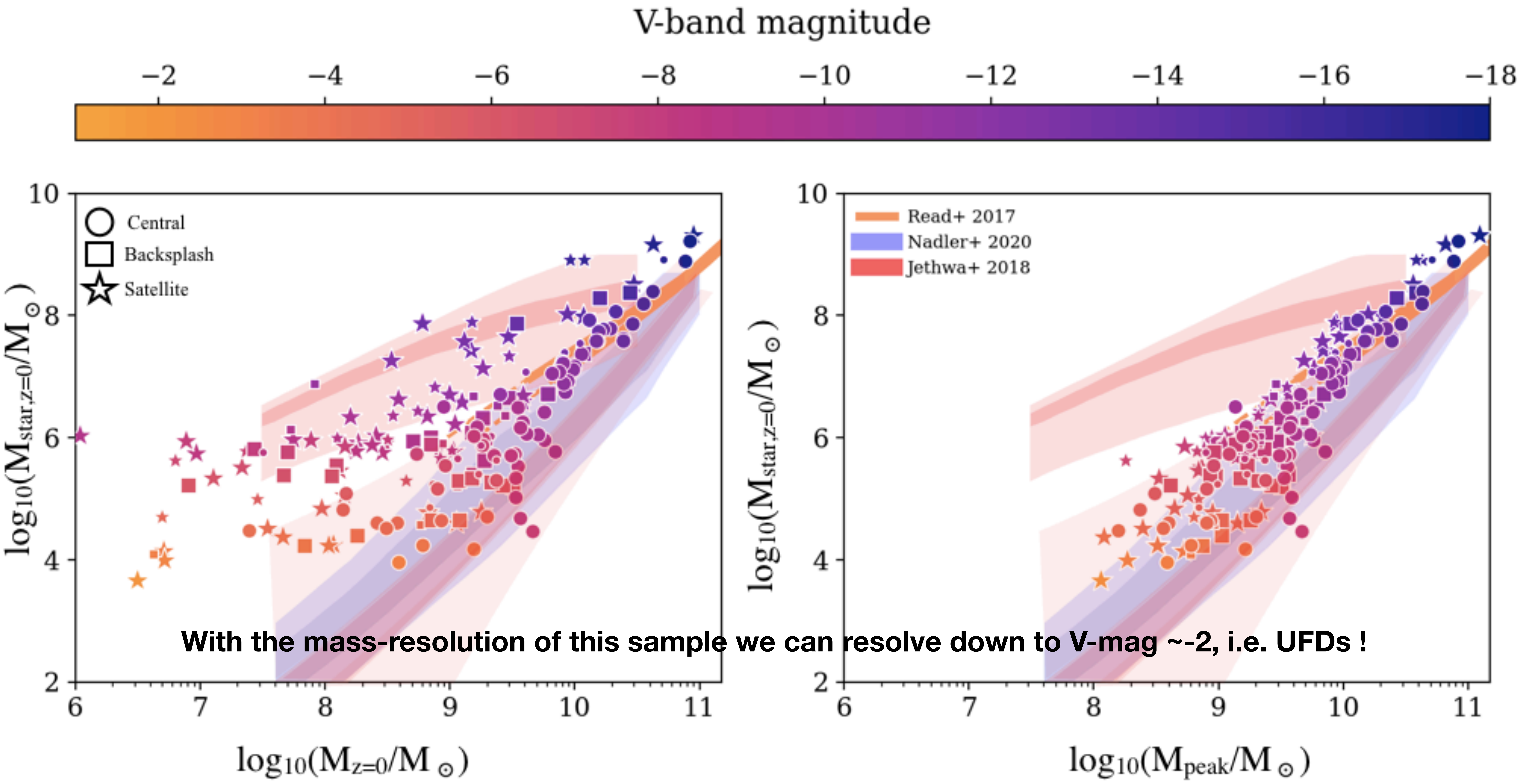


Dwarfs (and UDGs) across environments

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

Want simulated dwarfs? I got 'em!

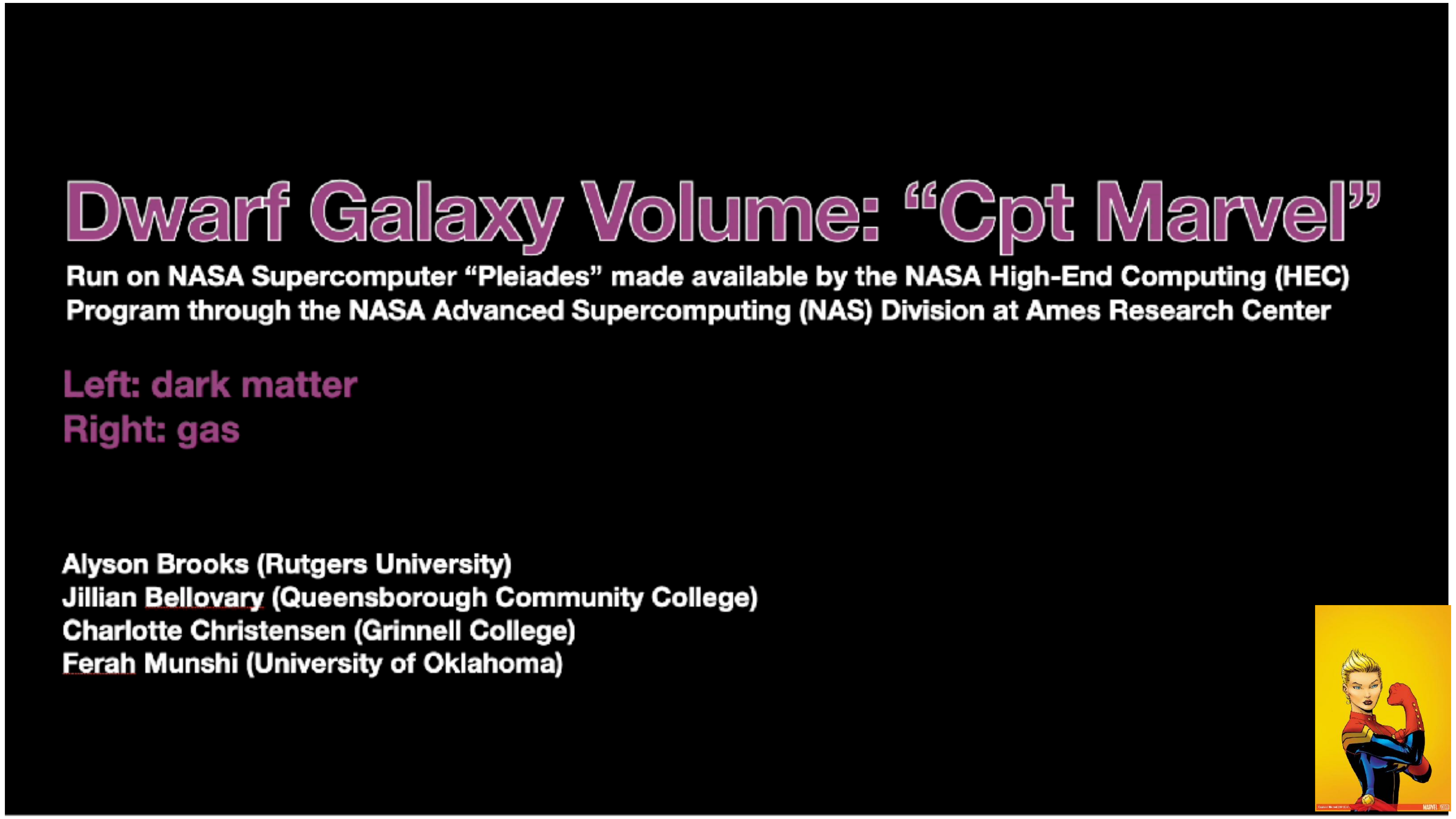


With the mass-resolution of this sample we can resolve down to V-mag ~-2, i.e. UFDs !

Munshi, Brooks, Applebaum+, 2021

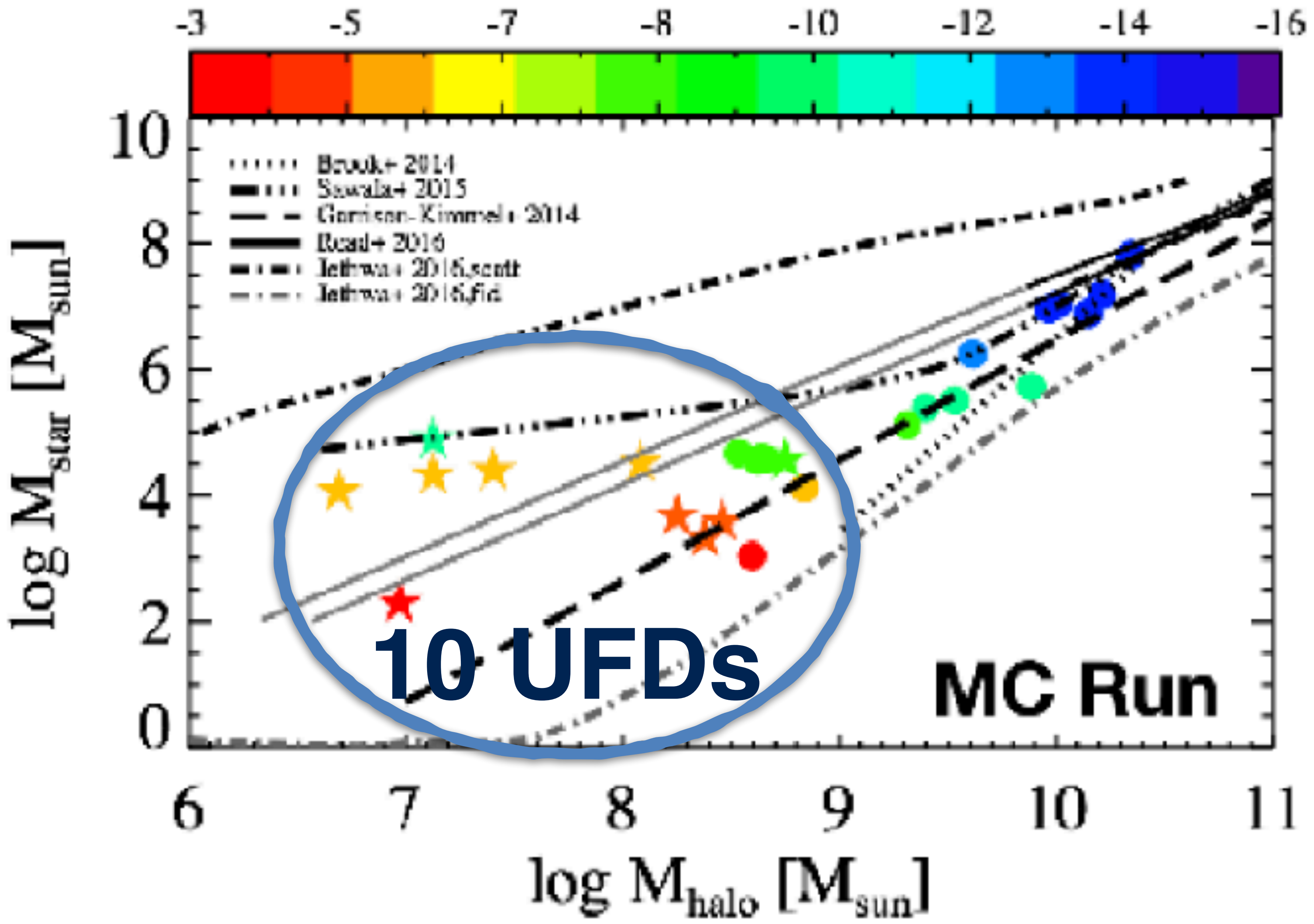
With a simulation sample like this, we can begin to constrain:

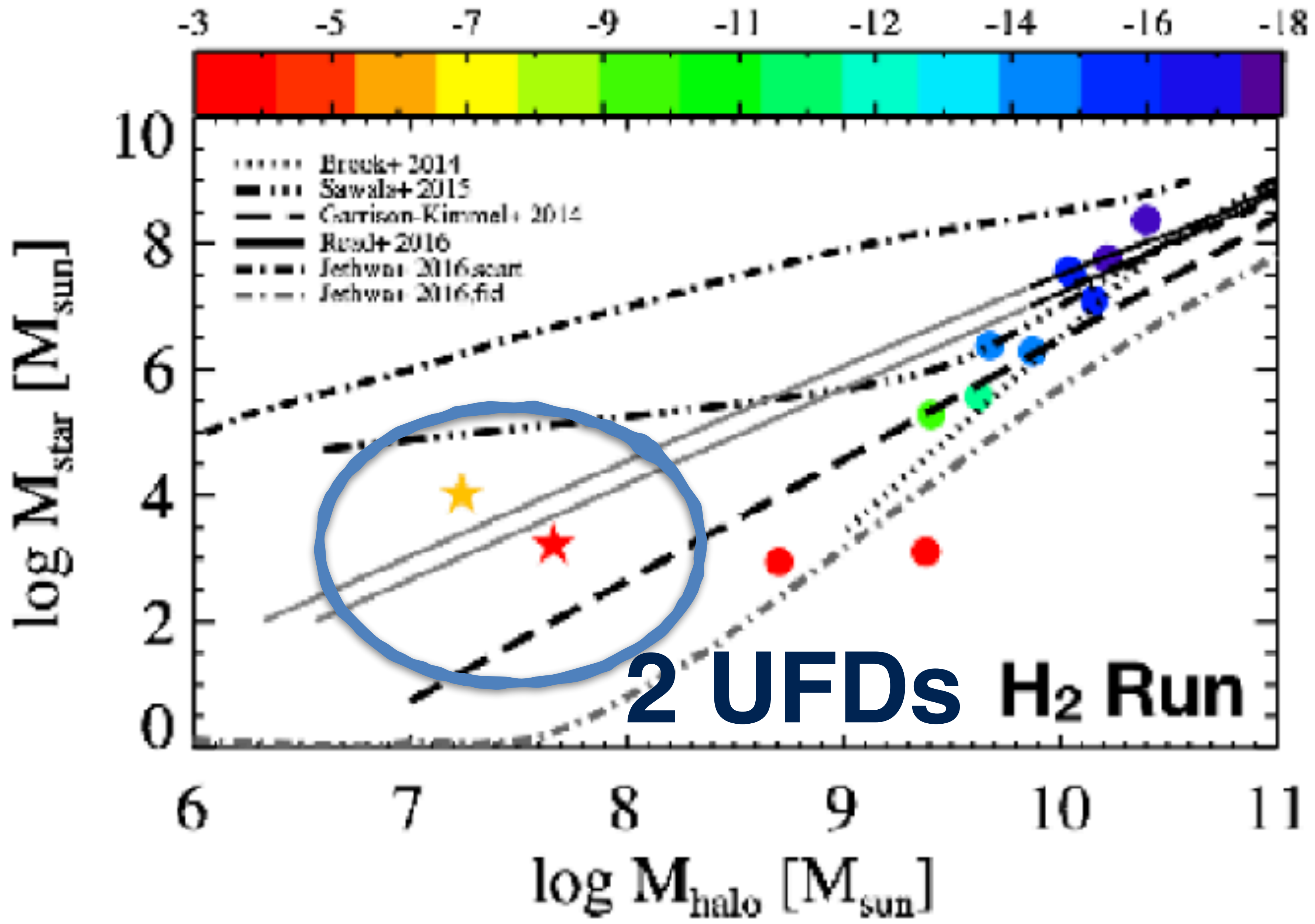
1. The abundance of ultra-faint dwarfs
2. How they populate dark matter halos

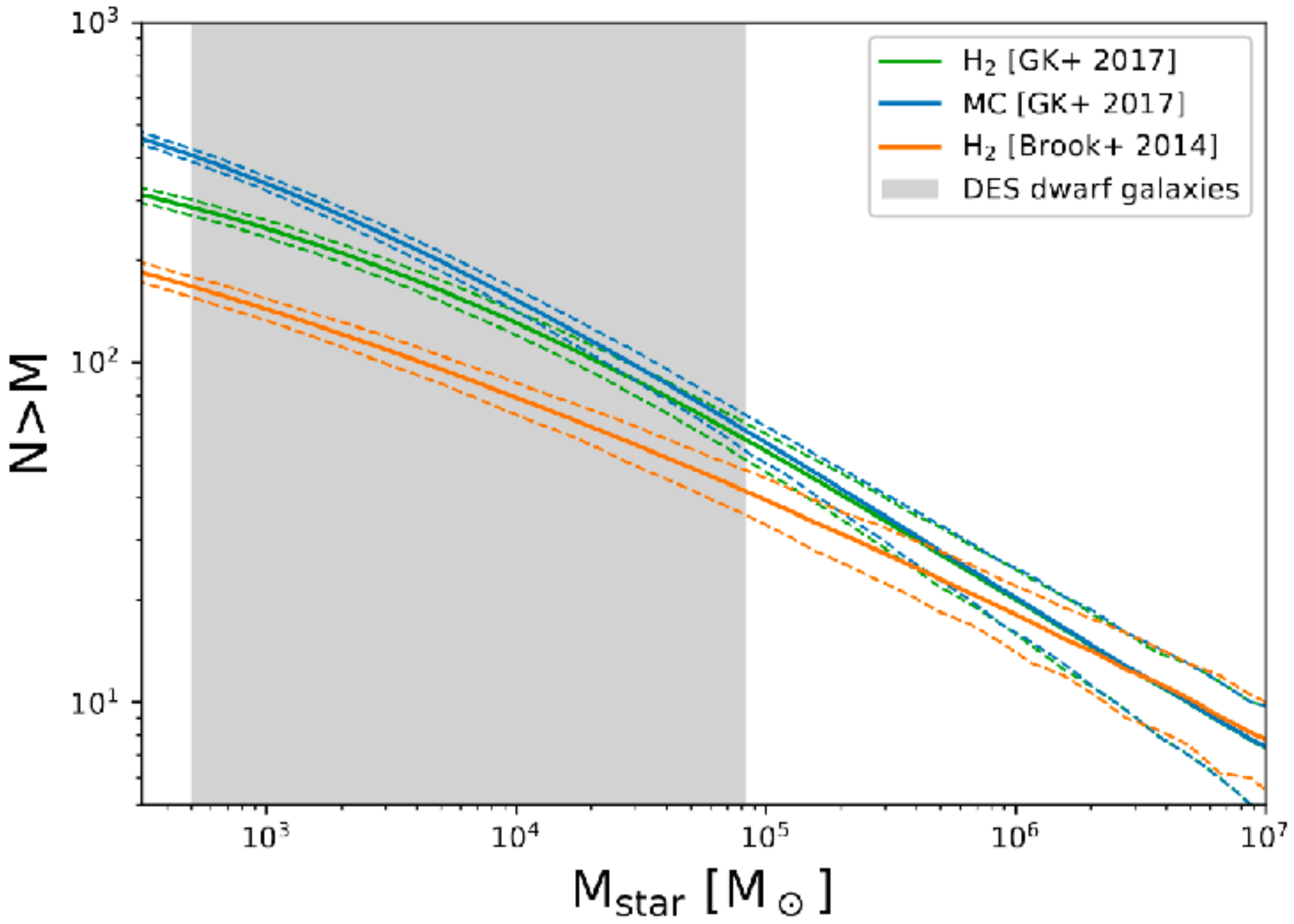


The abundance of ultra-faint dwarf galaxies- can we use this to constrain DM?

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



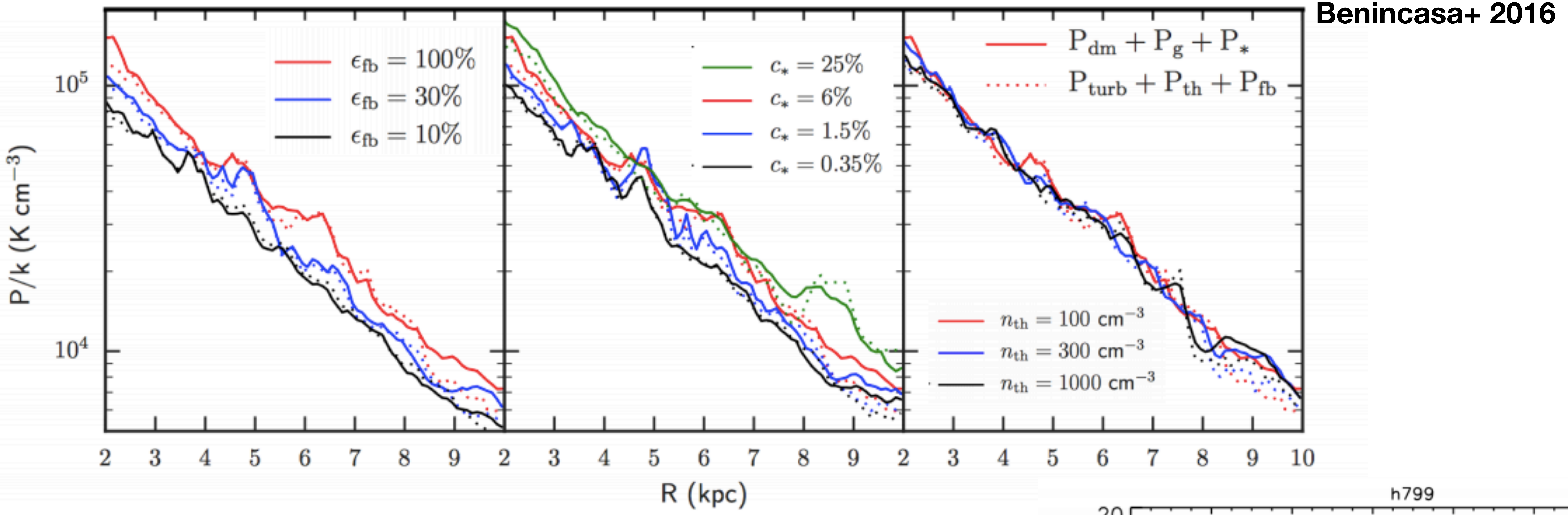




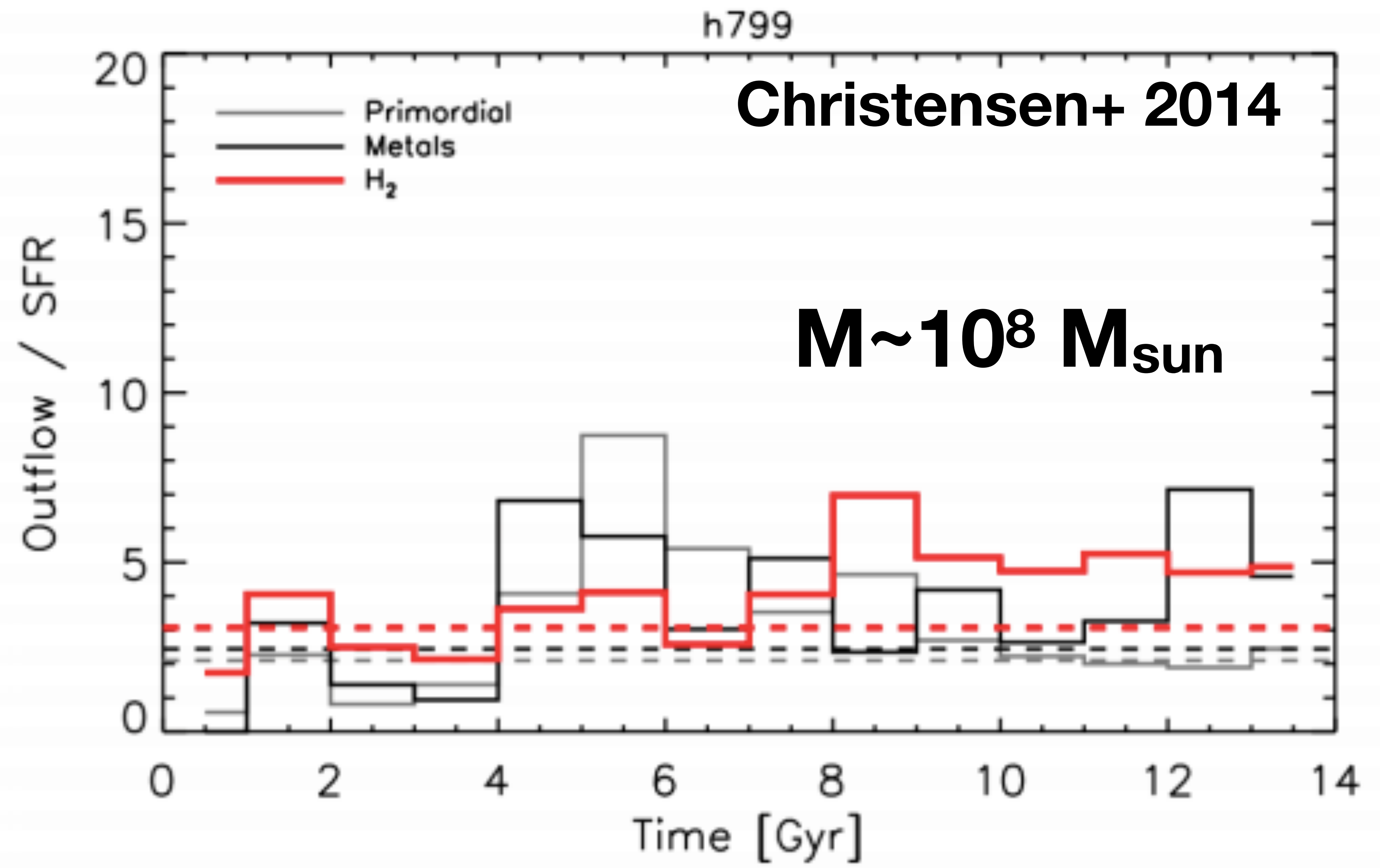
Any predictions you make depend on your star formation and feedback model

