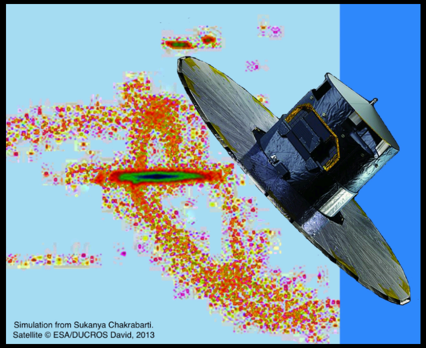


Simulation from Sukanya Chakrabarti.
Satellite © ESA/DUCROS David, 2013

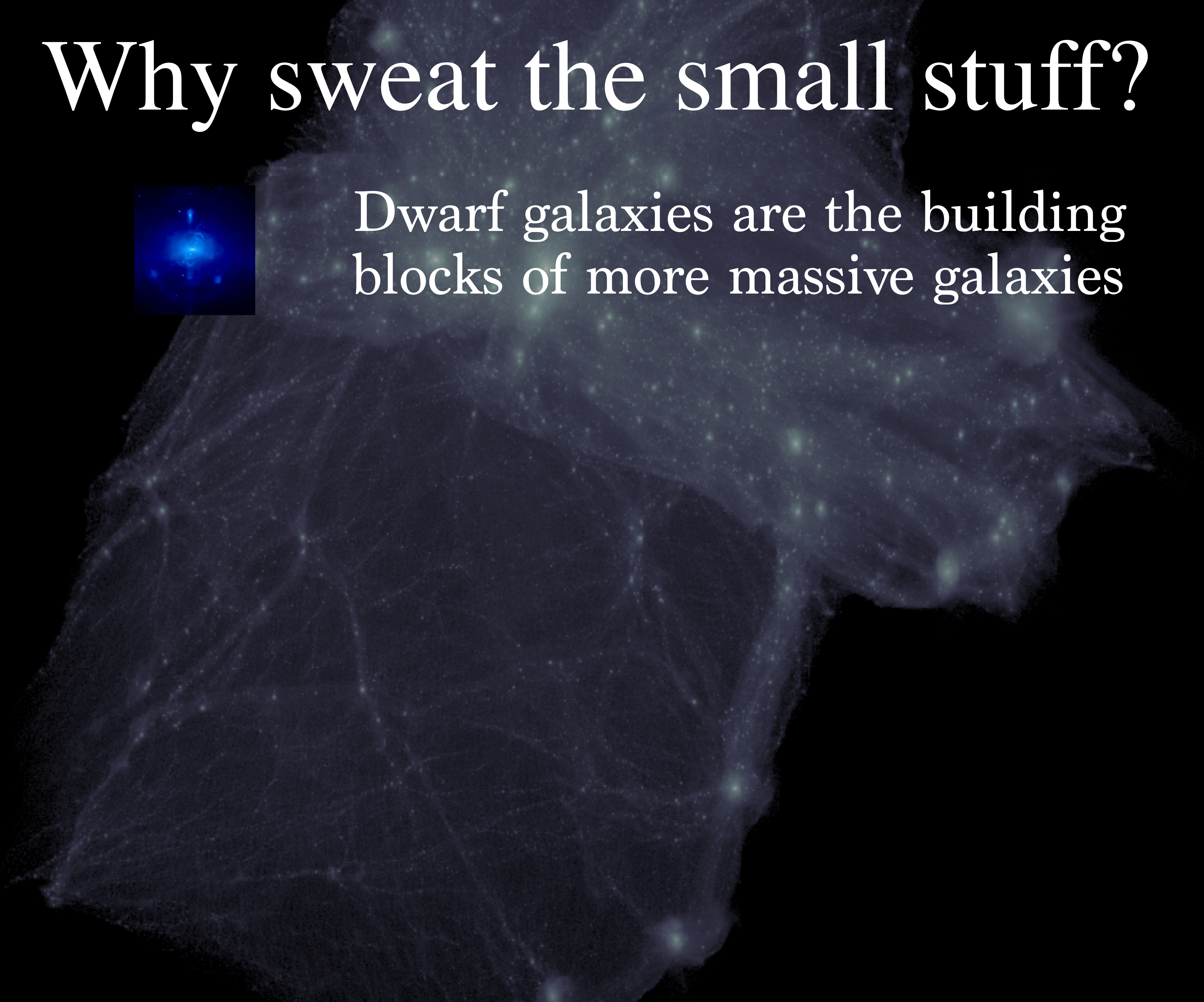
Sweating the small stuff: Or how I learned to START worrying and love the smallest galaxies

Coral Wheeler
Caltech
@coralrosew

Phil Hopkins (Caltech)
Ivanna Escala (Caltech)
Evan Kirby (Caltech)
Mike Boylan-Kolchin (UT Austin)
Shea Garrison-Kimmel(Caltech)
Olivier Dore (Caltech)

Jose Oñorbe (MPIA)
Oliver Elbert (UCI)
Alex Fitts (UT Austin)
James Bullock (UCI)
FIRE Collaboration

Why sweat the small stuff?



Dwarf galaxies are the building blocks of more massive galaxies

Why sweat the small stuff?

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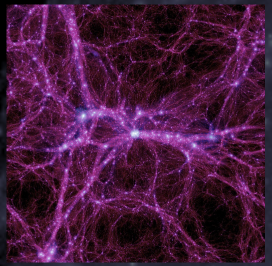
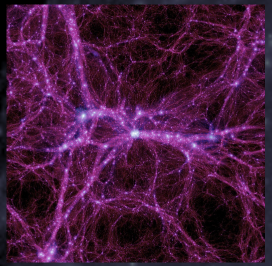


Dwarf galaxies can teach us about dark matter

Why sweat the small stuff?



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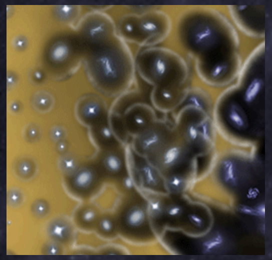

Dwarf galaxies can teach us about reionization

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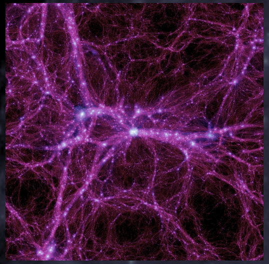

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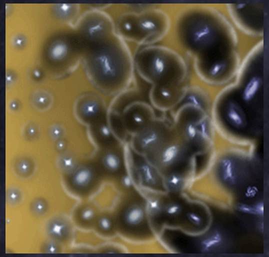
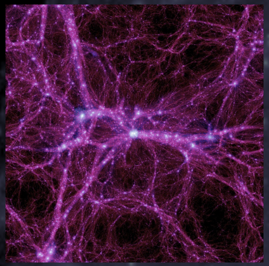


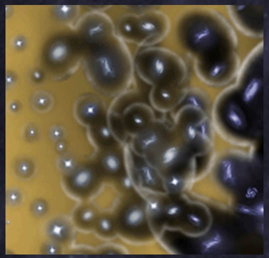
Dwarf galaxies can teach us about reionization

Dwarf galaxies can teach us about star formation and feedback

Why sweat the small stuff?