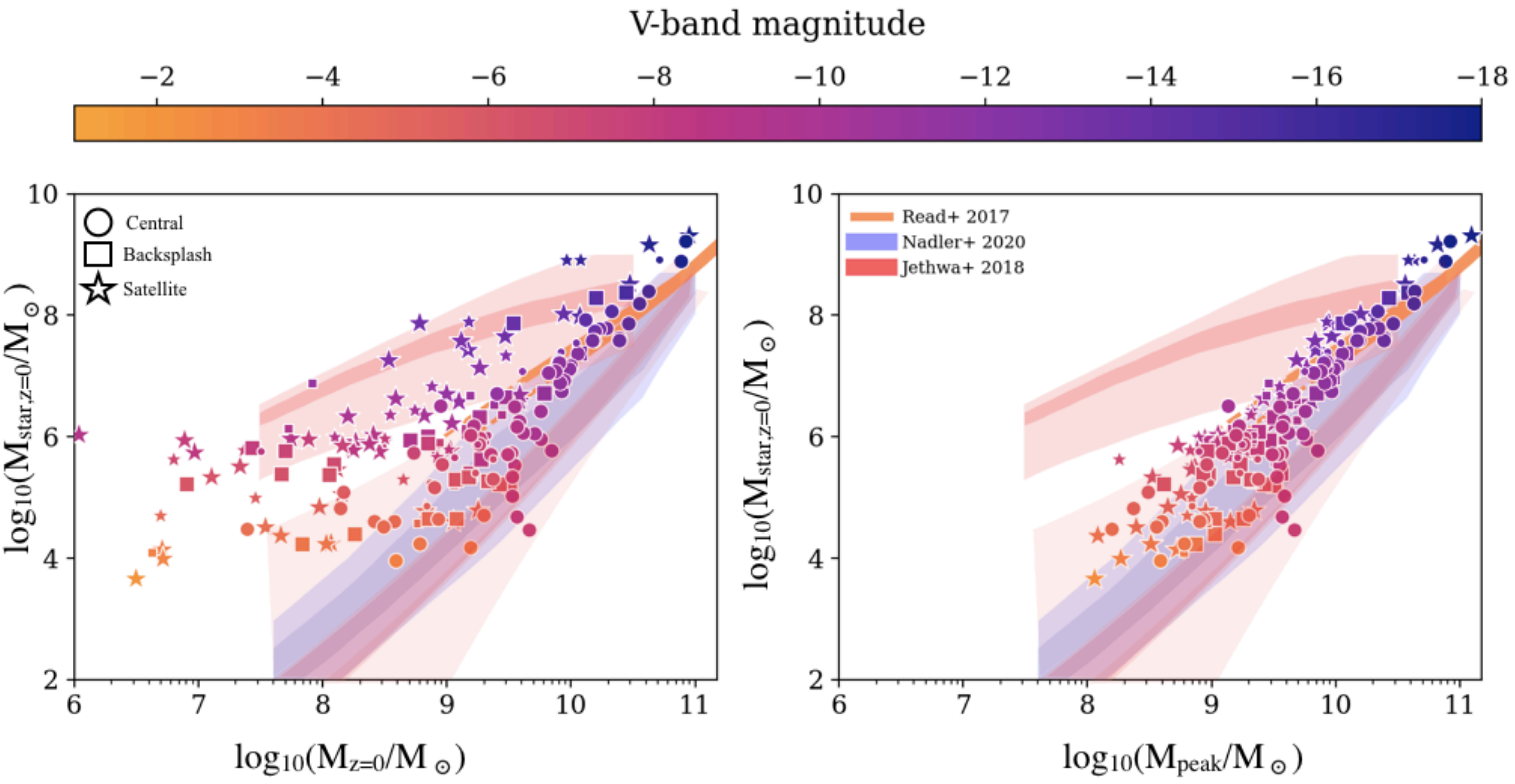
Munshi+ 2019, with former graduate student E. Applebaum

Why haven't we worried before?

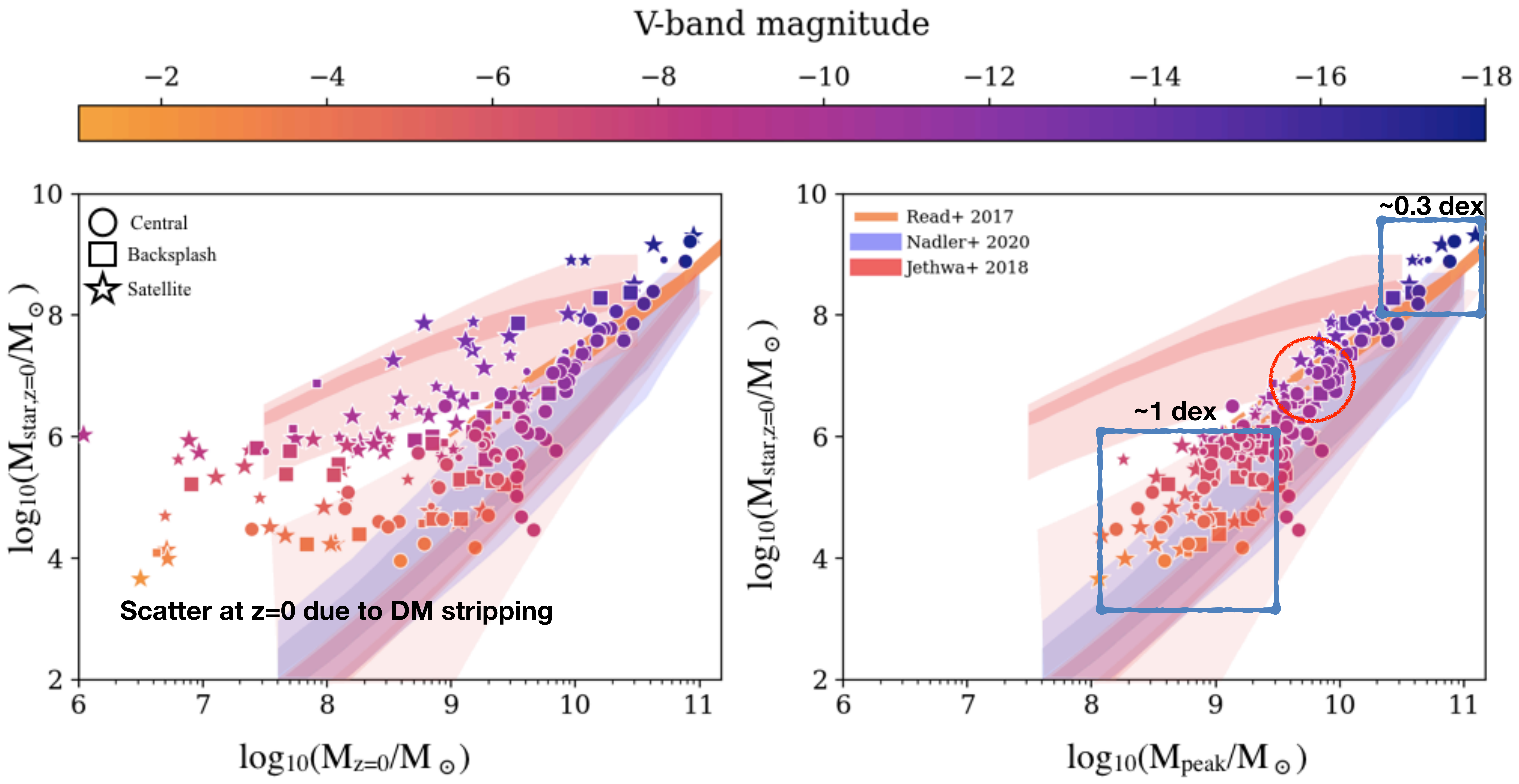


Star formation and feedback self-regulate at classical dwarf masses and above.



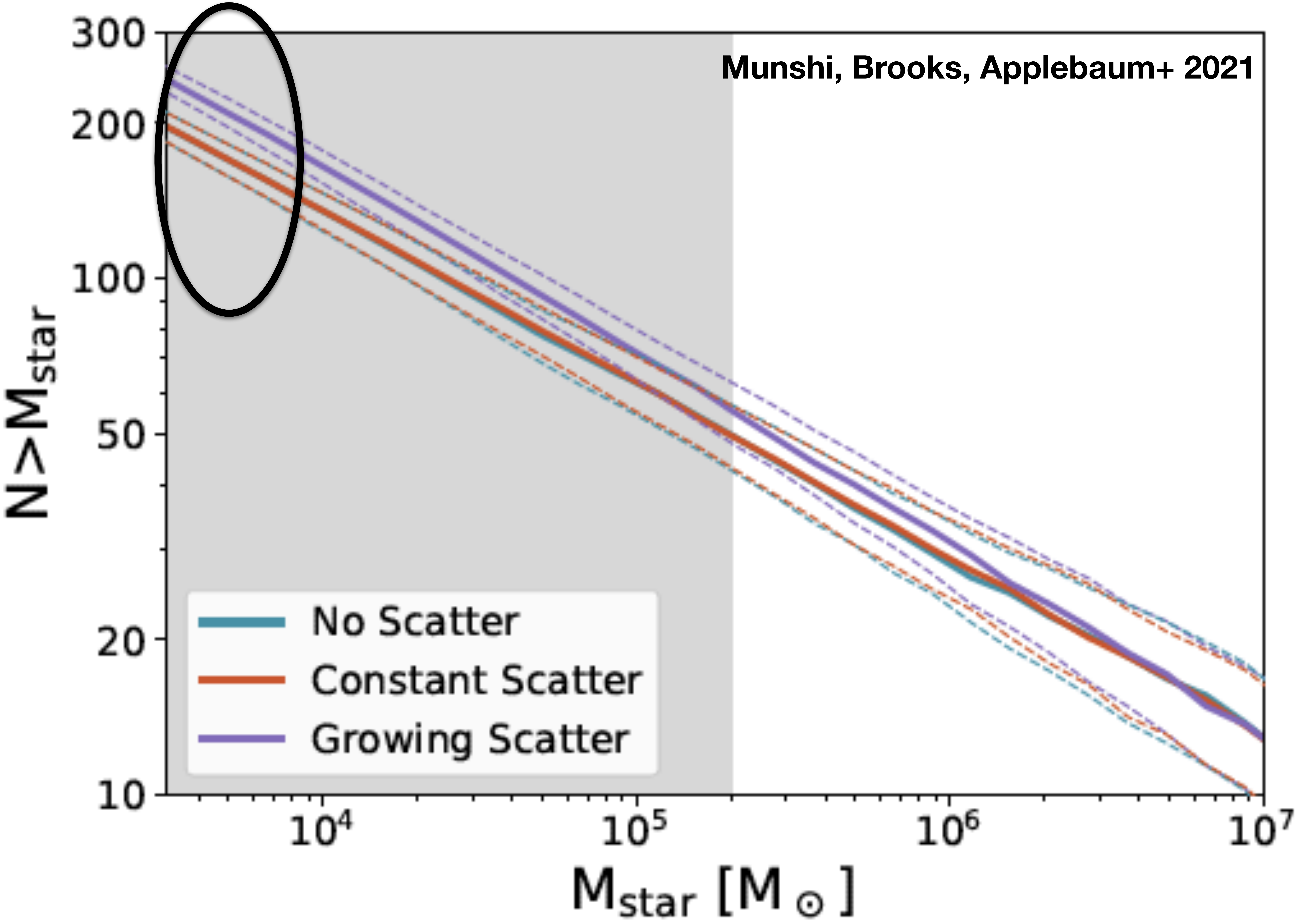


Munshi, Brooks, Applebaum+, 2021



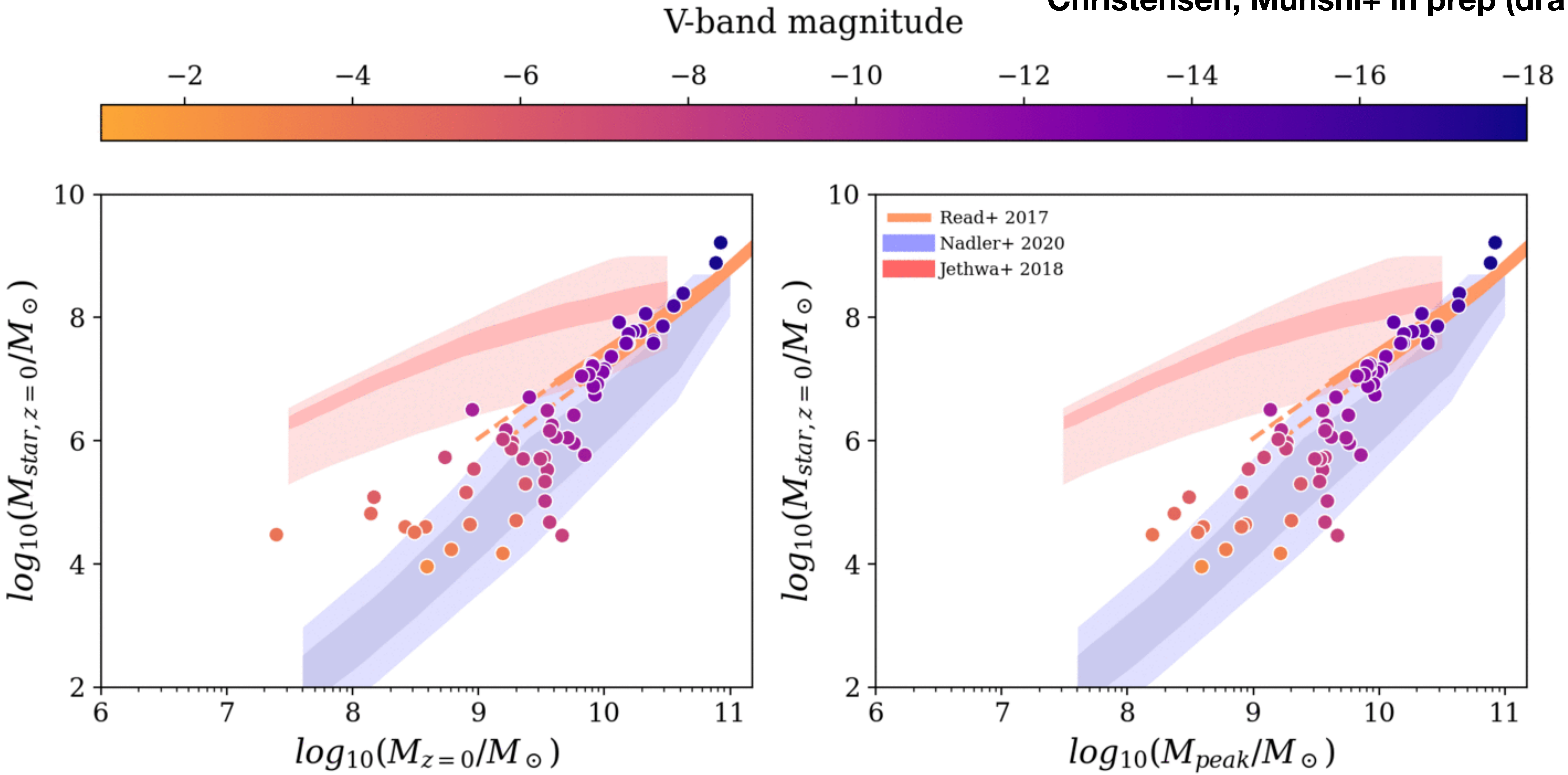
Munshi, Brooks, Applebaum+ 2021

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



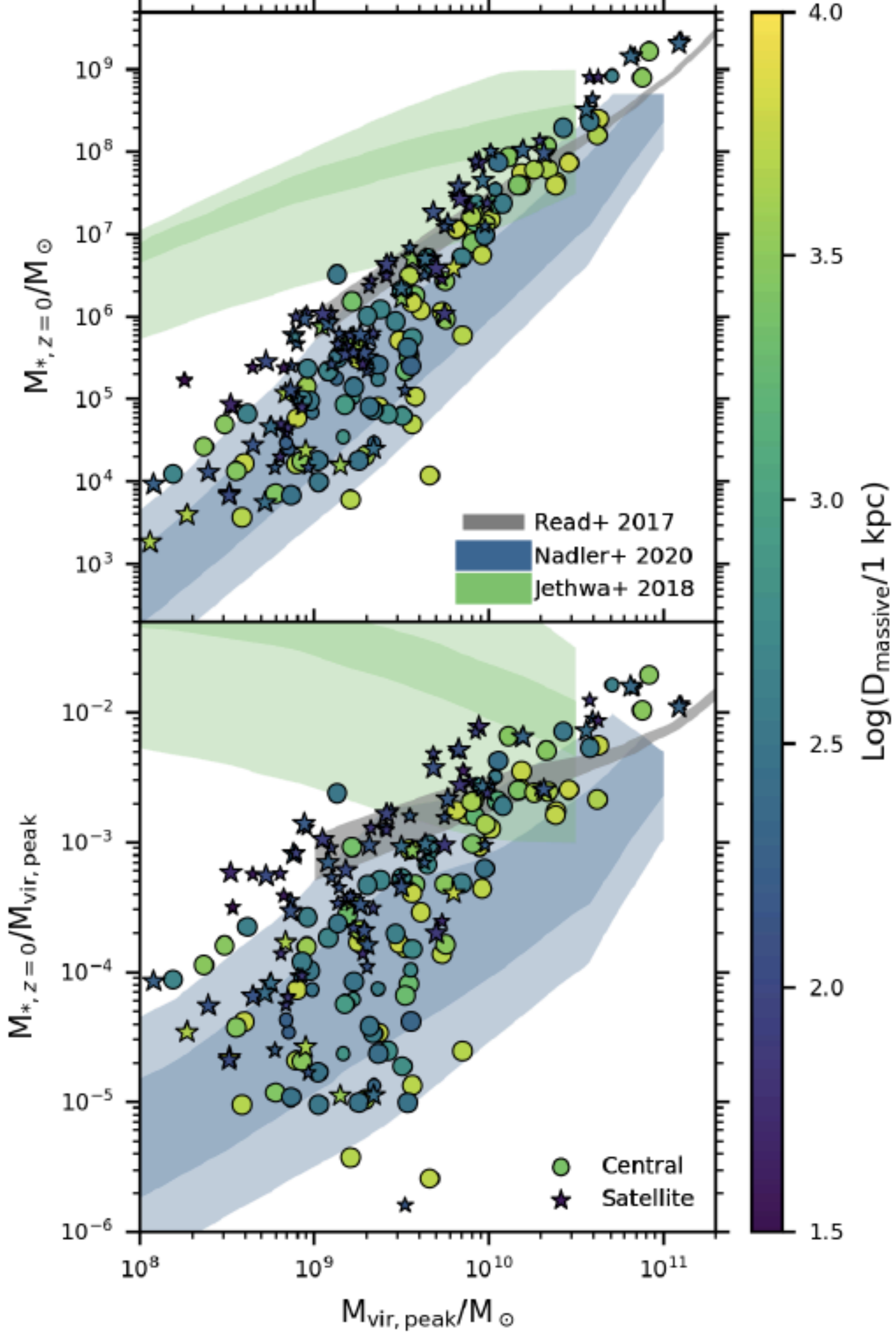
Upcoming: Effect of Environment

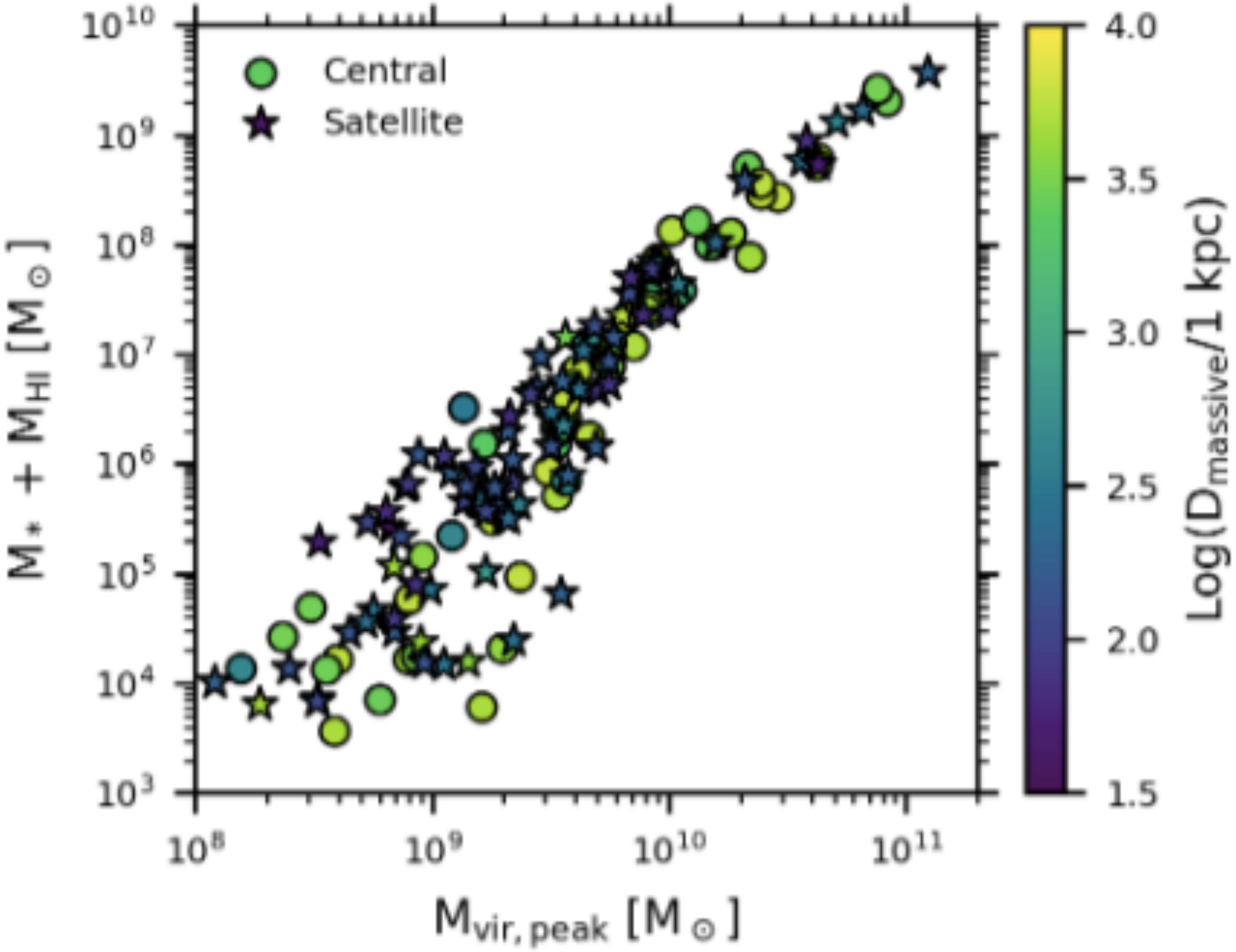
Christensen, Munshi+ in prep (draft circulating!)



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

Upcoming: Effect of Environment

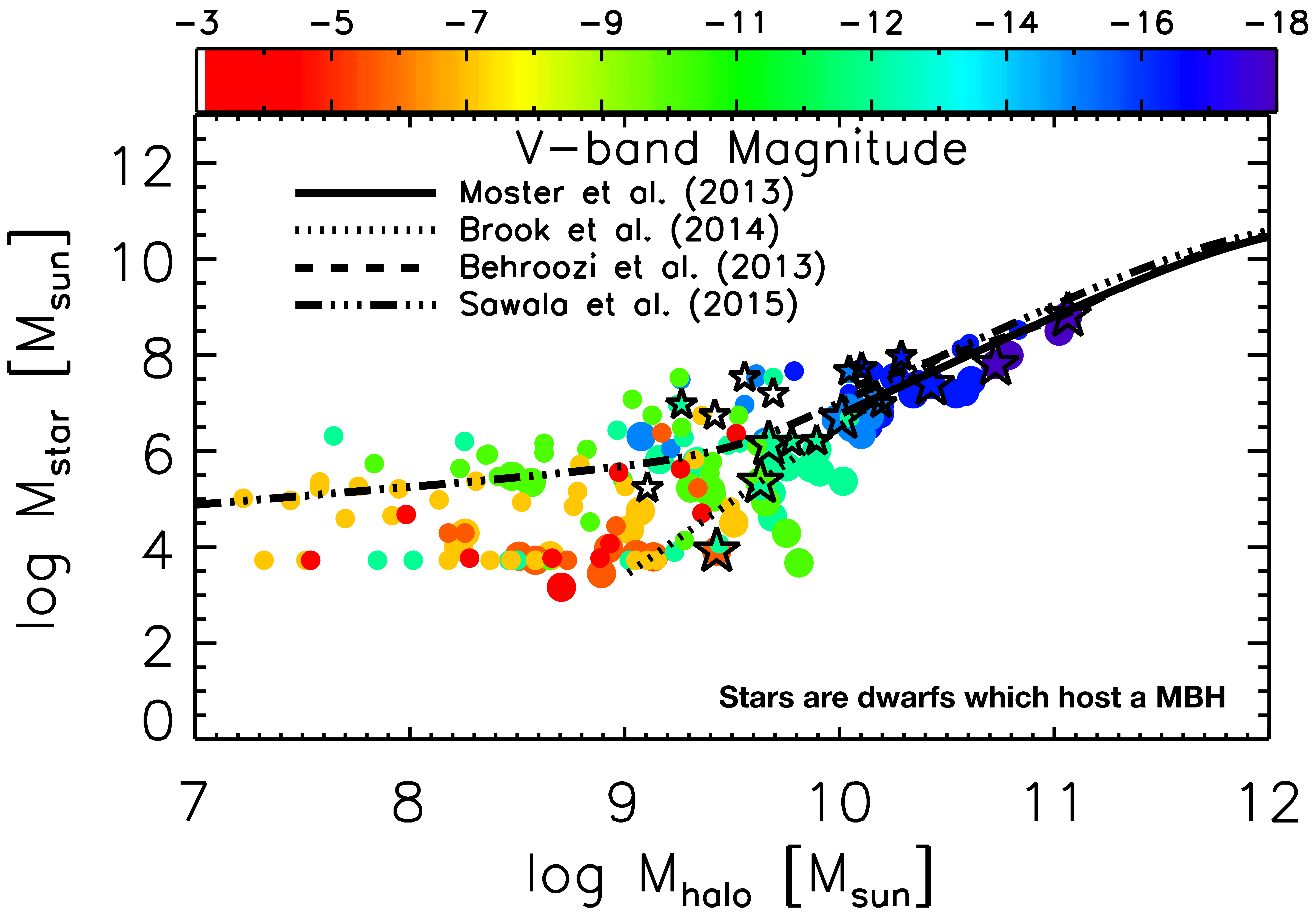




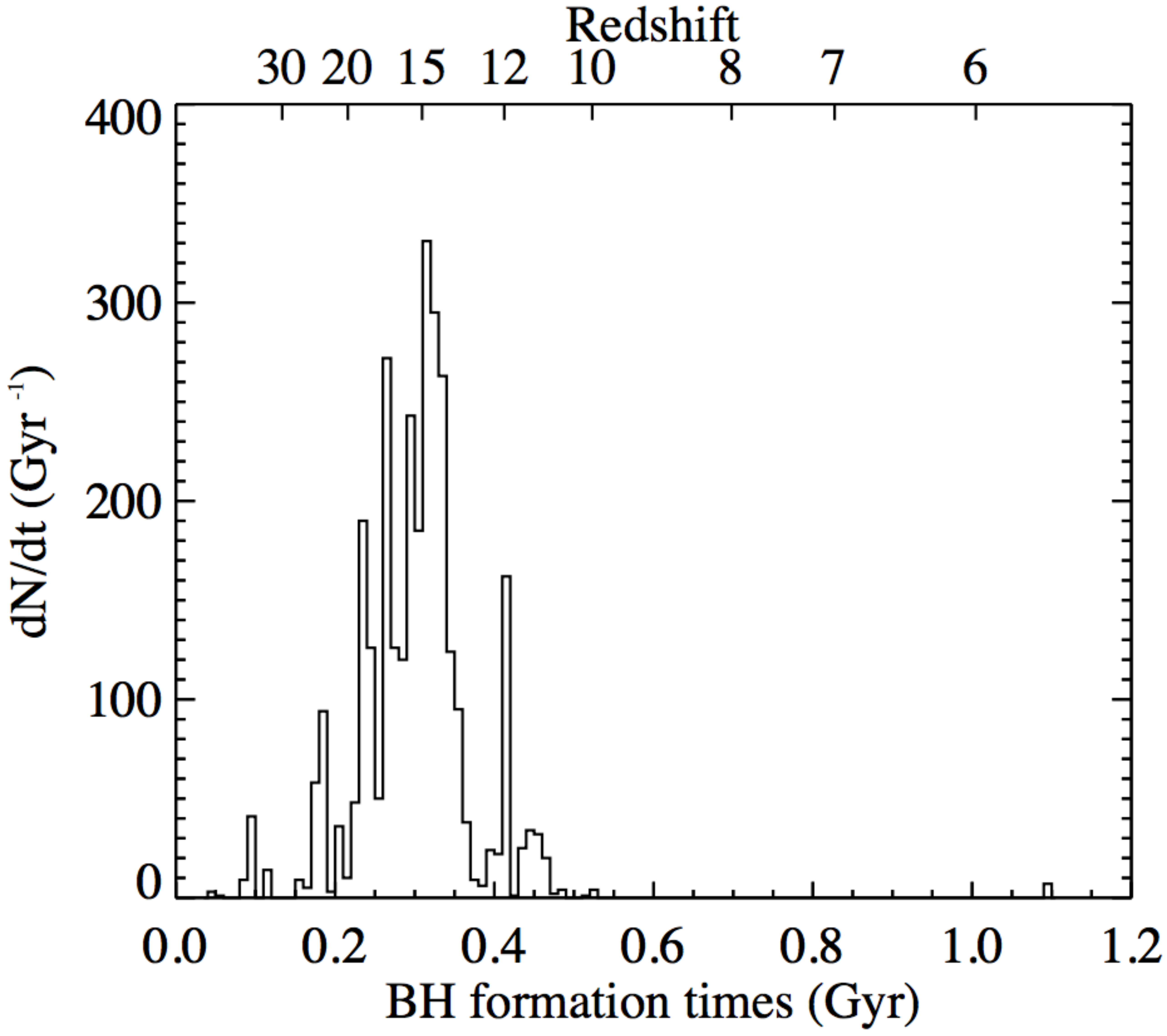
Christensen, Munshi+ in prep (draft circulating!)

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



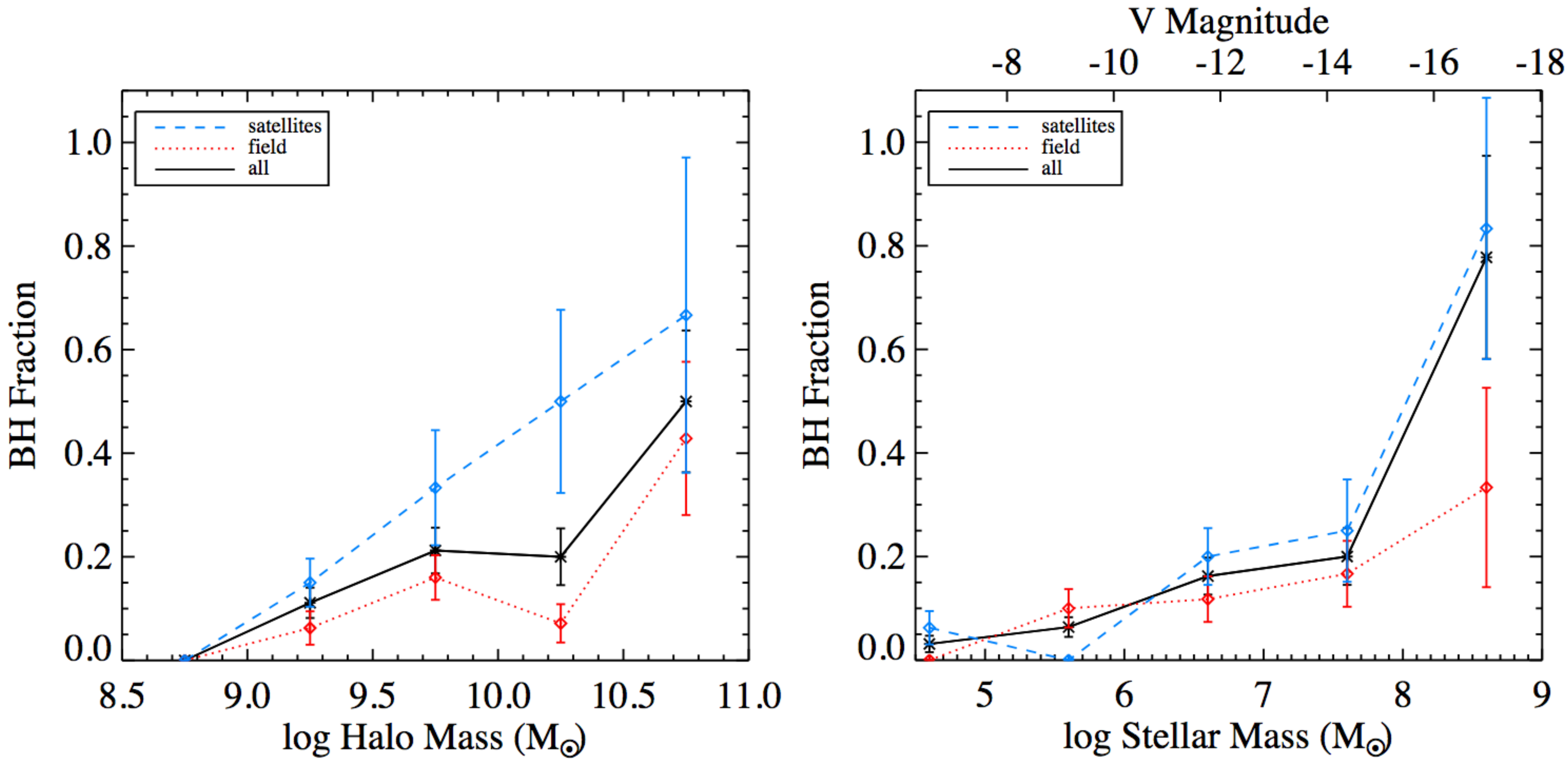
Bellovary, Cleary, Munshi + (2018)



- 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)

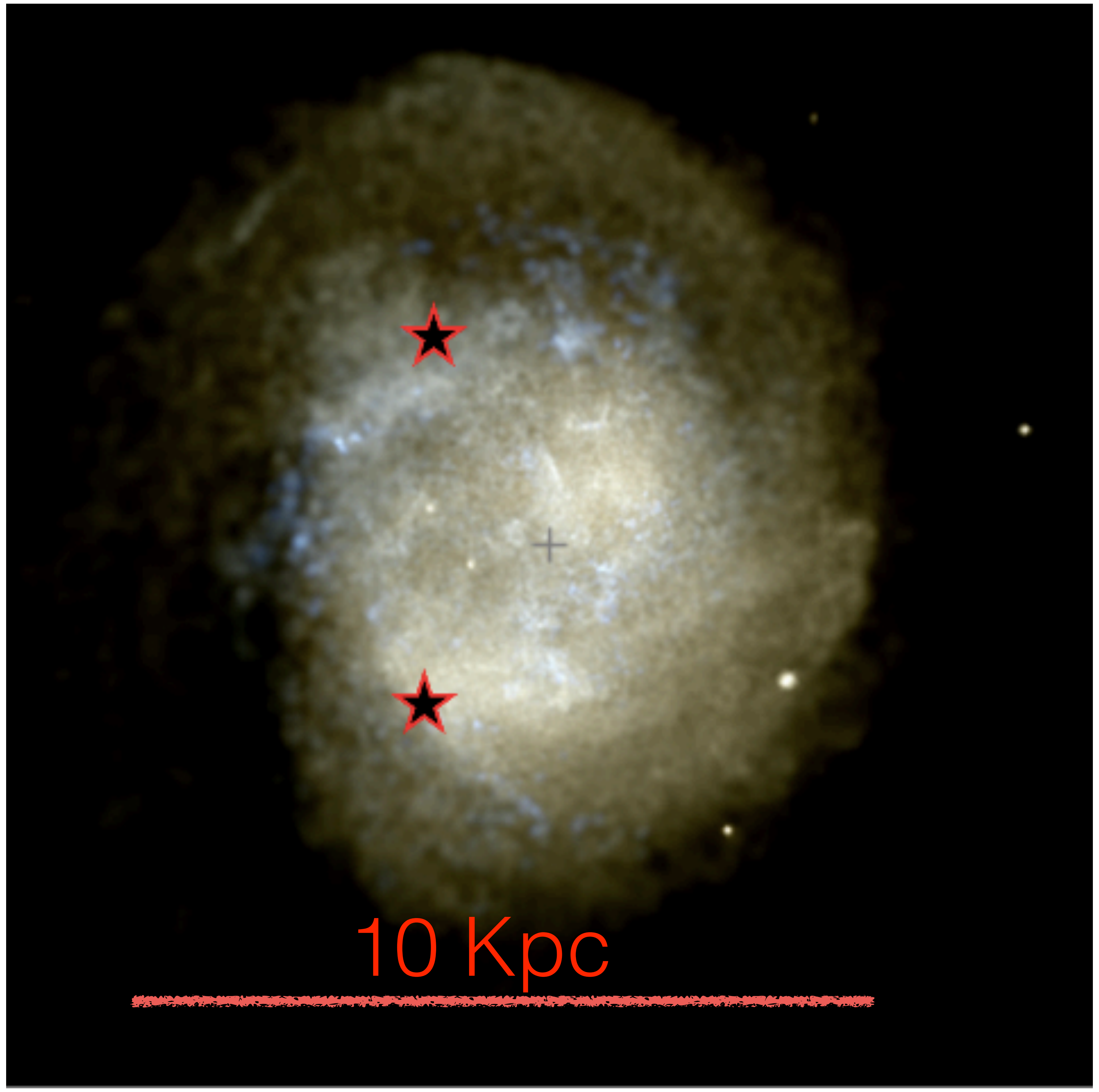
Bellovary, Cleary, Munshi + 2018

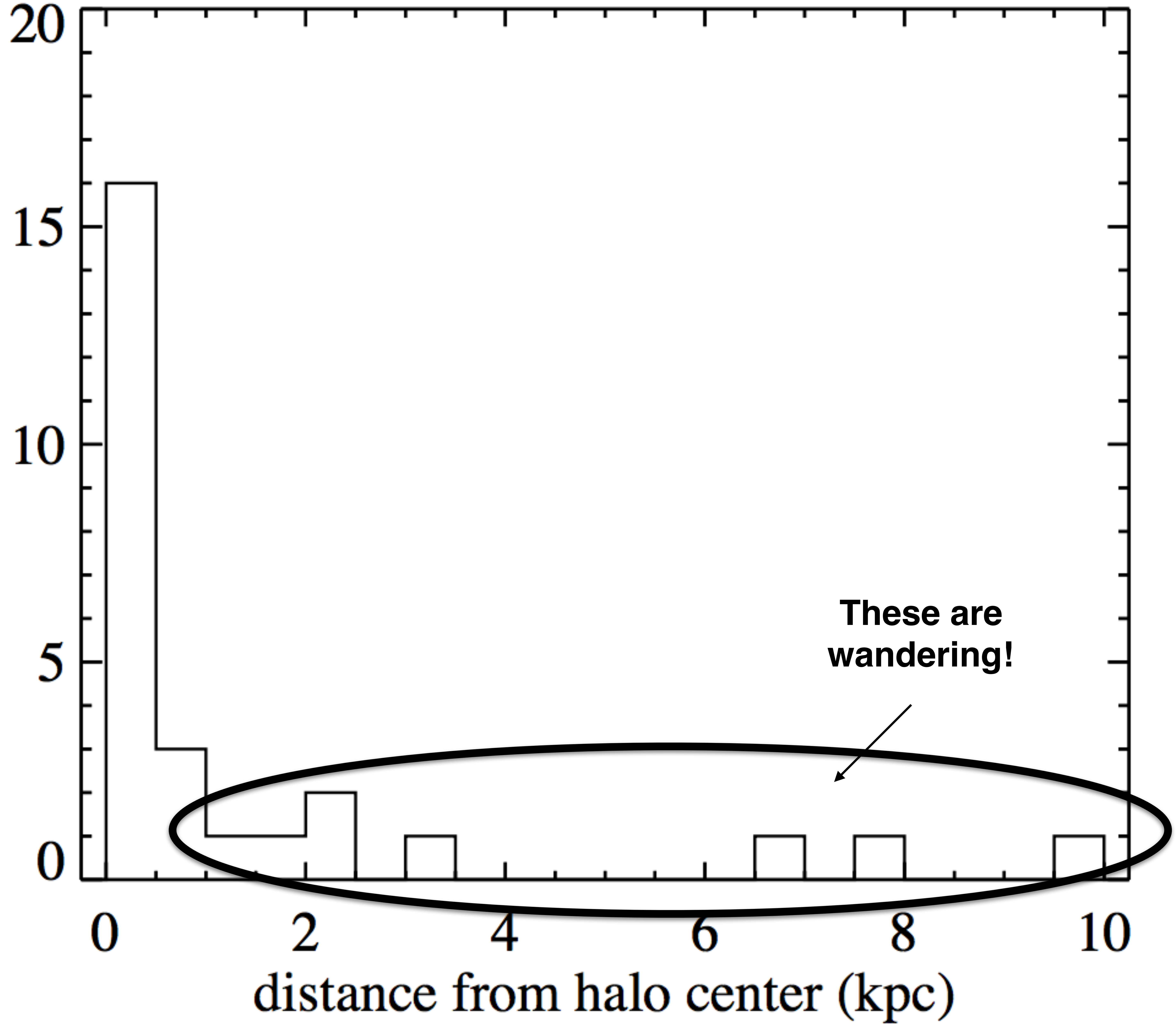


- **No environmental difference in occupation fraction**- halo masses are sensitive to environment due to tidal stripping

Bellovary, Cleary, Munshi + 2018

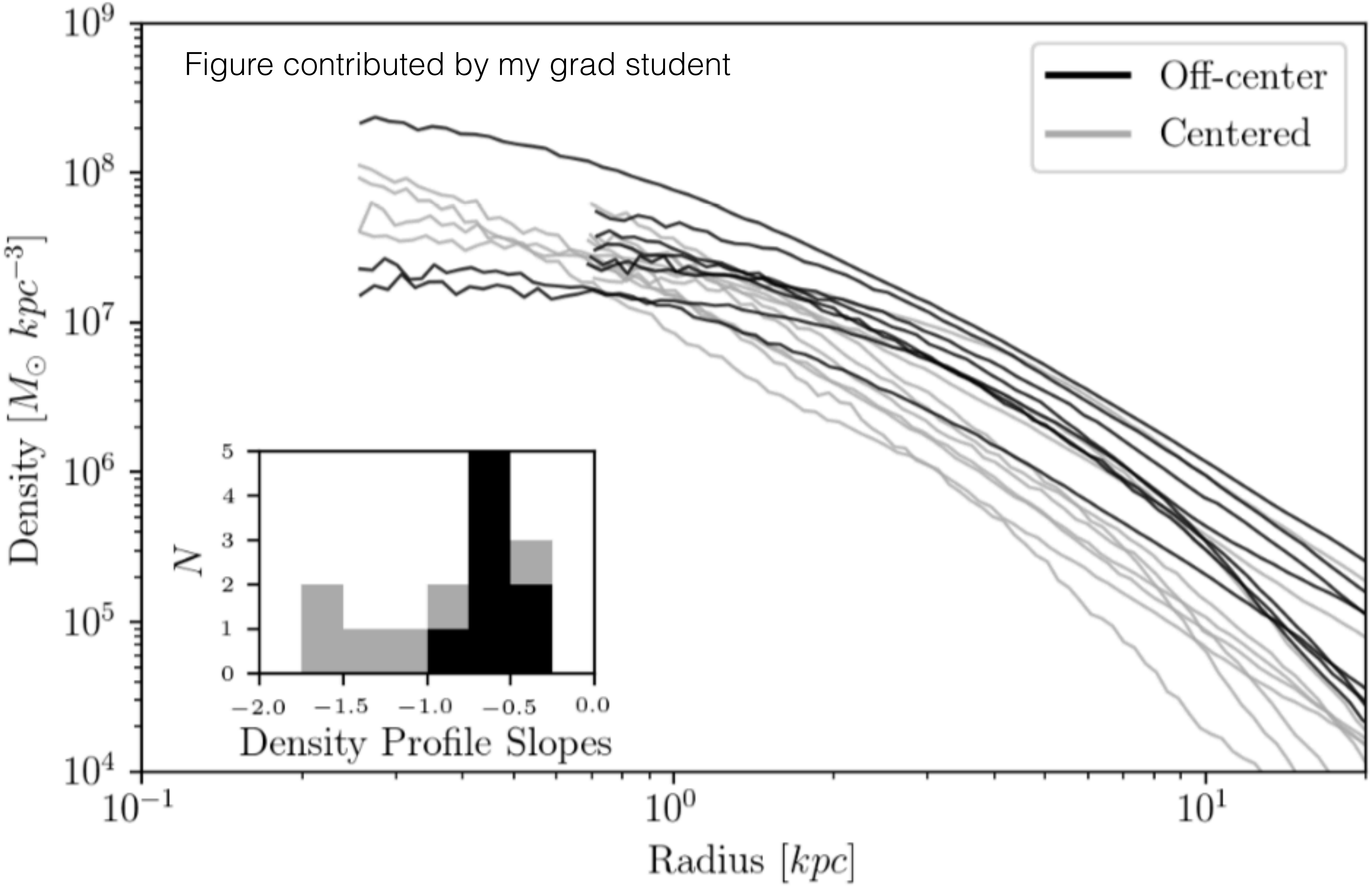
They are not necessarily in the center of dwarf halos!



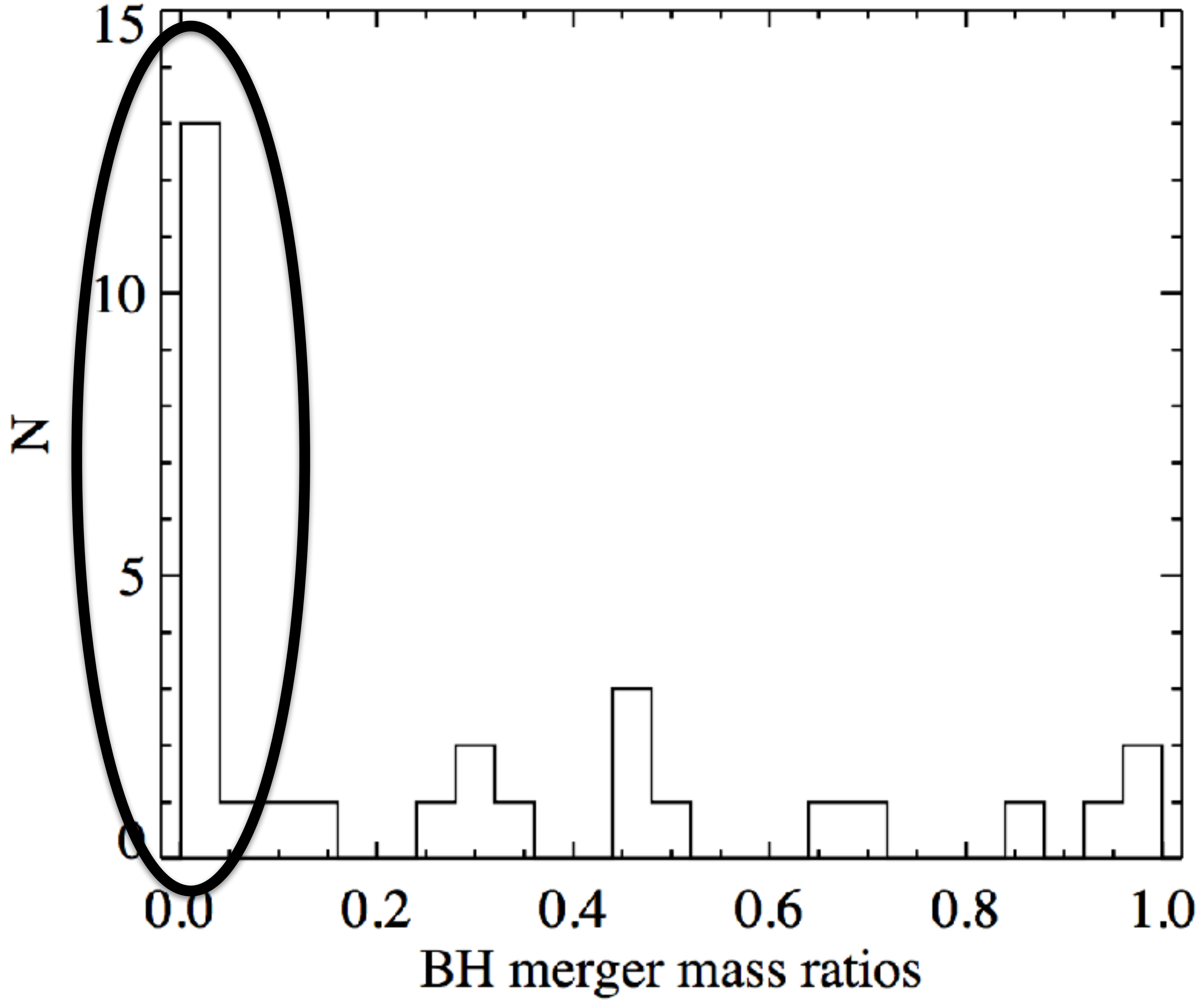


Bellovary, Cleary, Munshi + (2018)

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



Bellovary, Cleary, Munshi + 2018
Bellovary…+ Munshi + 2021



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

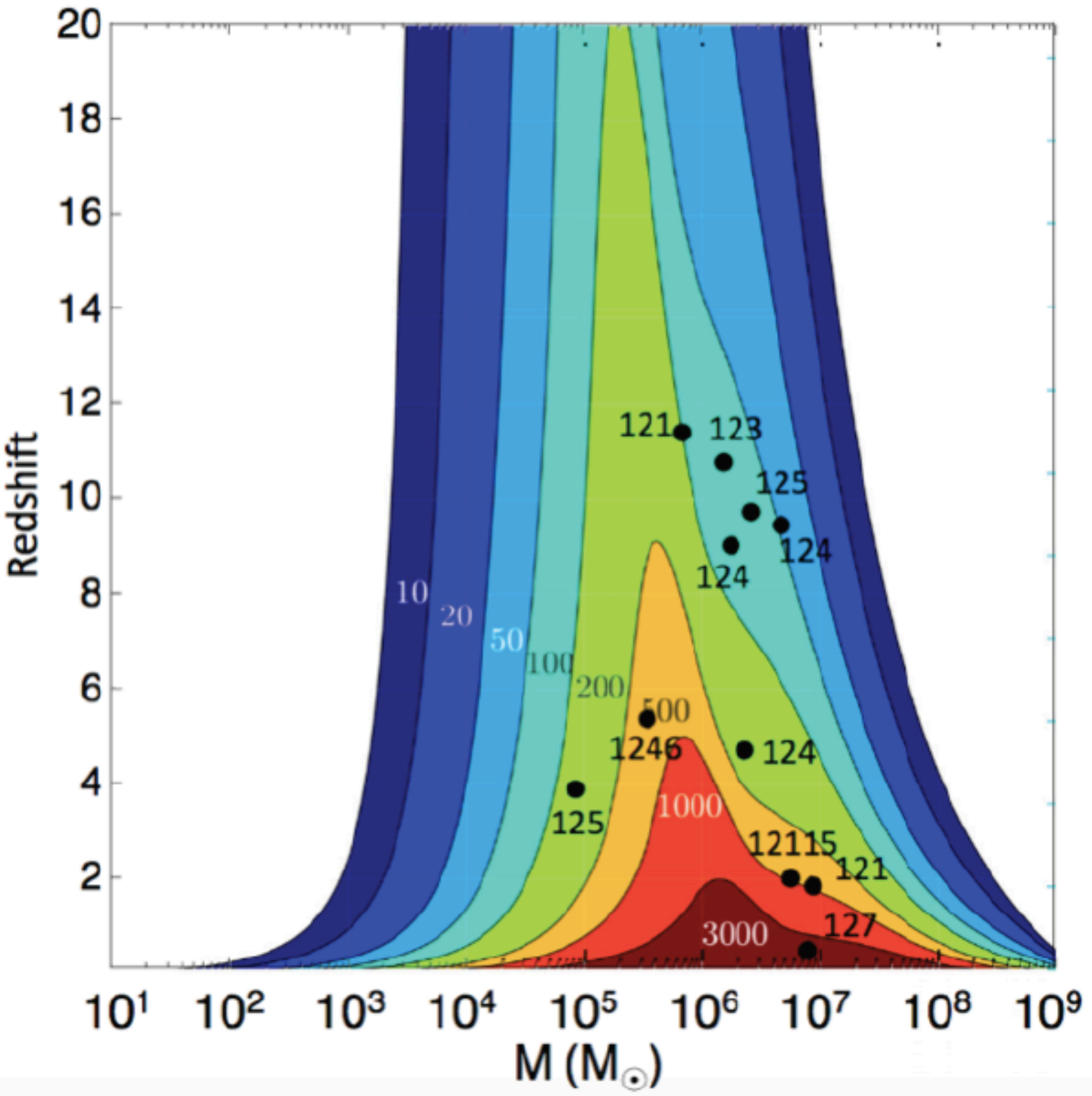
"wandering" off-center MBHs are due to mergers (usually with a larger galaxy)

Core stalling happens 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?

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.**

Key Problems

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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 ($M_{star} < 10^7 M_{sun}$) 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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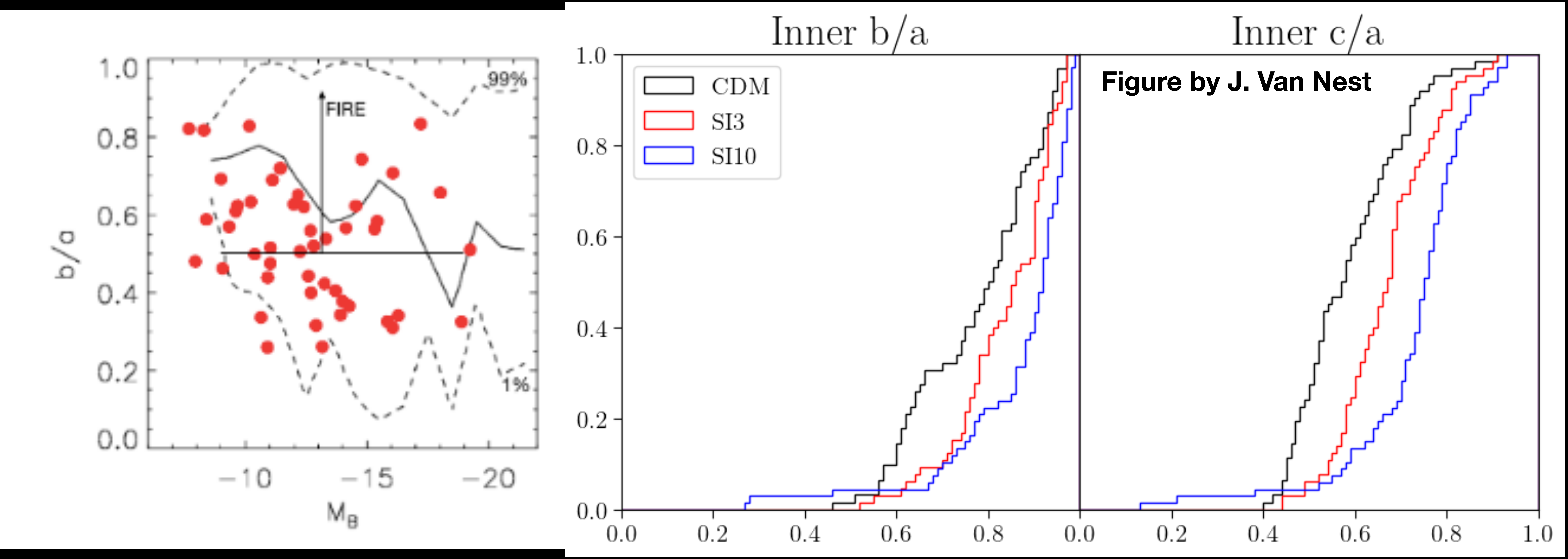
Dwarf halo shape as a tracer of dark matter physics?



Only simulations to reproduce full range of dwarf shapes

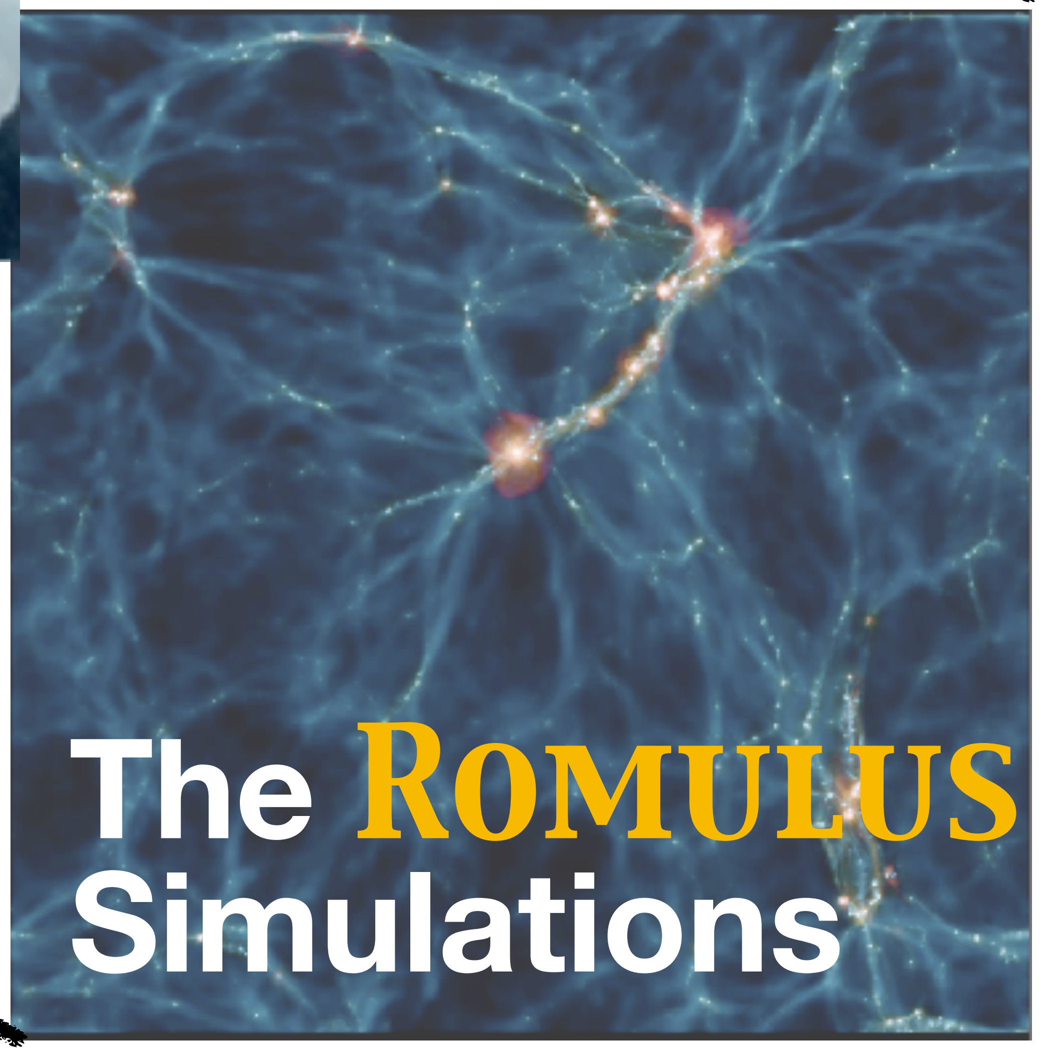
Funded NSF proposal to study SIDM in zooms

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

Ultra-faints in isolation

Ultra-faints in the vicinity of a MW

Dwarfs (and UDGs) across environments

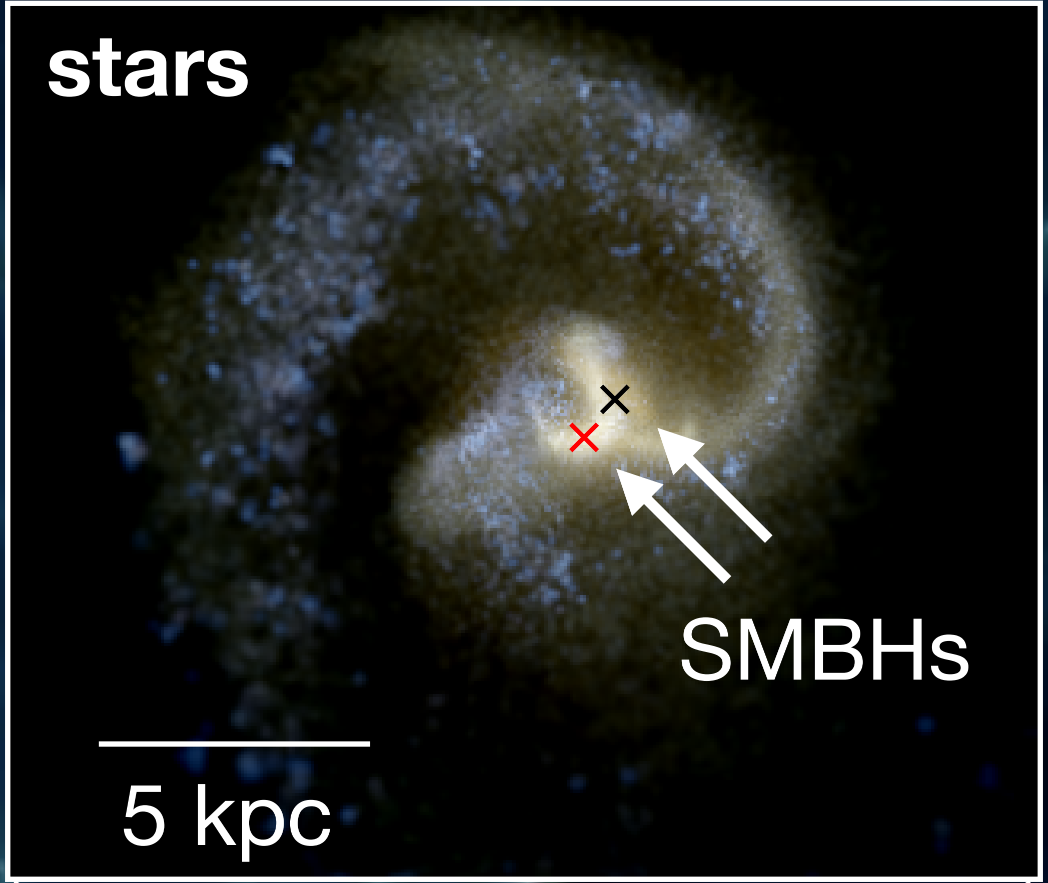


The ROMULUS Simulations

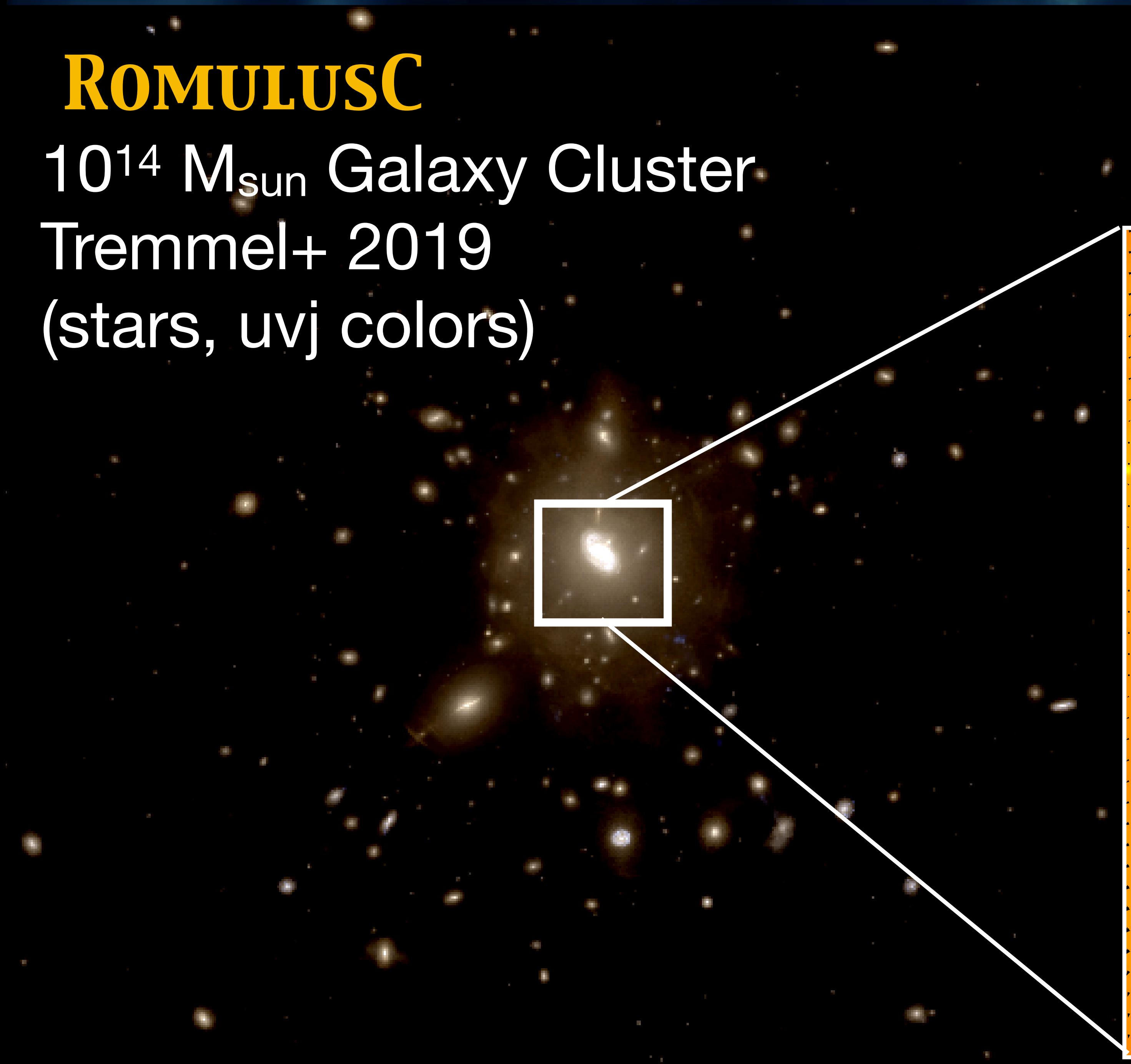
Certified organic, free-range, locally grown supermassive black holes

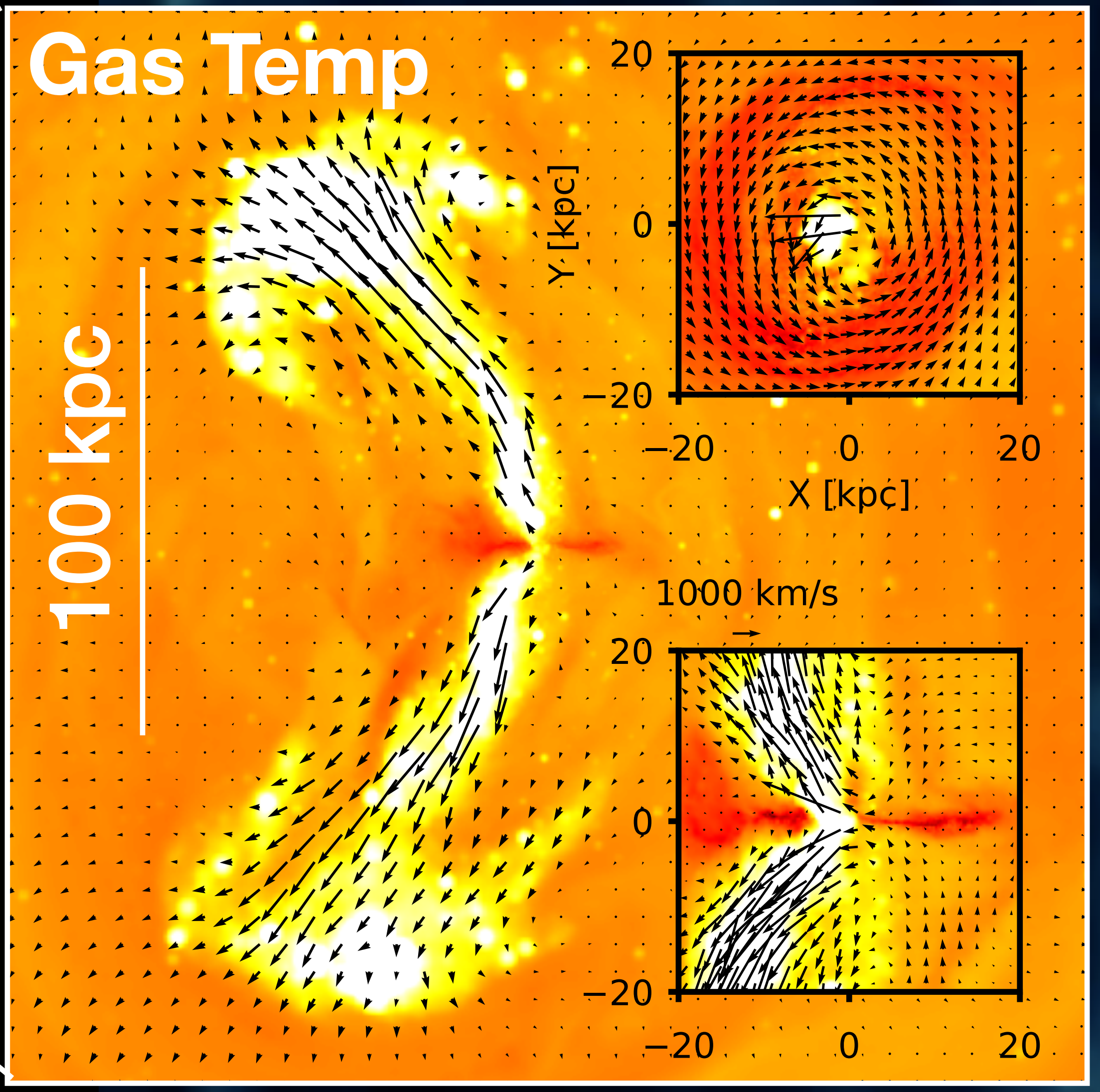
- ✓ Early Seeding in low mass halos
- ✓ Self-consistent and physically motivated dynamics, growth, and feedback
- ✓ Naturally produces large-scale outflows
- ✓ **No unnecessary additives or assumptions**

ROMULUS25
25 Mpc Volume
Tremmel+ 2017
(gas temp)



ROMULUSC
10^{14} M_{sun} Galaxy Cluster
Tremmel+ 2019
(stars, uvj colors)

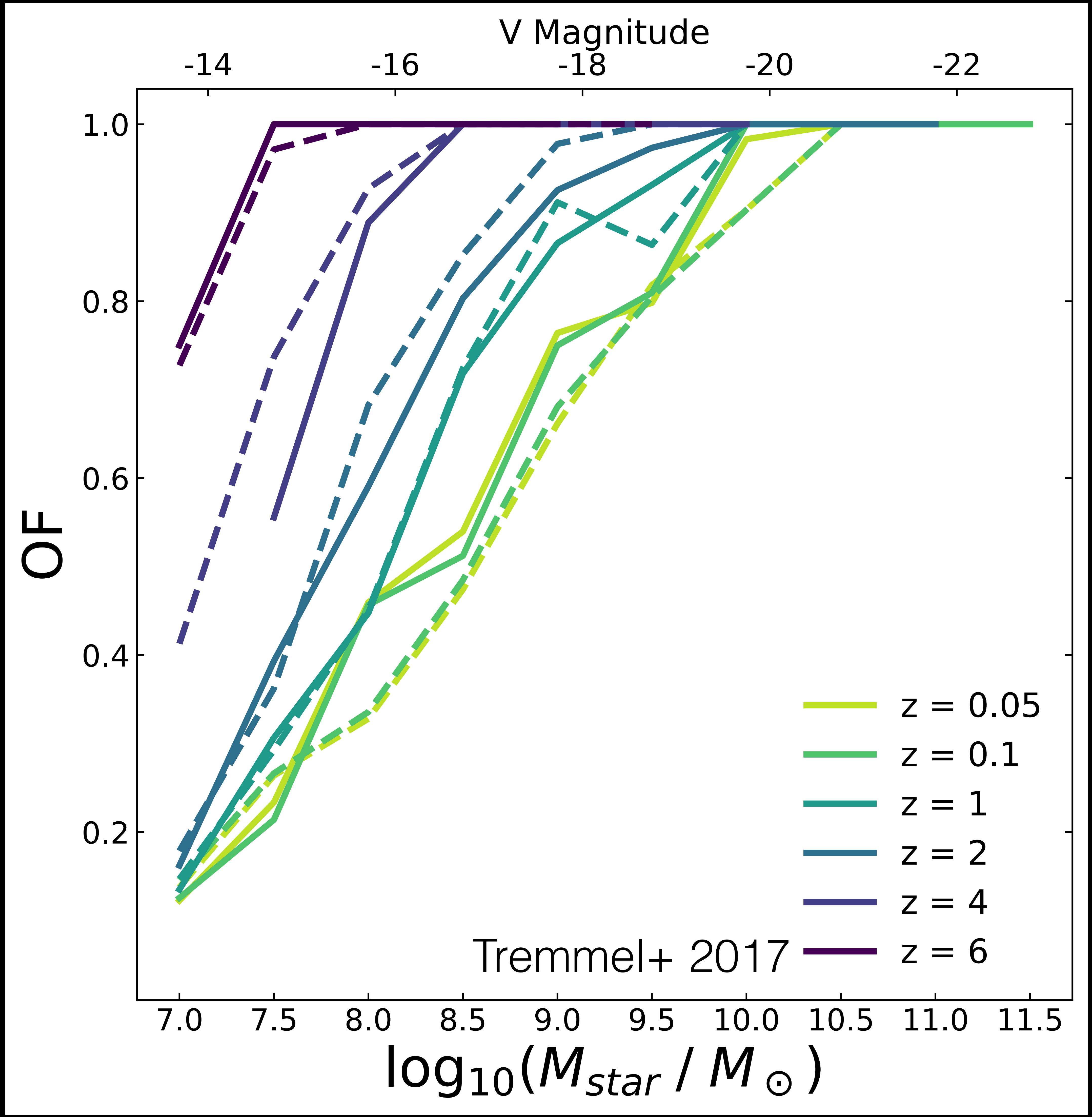




Resolution:
250 pc (grav)
70 pc (hydro)
~1e5 M_{sun}

The Romulus25 Simulation

Physically motivated models for SMBH formation, growth, and dynamics



SMBHs are seeded **early** and exist in **small halos** with **evolving halo occupation**

✓ High **Resolution**

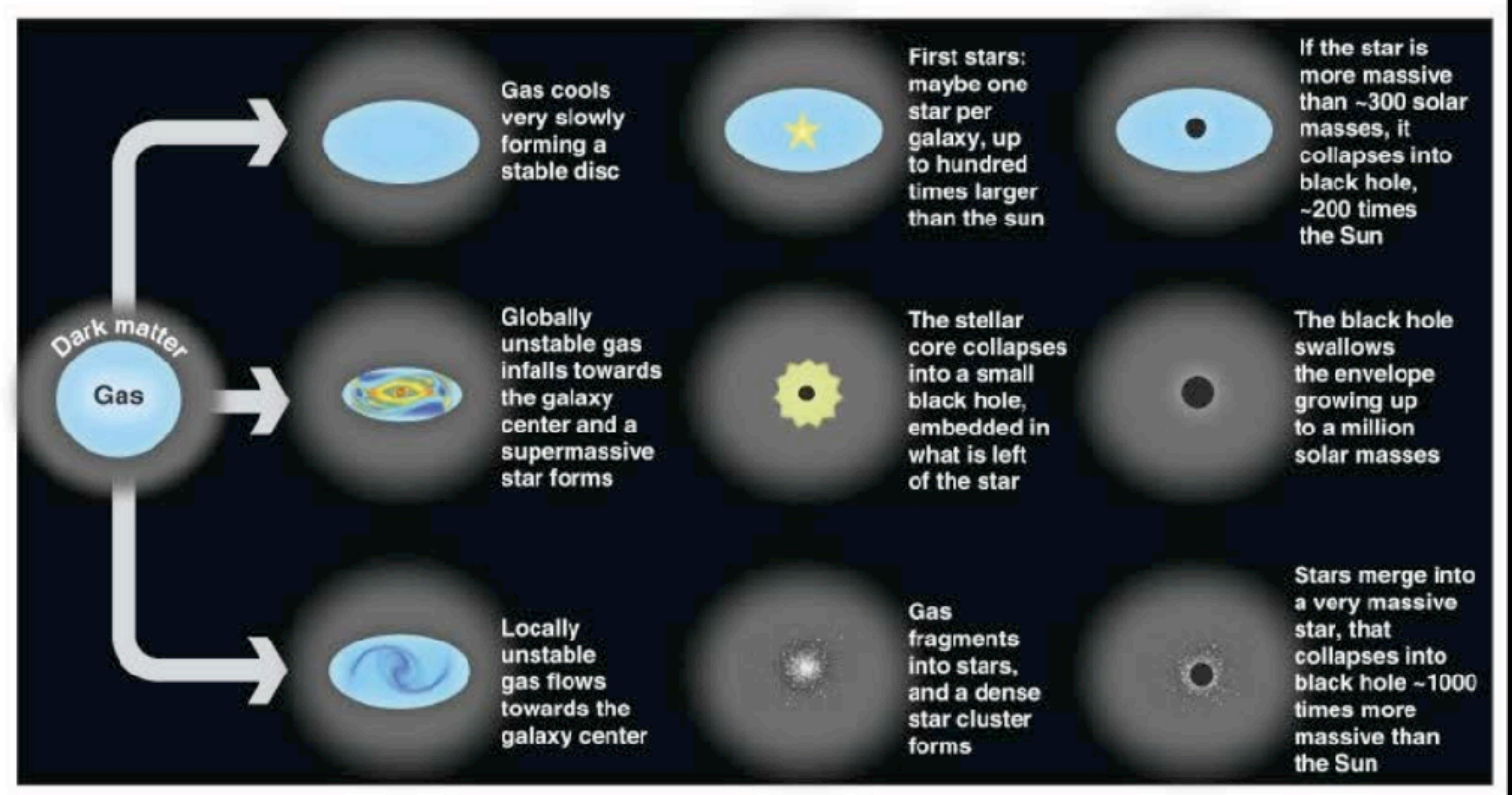
✓ Resolved SMBH **dynamics**

✓ **Predicts** Large-scale AGN outflows that regulate star formation

Supermassive Black Holes and Galaxies

Where are the intermediate mass BHs?

- Where do they come from?
  First stars? -> Common, low mass ~10-100 M_{sun}
  Direct collapse? -> Rare, 10^4-10^6 M_{sun}
  Collapsing nuclear star cluster? -> Rare, ~10^3 M_{sun}

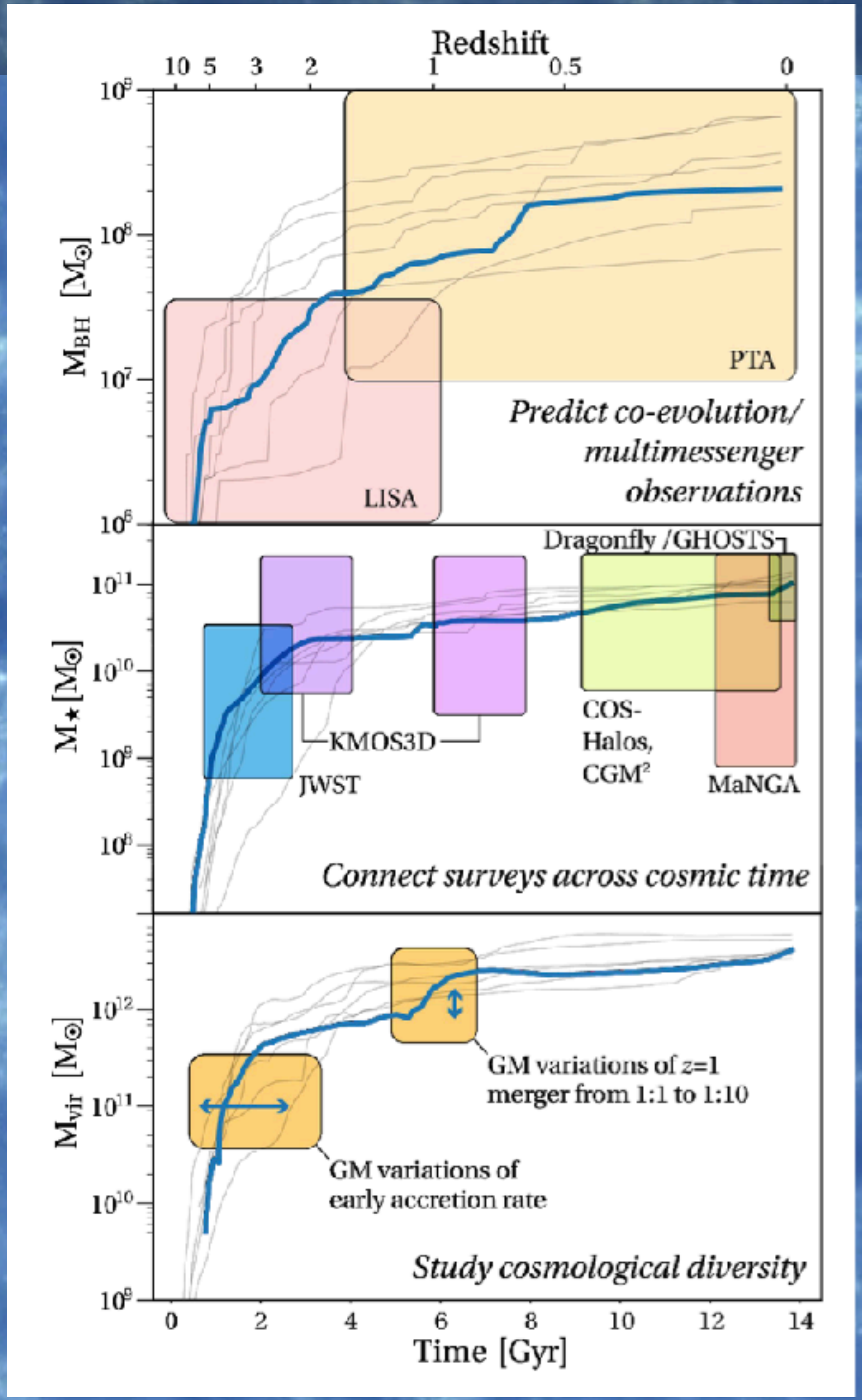


Current DCJL zooms, Romulus25 can be used to study the above- **providing powerful predictions for GW studies, like LISA**

Volonteri 2012

Collaborator on NSF proposal to study black hole seed mechanisms in cosmological zooms

Research Synergy with GMU Physics & Astronomy: Unique implementation for BH seeding and feedback in both zooms and volumes- predictions for feedback, galaxy co-evolution- particularly at low masses!



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

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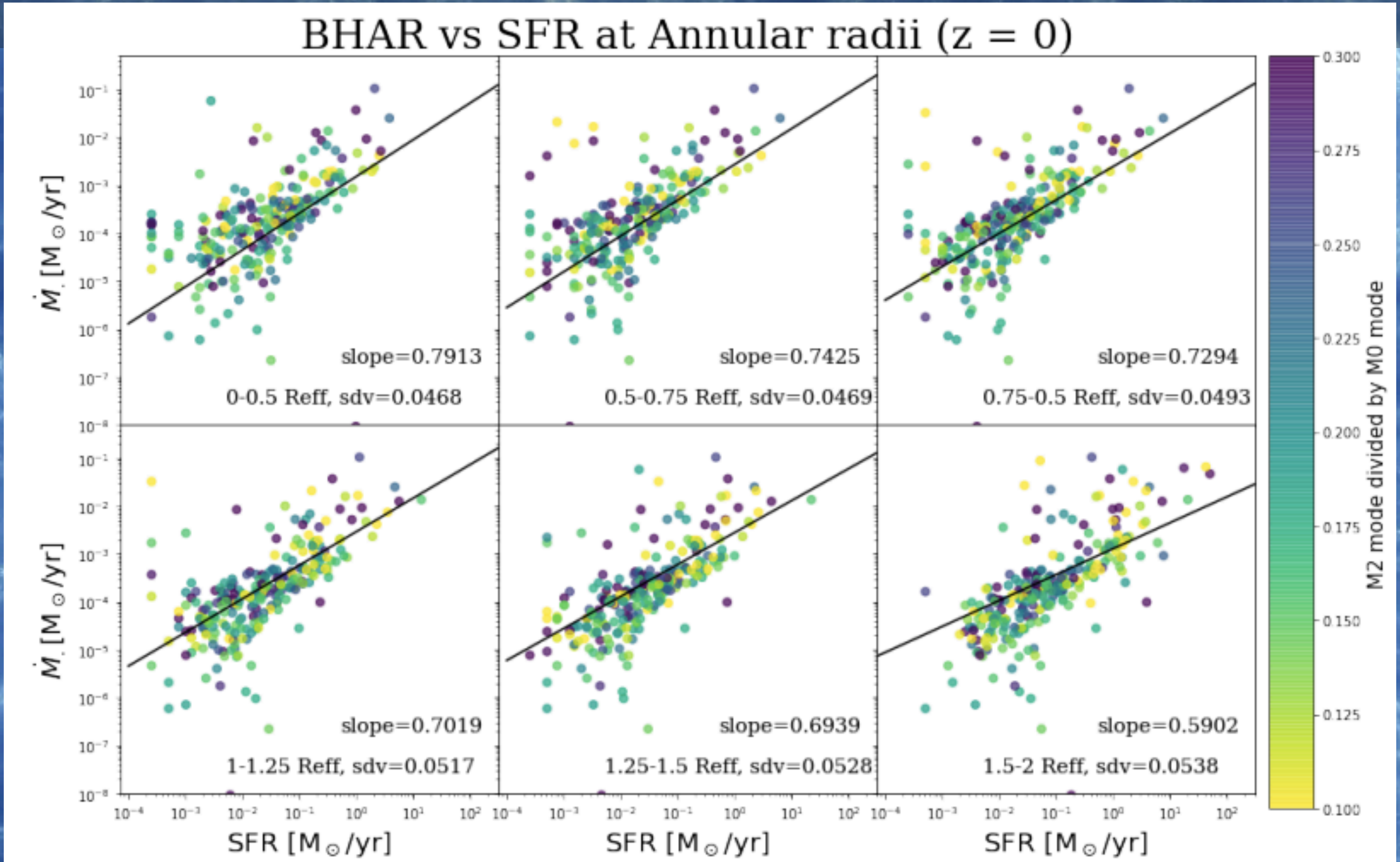
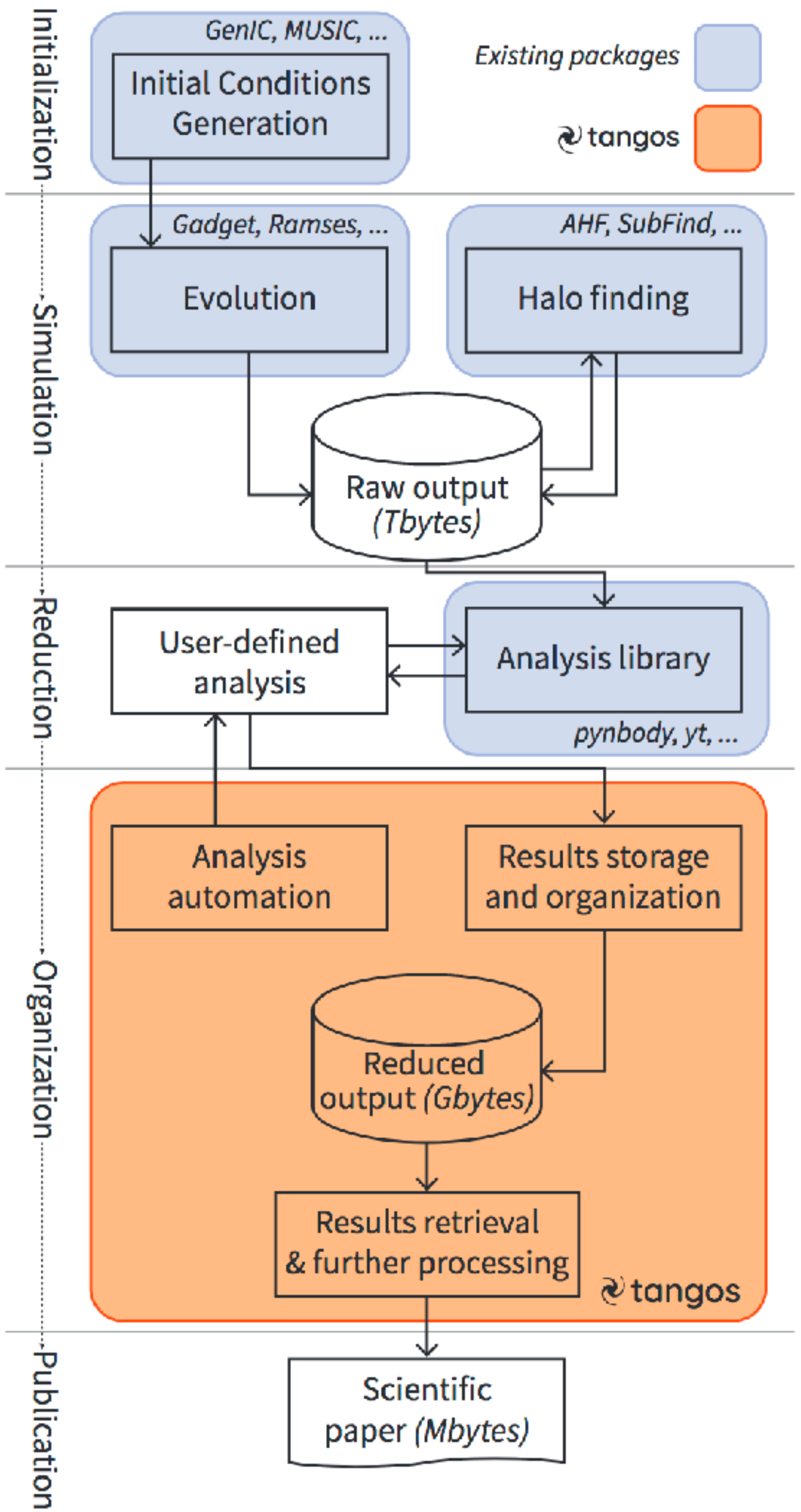


Anna Engelhardt (OU REU)

Leveraging “Big Data” techniques

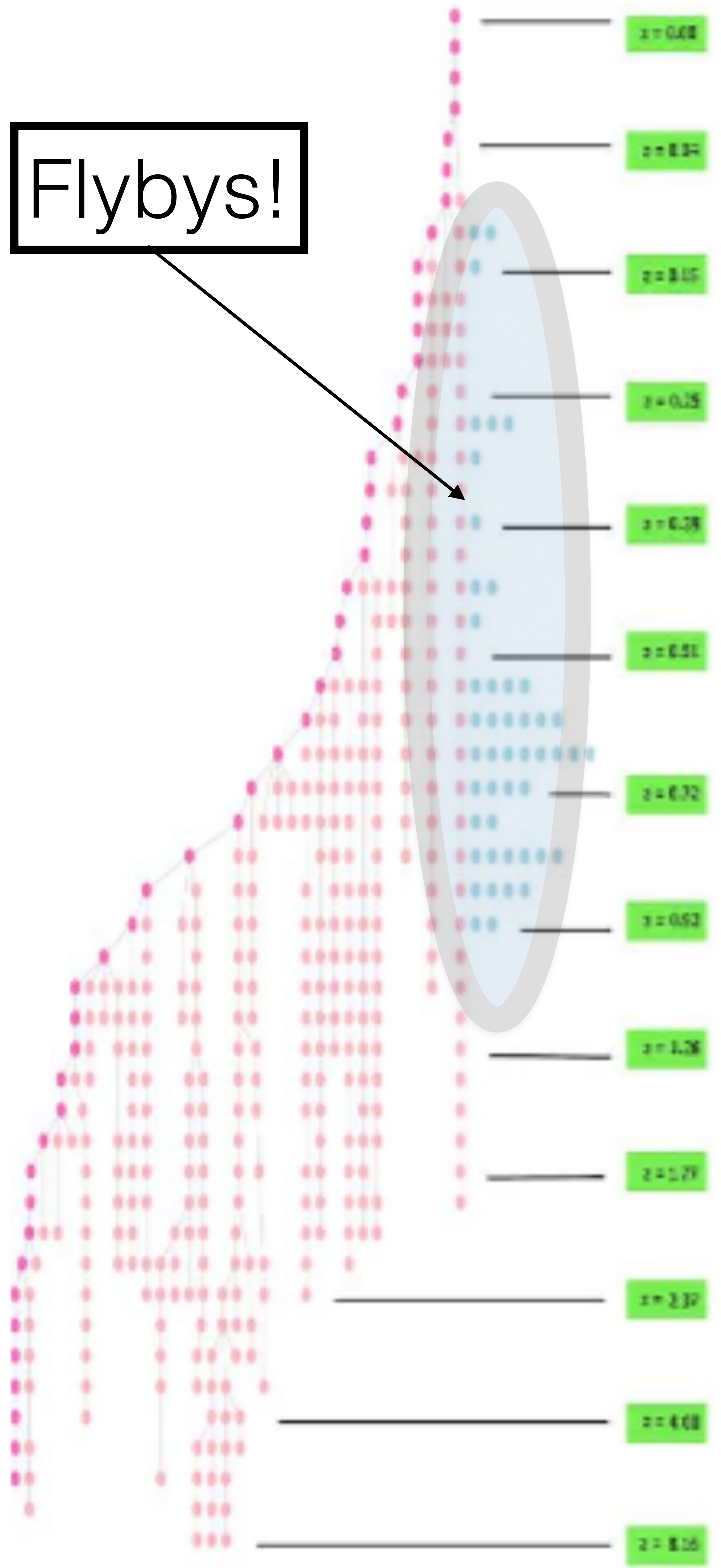
TANGOS **Halo Database:** ingests, runs and calculates various basic properties of all halos in a simulation (including profiles, images etc) then exposes them through a python interface and webserver.



Pontzen+ 2018

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

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?)

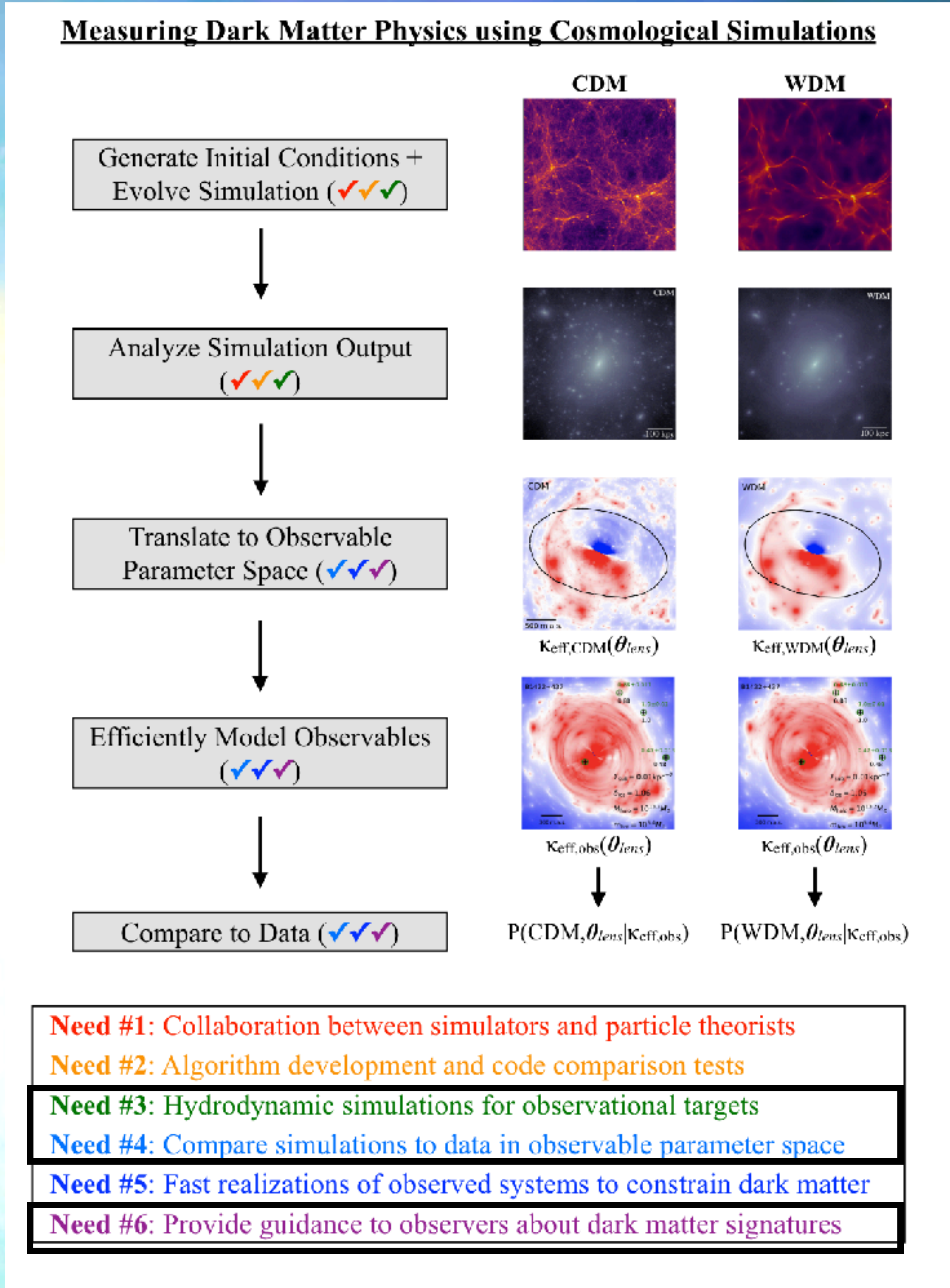
e.g. DiCintio+ 2019

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?

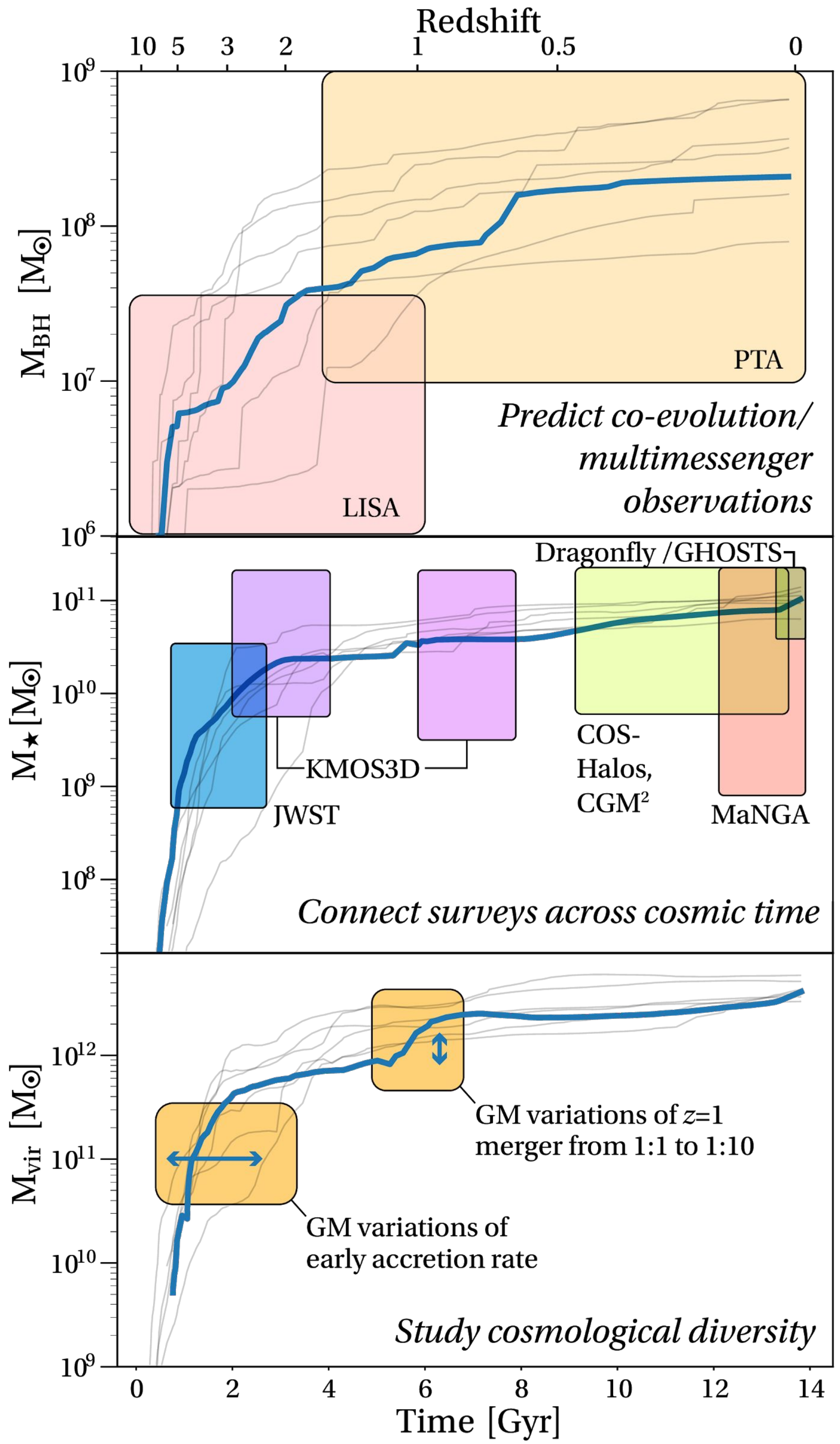
FDM acknowledges that Oklahoma's land is the traditional territory of the Osage, Cherokee, Choctaw, Chikasaw and Patowatomi Peoples.

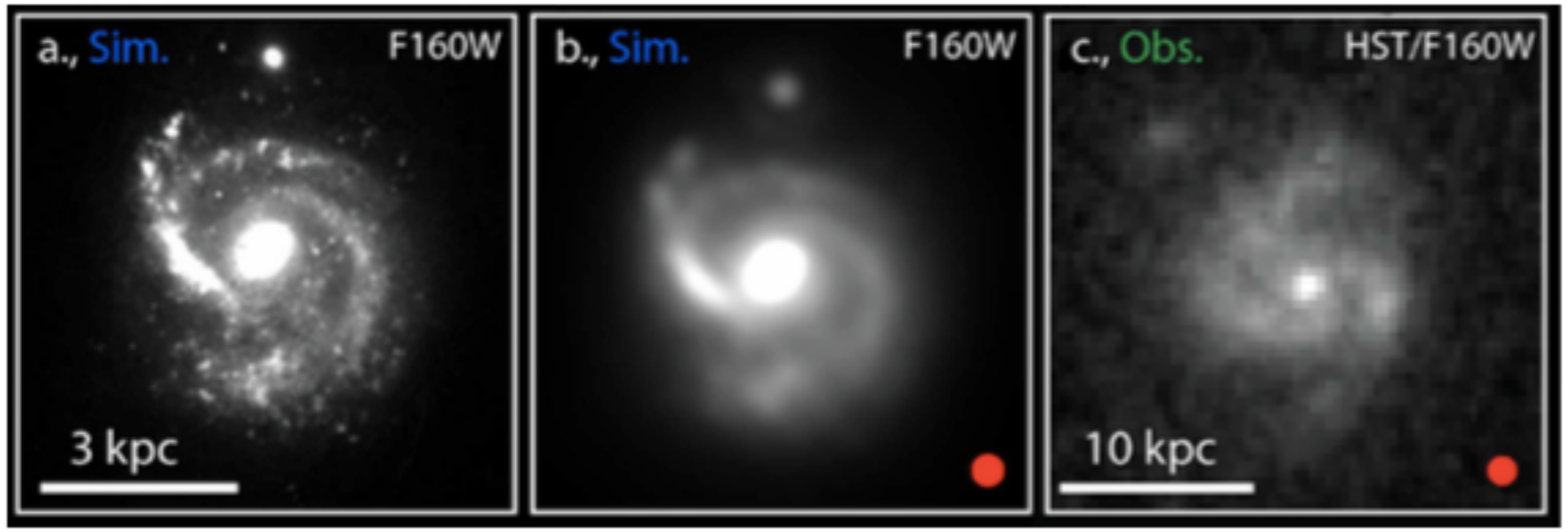


From the Snowmass draft cosmic frontier numerical simulation white paper (FDM lead)

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

5 years- short term

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

4-5 more MW mass galaxies

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

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

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

5+ years - long term

1 CDM cluster **(+ 2** not quite at same resolution)

1 25 Mpc volume

Predicting LISA SMBH merger stats

How “normal” is the MW? How do you define a MW analog?

How many MWs have an LMC?

Are satellites different in Local Group environments?

Have submitted computational proposal for this (pending)

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

1 CDM cluster at x10 RomulusC resolution

1 Romulus25 to z=4 in SIDM

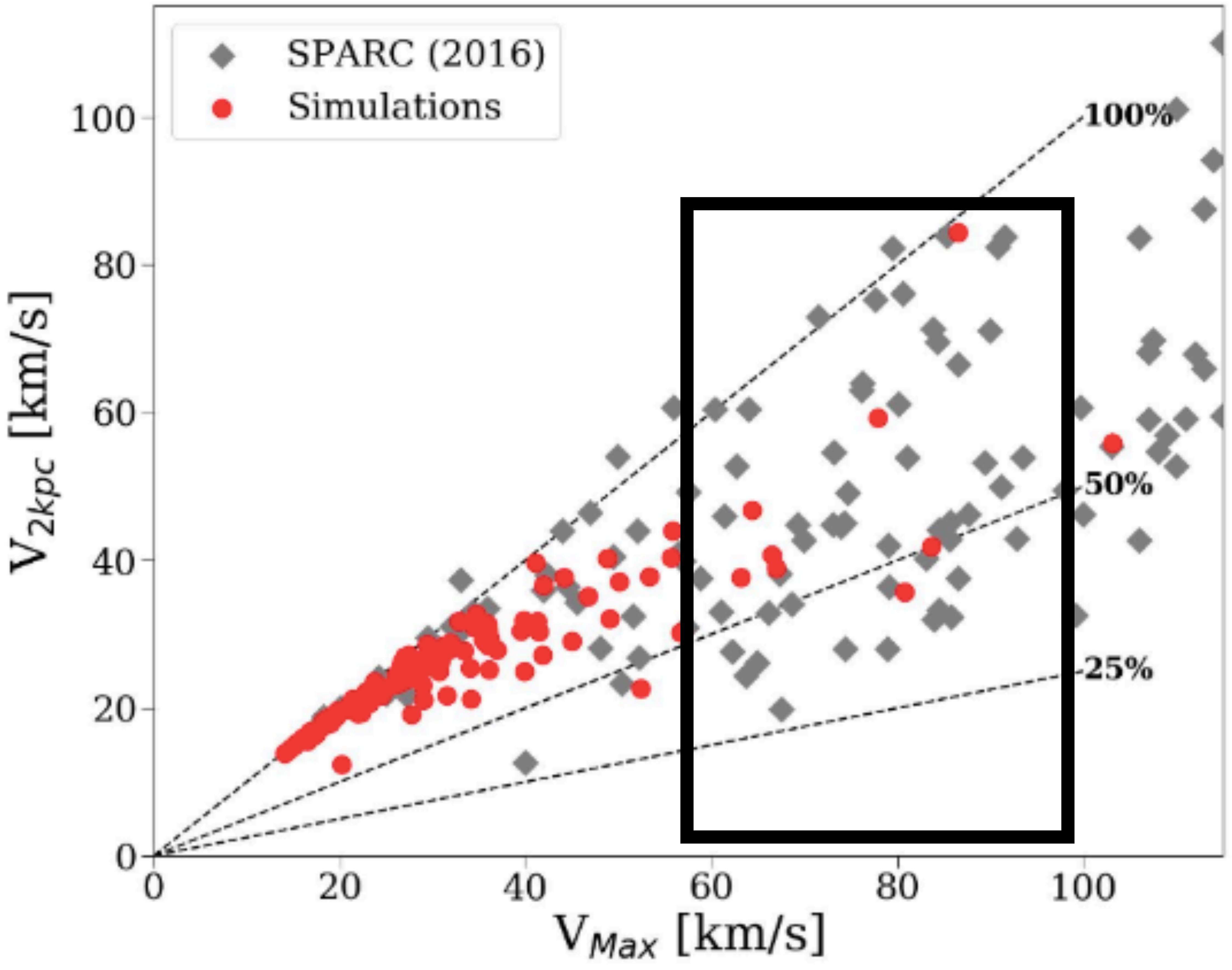
1 SIDM cluster

LISA SMBH constraints using SIDM

Intracluster light constraints on DM

In collab with K. Holley - Bockelmann, LISA science chair

SIDM Dwarfs: smoking gun in rotation curves?



New velocity dependence based on latest literature

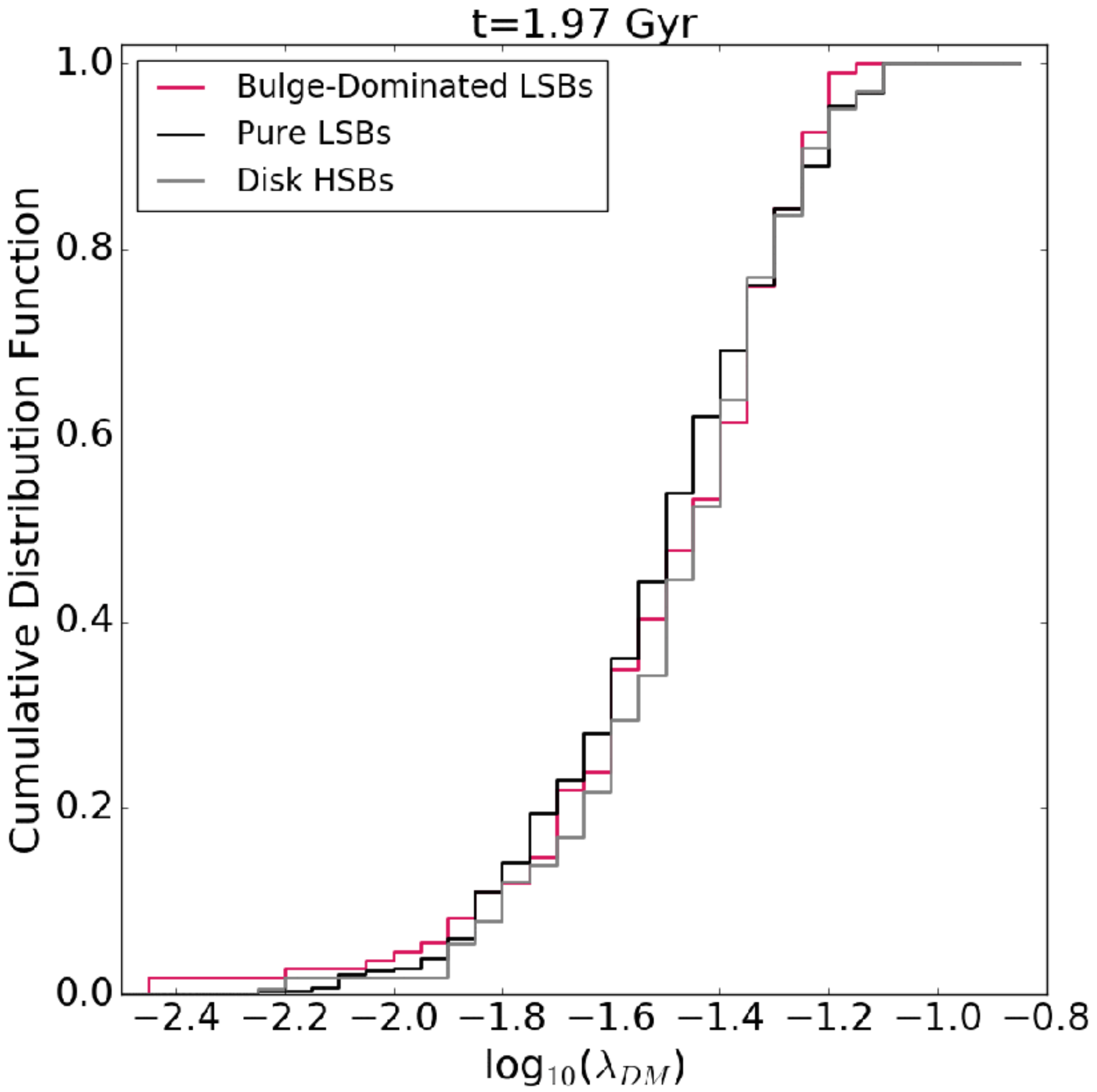
New CDM/SIDM dwarfs fill in parameter space

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



Martin et al. (2019), DiCintio et al. 2019

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

Former graduate student A. Wright has done pilot work on this

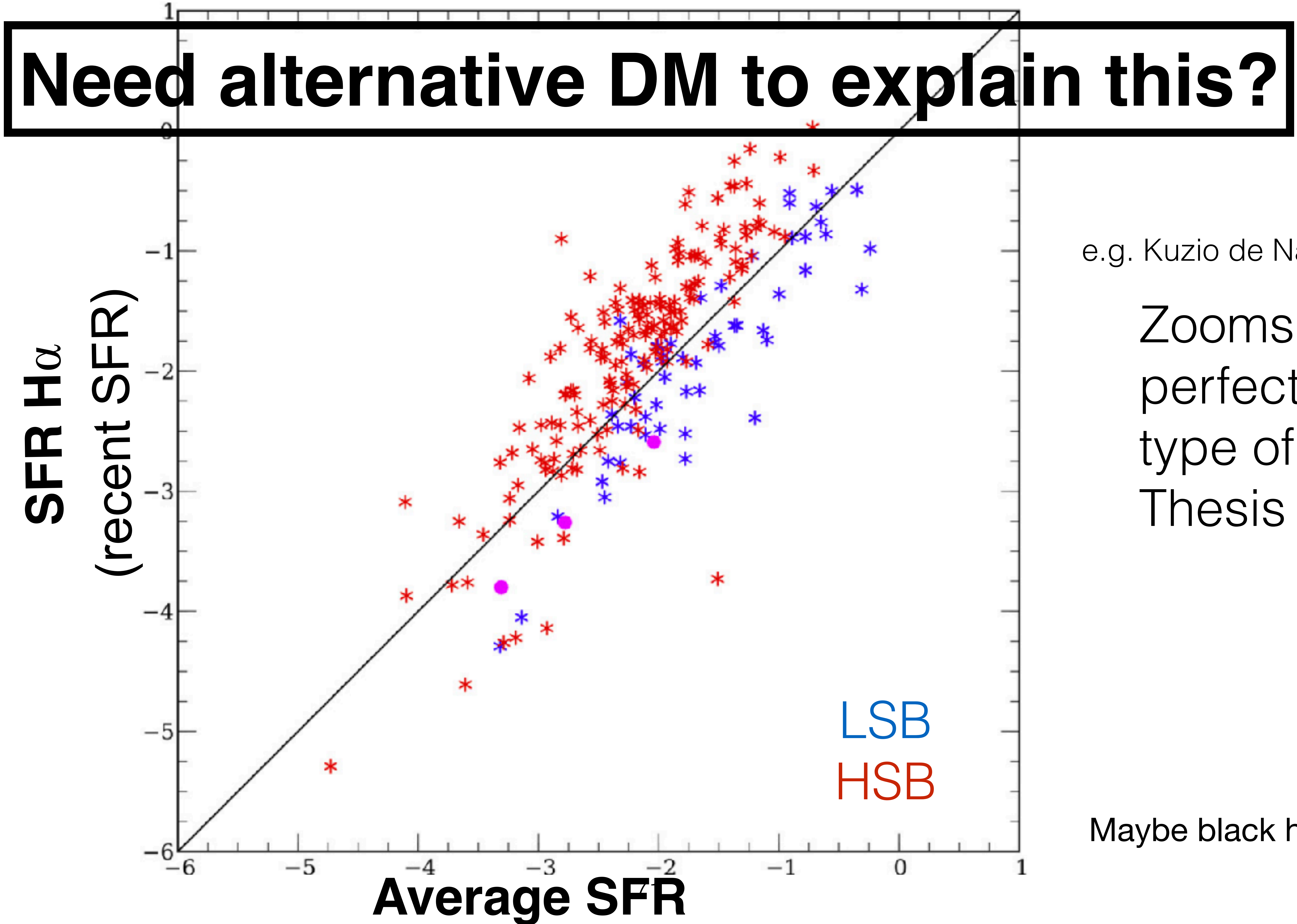
LSB zoom-in simulations

- 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



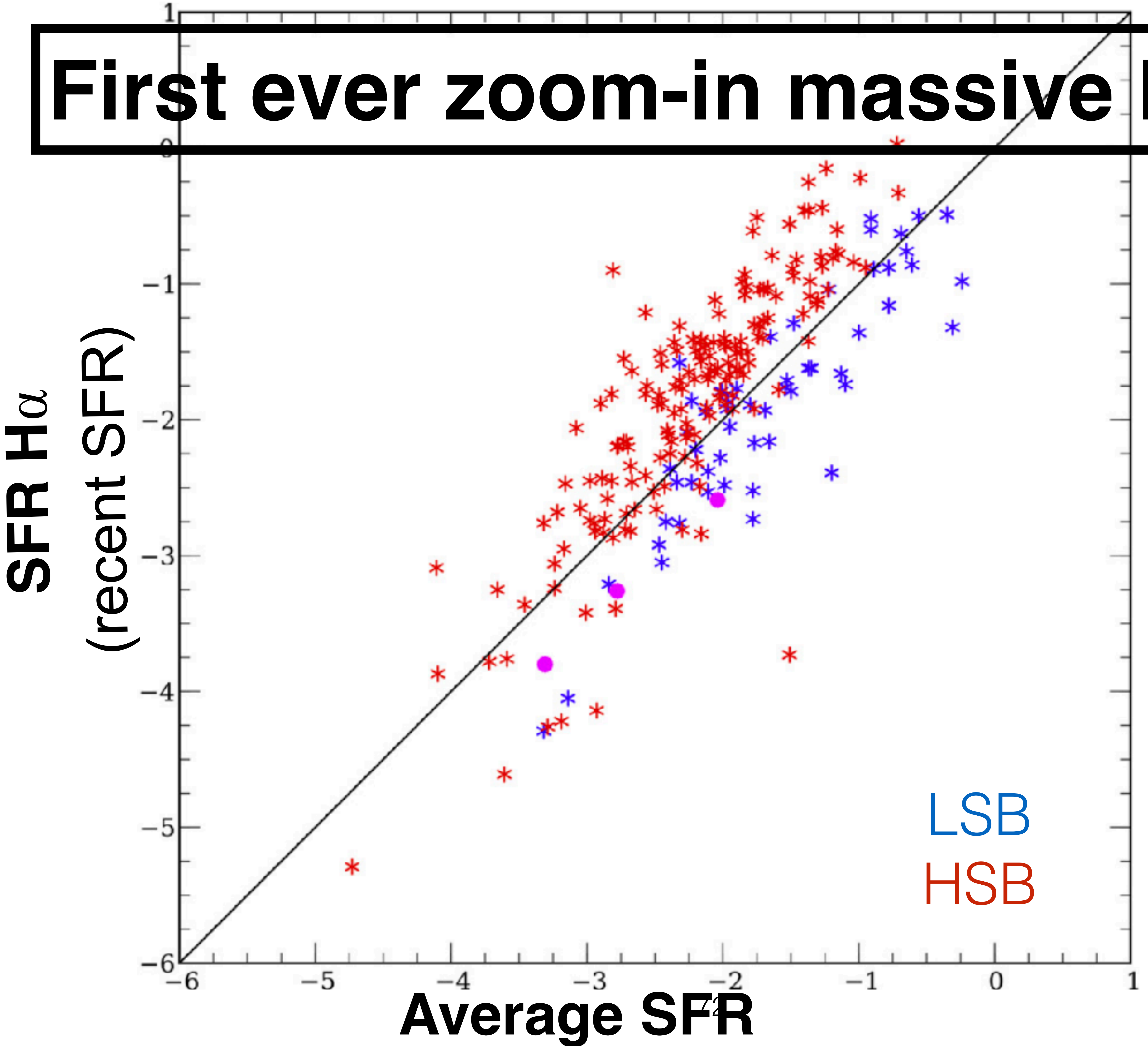
e.g. Kuzio de Naray + (2010)

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

Maybe black holes?

LSB zoom-in simulations

First ever zoom-in massive LSBs!



e.g. Kuzio de Naray + (2010)

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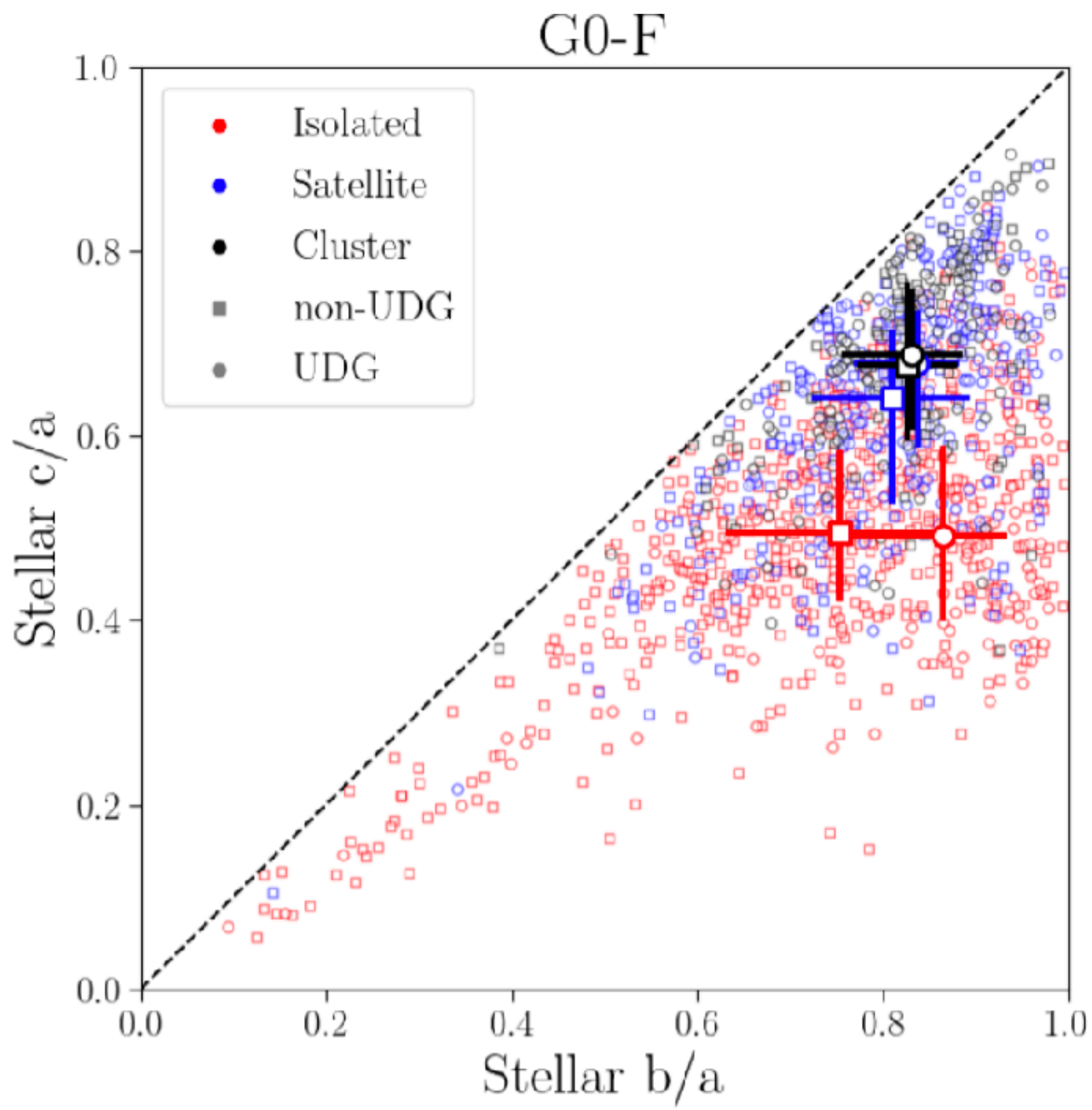
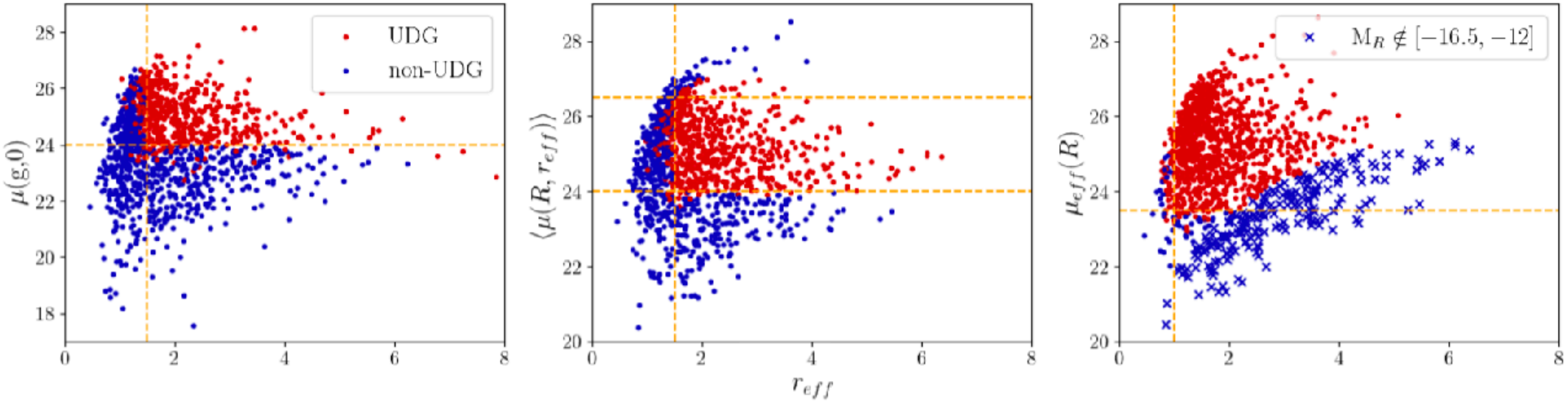
The Low Surface Brightness Universe: UDGs

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

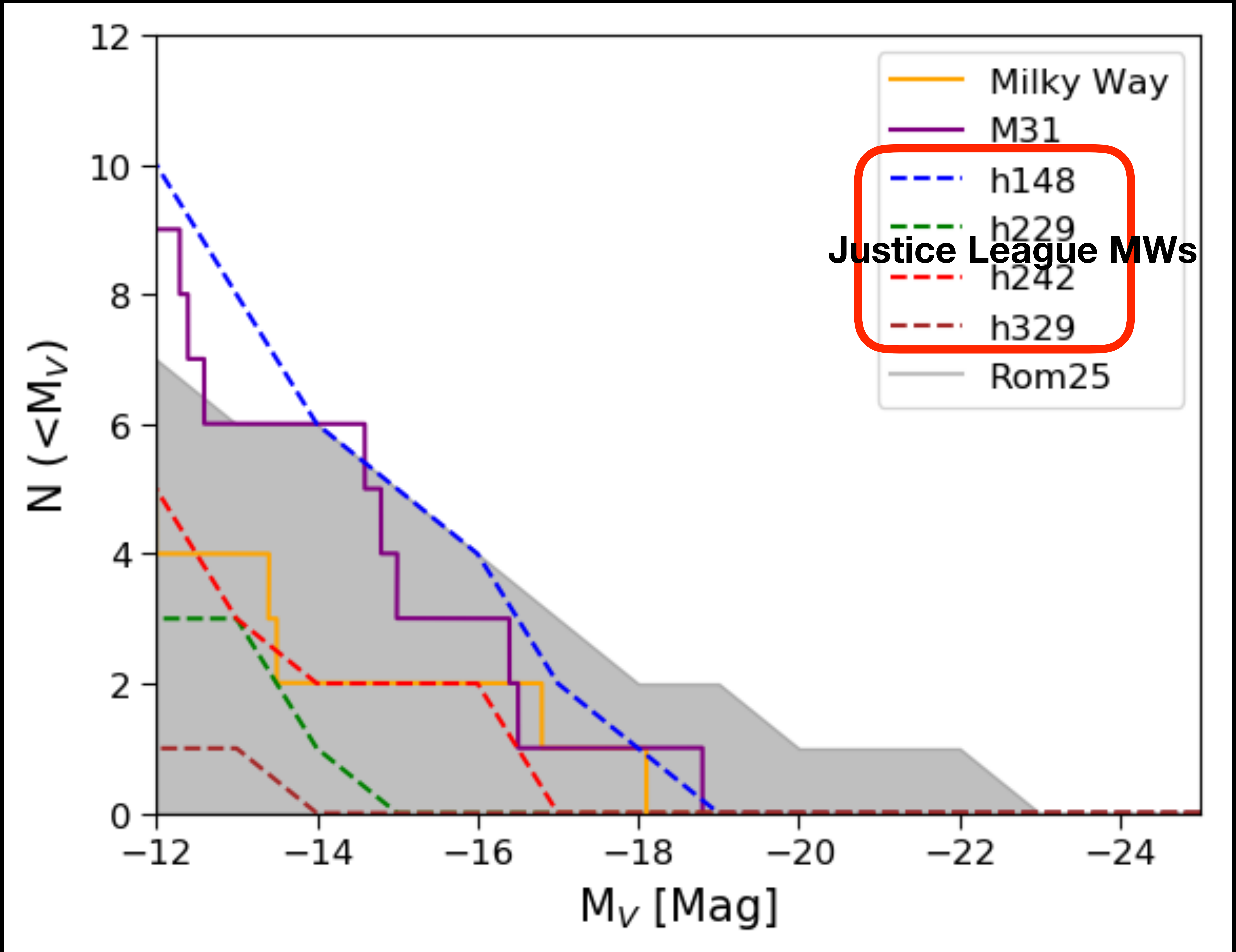


Observational comparison with Kado-Fong (Princeton), Greene (Princeton)- paper submitted, Munshi, Van Nest coauthors



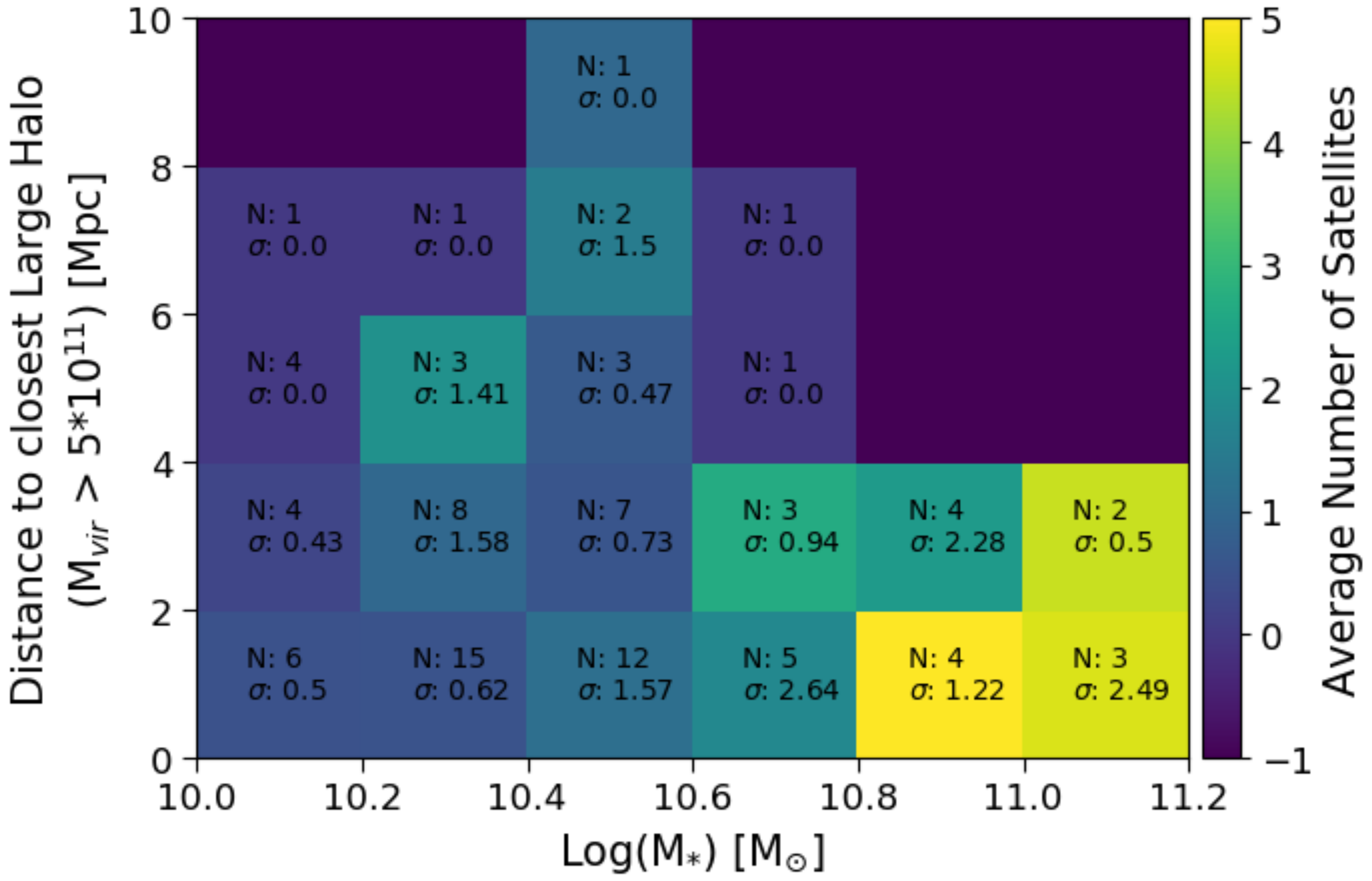
My current graduate student Jordan Van Nest has had his first paper accepted on this work.

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



VanNest, Munshi +, in prep

Romulus25 Milky-Way analogs with satellites resolved down to $M_{star} = 10^7$ M_{sun} (includes MW/M31-like systems)



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.

VanNest, Munshi +, in prep

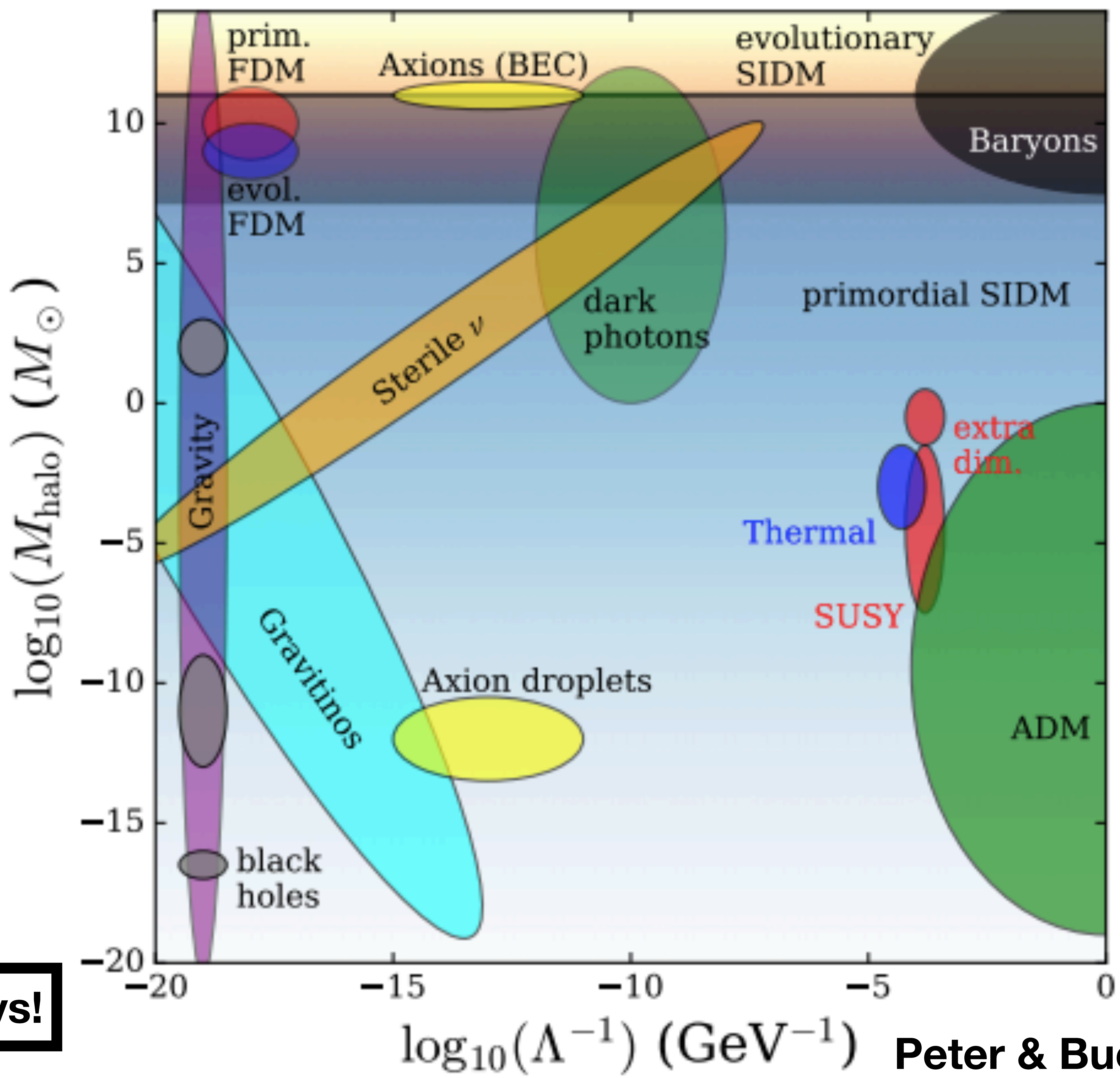
Interested in modifying/contributing to the code? [e.g. potential thesis coding projects]

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

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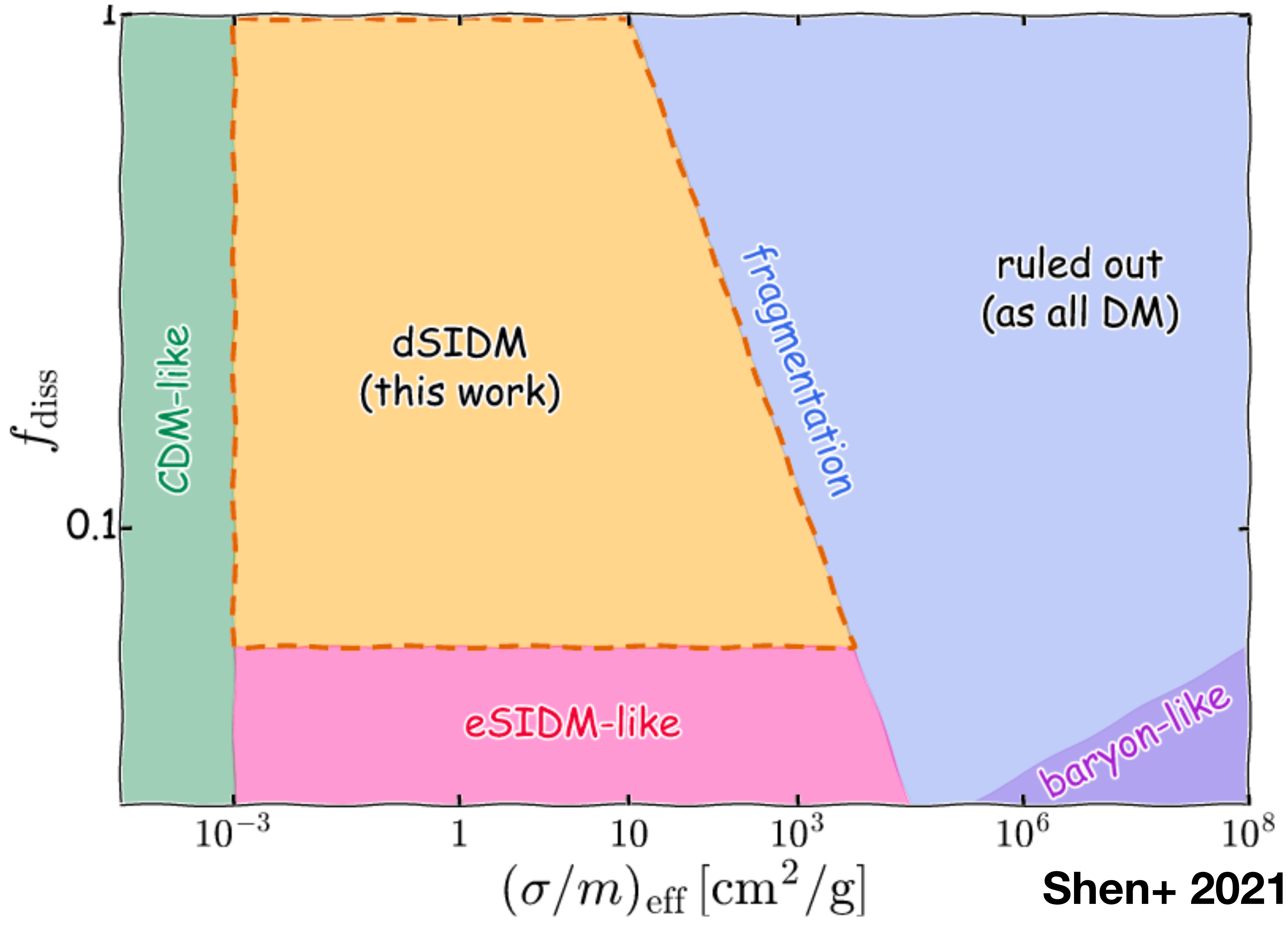


Shen+ 2021

Big Idea: Create the "col*laboratory*"

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.

Fundable by NSF MRI, Microsoft Faculty Grants

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**

Innovative Research Plan

"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)

Education Plan

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"

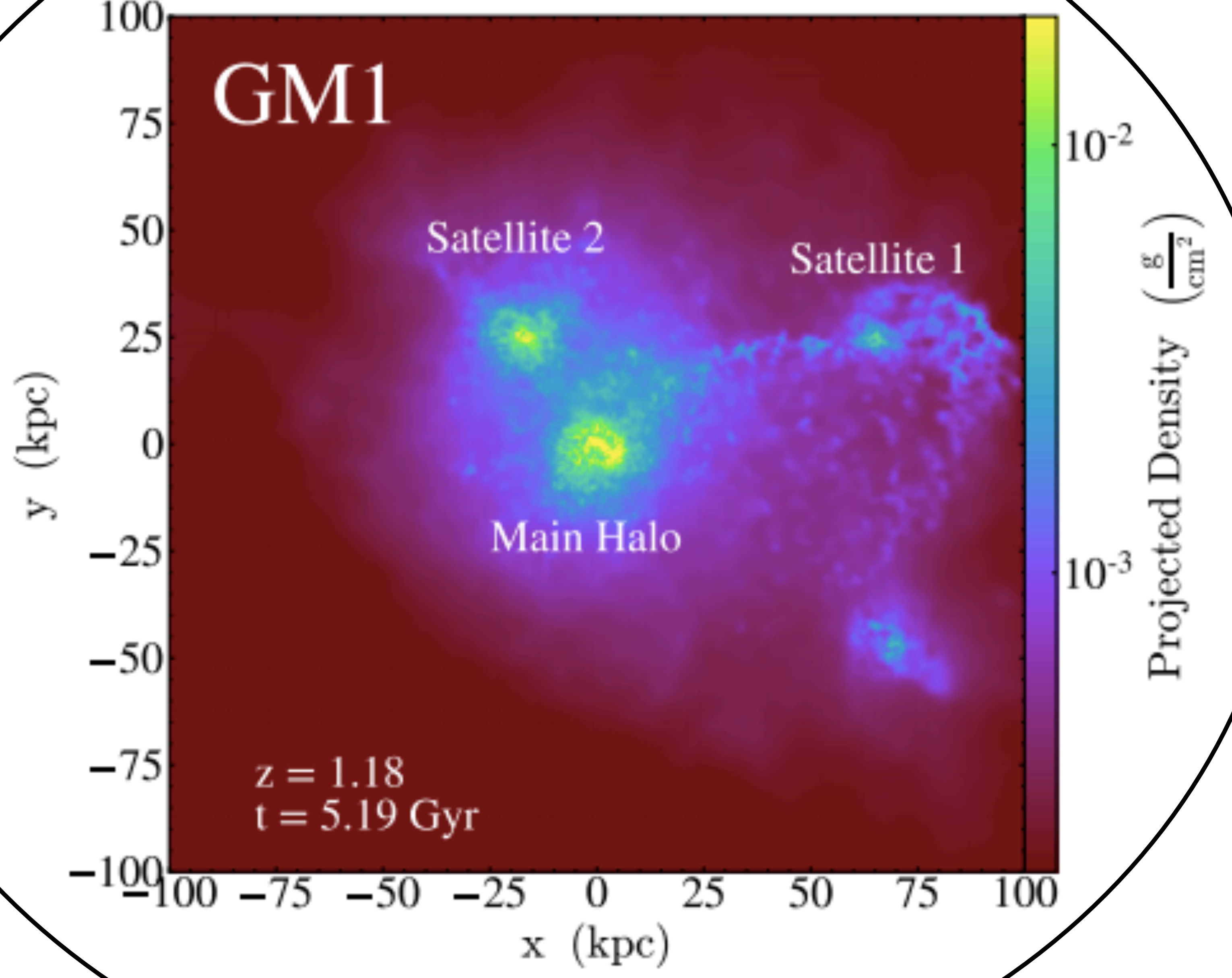
Community engagement

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

Alignment with Dept mission

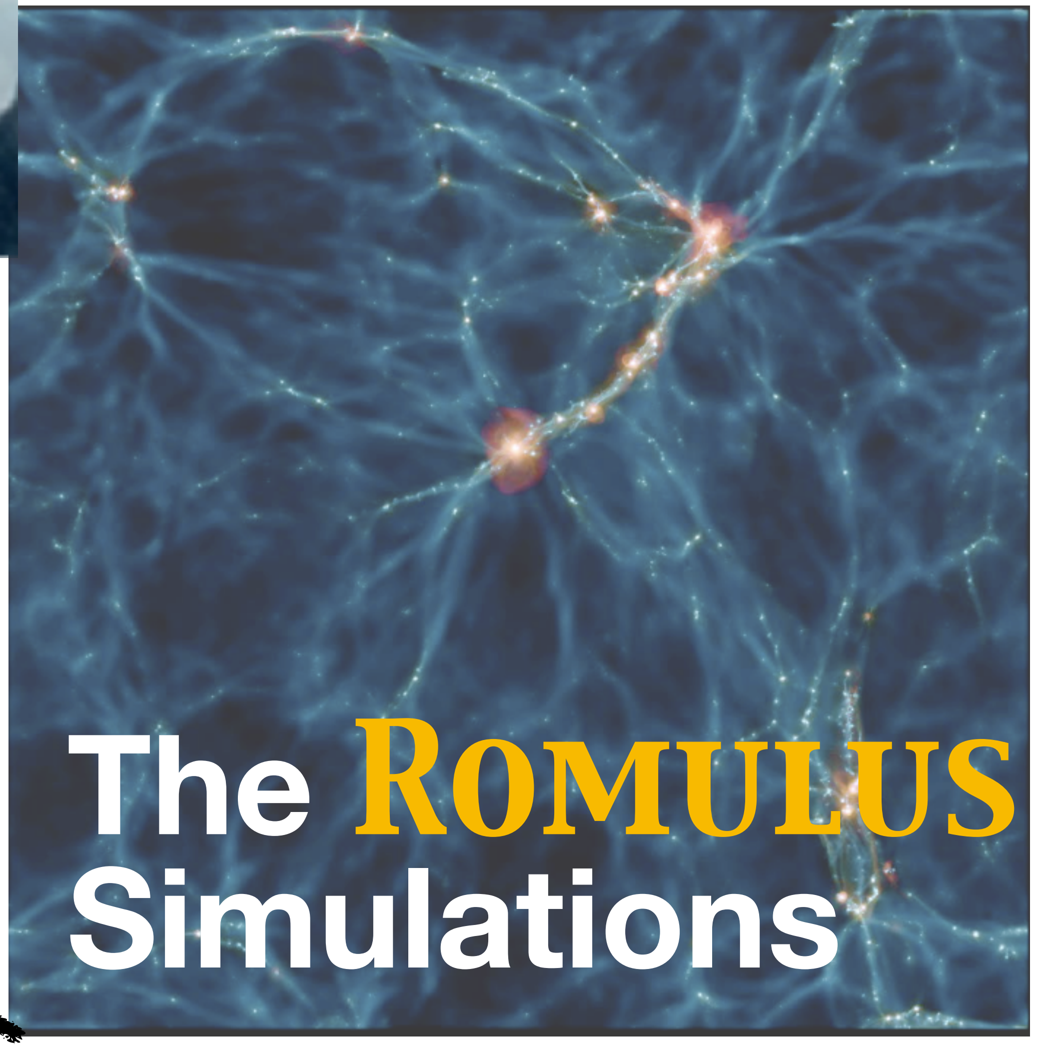
1. Enhance Dept's inclusion and equity goals
2. Broaden department's visibility both within the university and community
3. Grow diversity of both the graduate and undergraduate students in the Dept

Genetically Modified Galaxies



Dwarfs in isolation

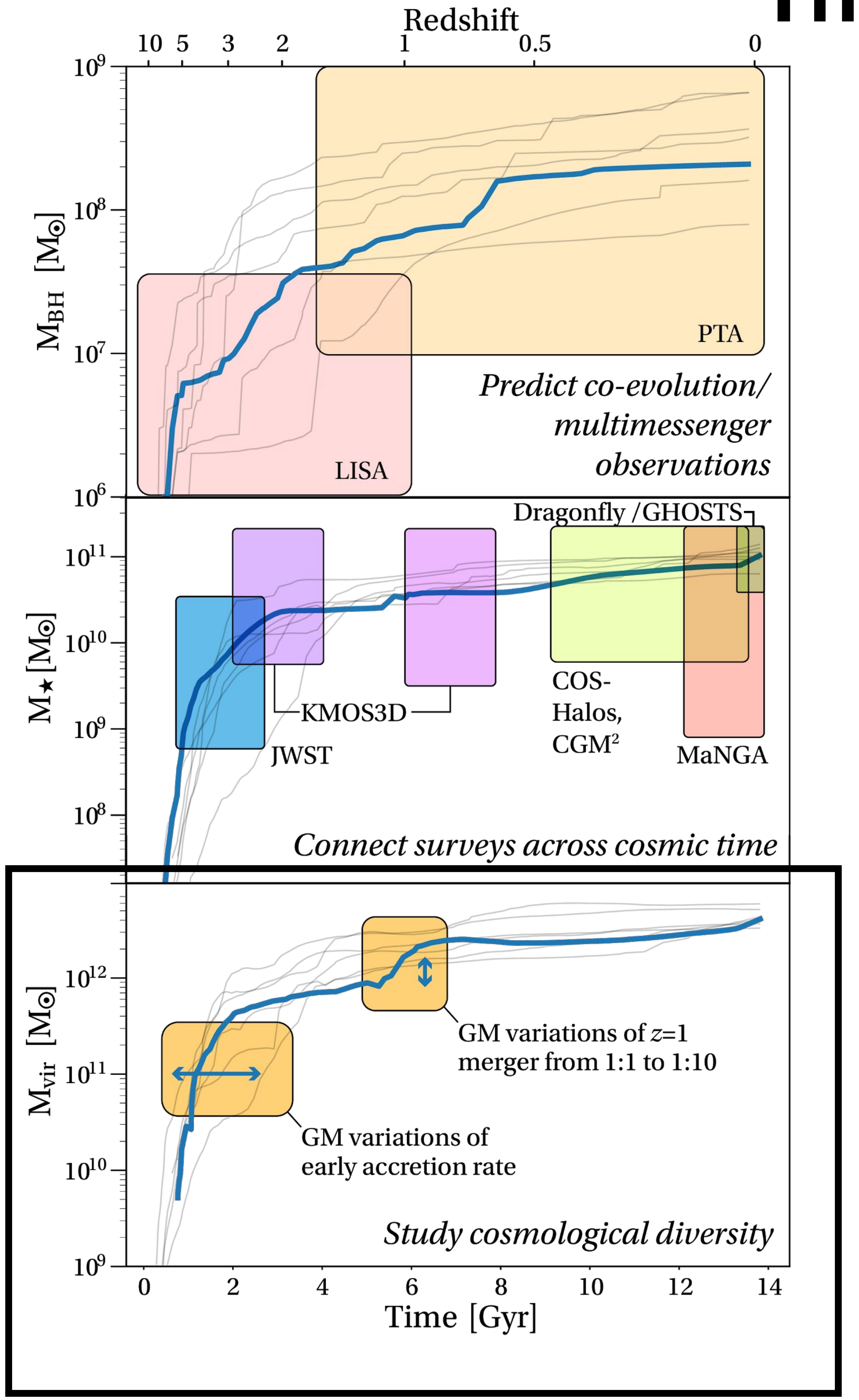
Dwarfs in the vicinity of a MW

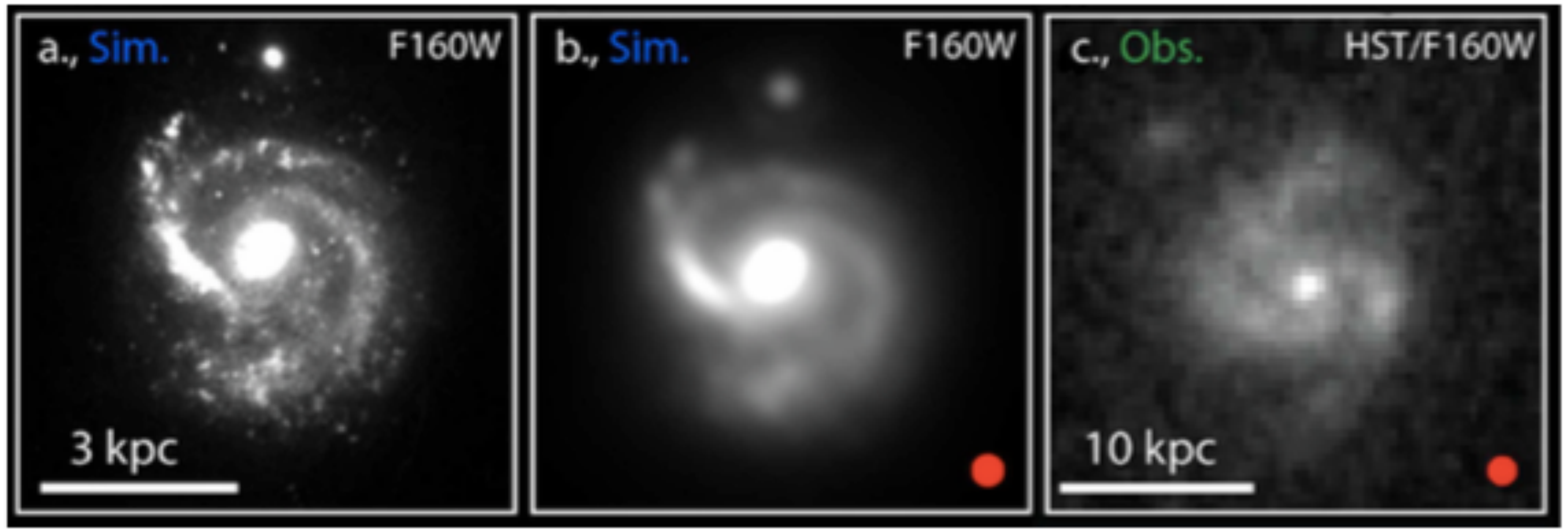


Current Data Sets

Dwarfs (and UDGs) across environments

There are new flagship runs on the horizon…





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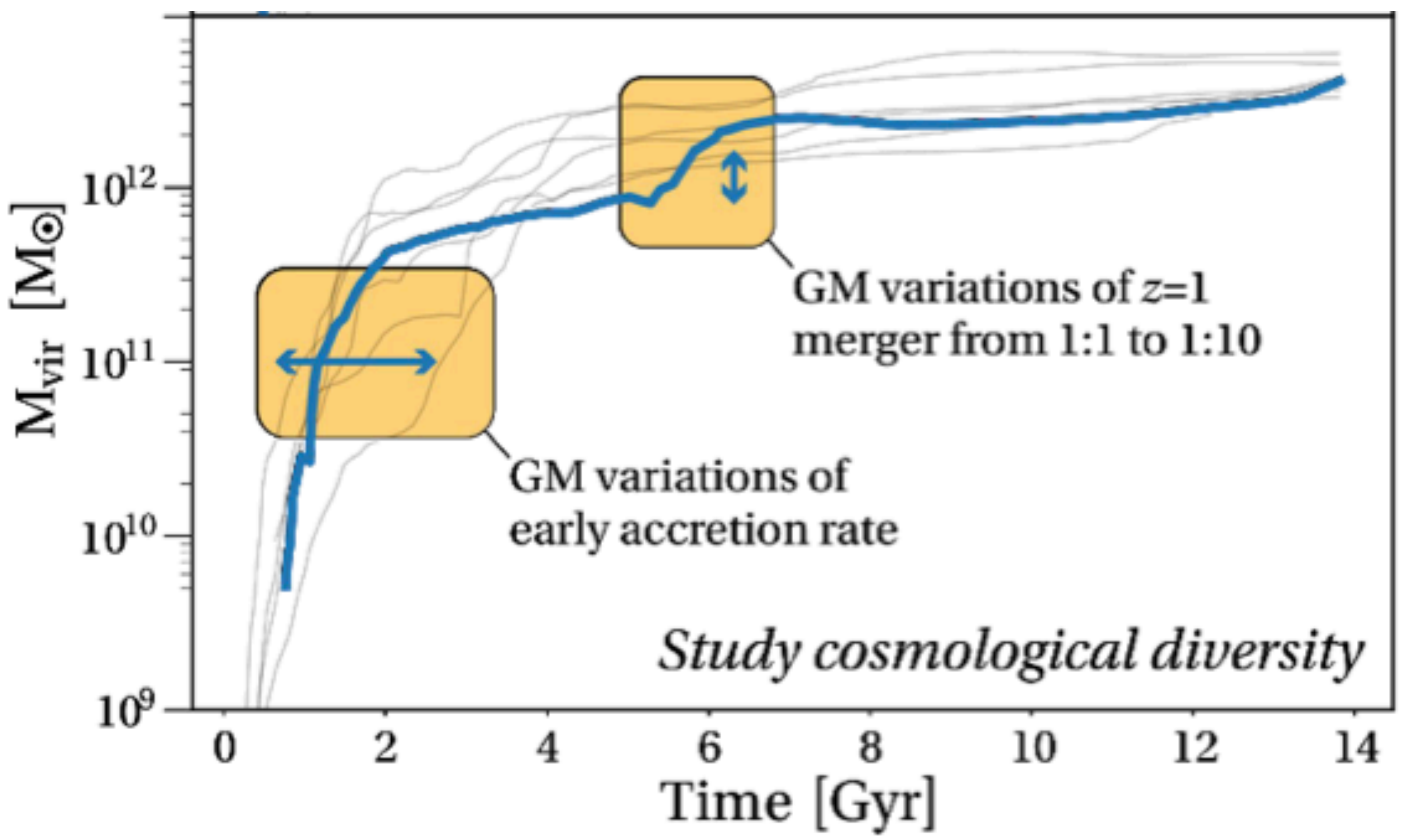
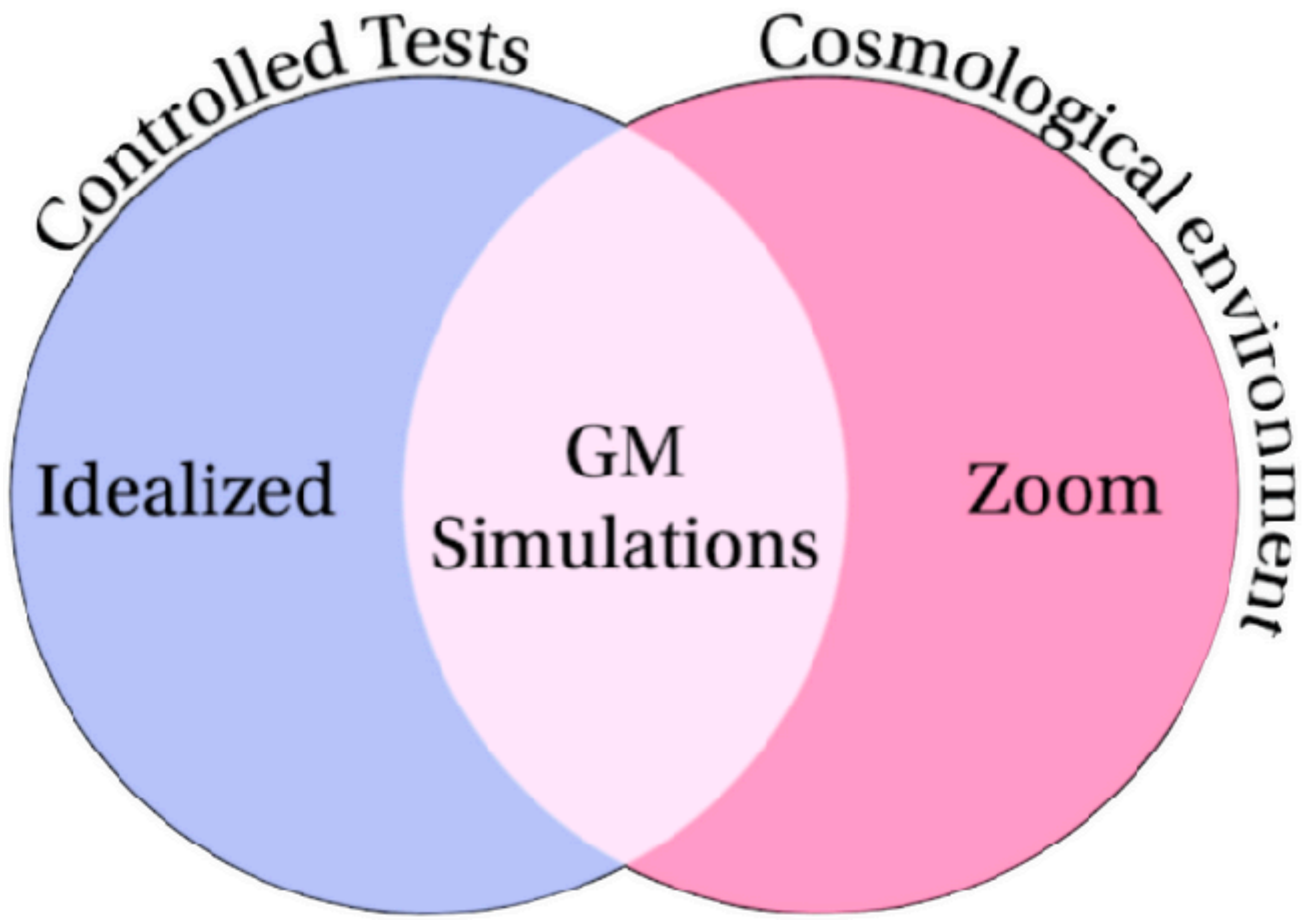
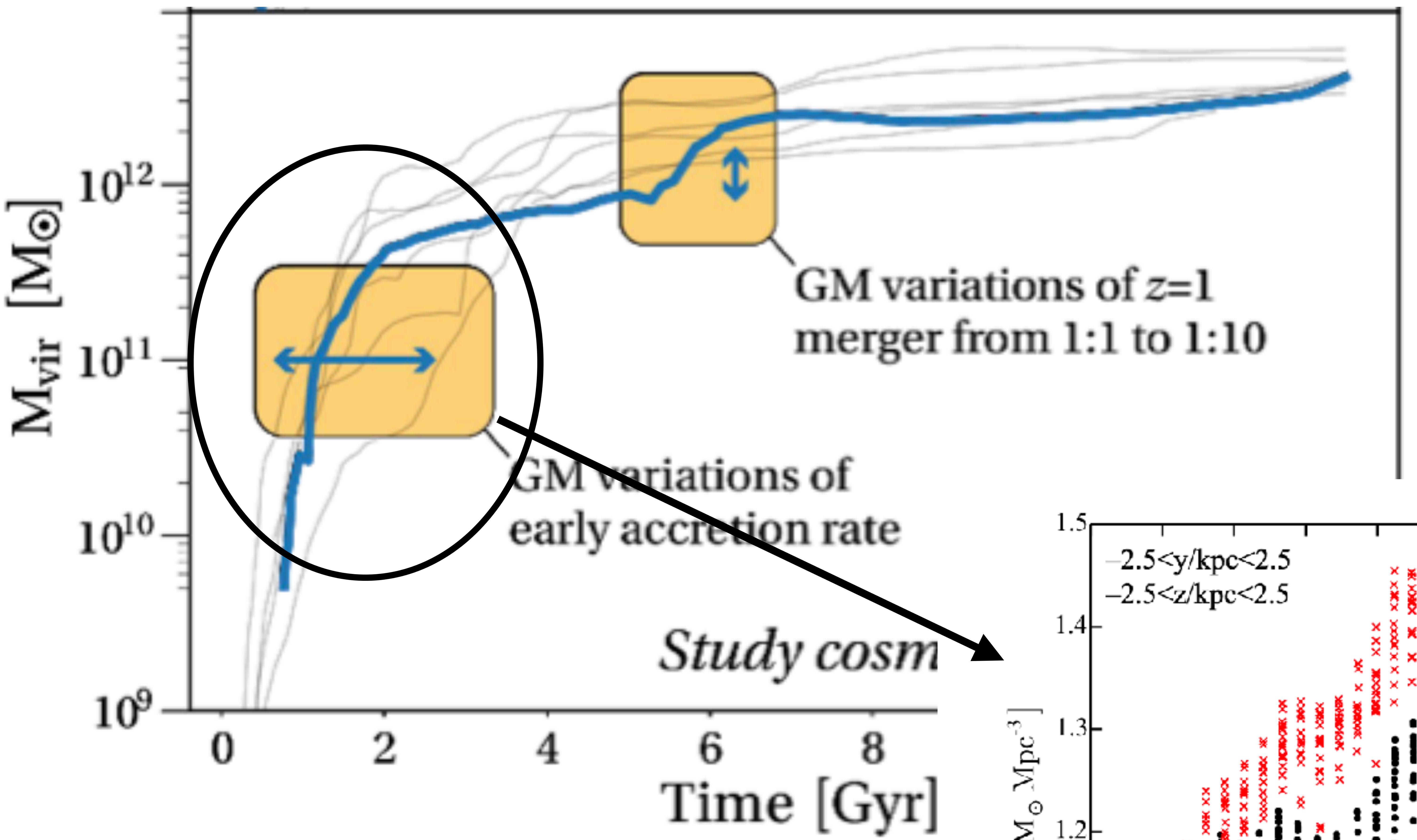
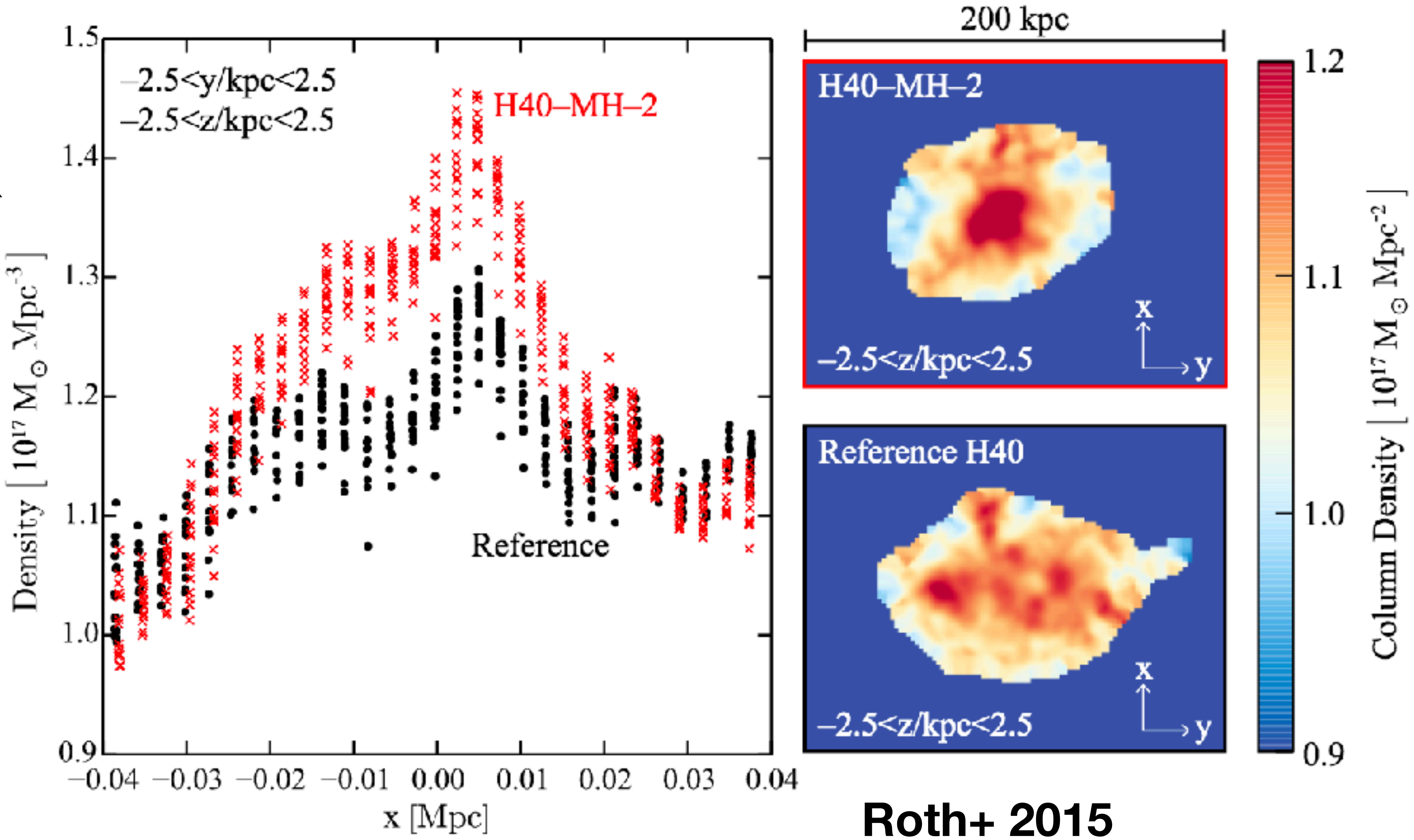




Genetic Modification (GM): Performing controlled experiments in galaxy formation

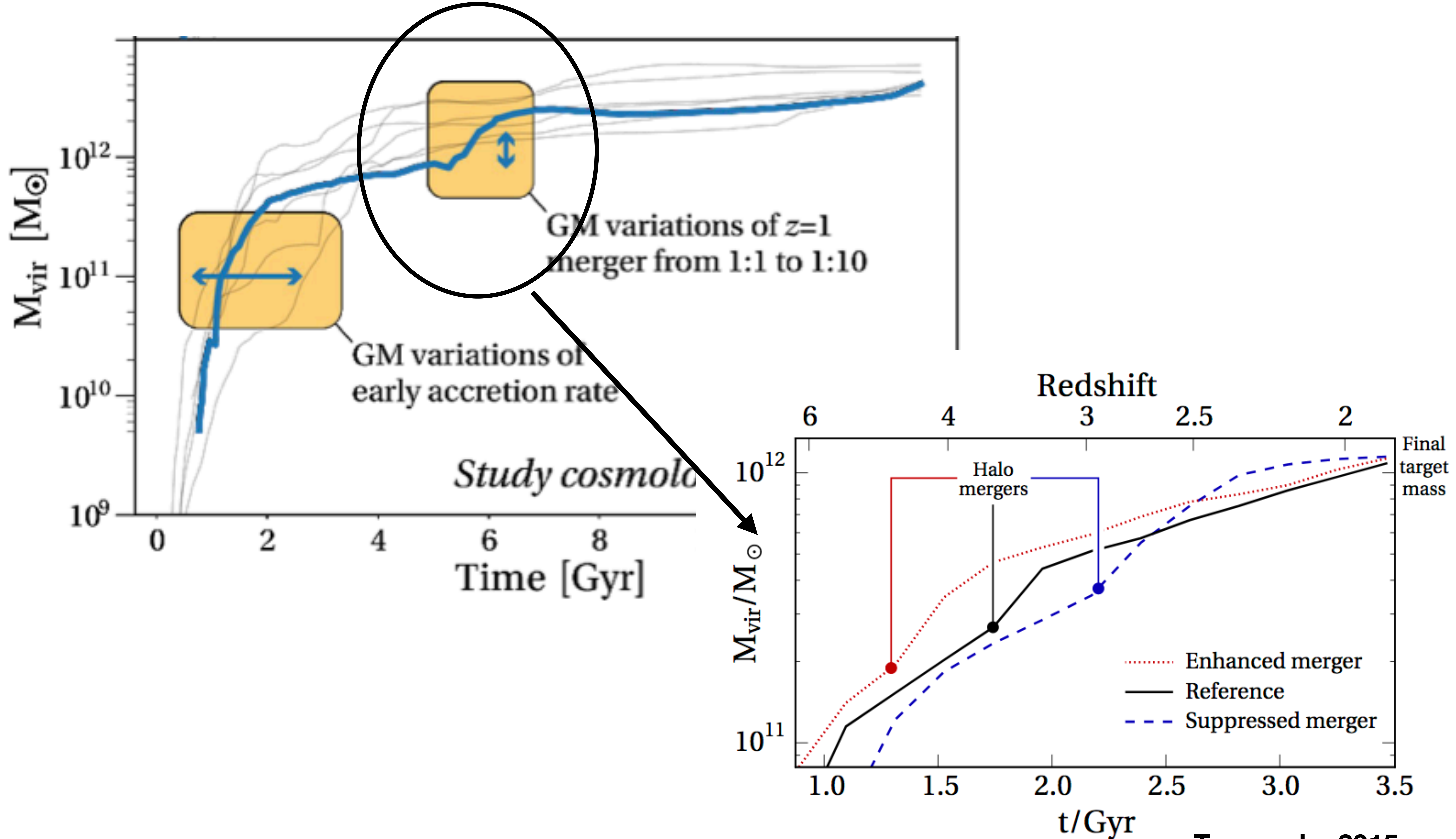


M_{vir} [$M_\odot$]
10^{12}
10^{11}
10^{10}
10^9
0
2
4
6
8
Time [Gyr]
GM variations of z=1 merger from 1:1 to 1:10
GM variations of early accretion rate
Study cosm



−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]
1.5
1.4
1.3
1.2
1.1
1.0
0.9
−0.04
−0.03
−0.02
−0.01
0.00
0.01
0.02
0.03
0.04
200 kpc
H40–MH–2
−2.5<z/kpc<2.5
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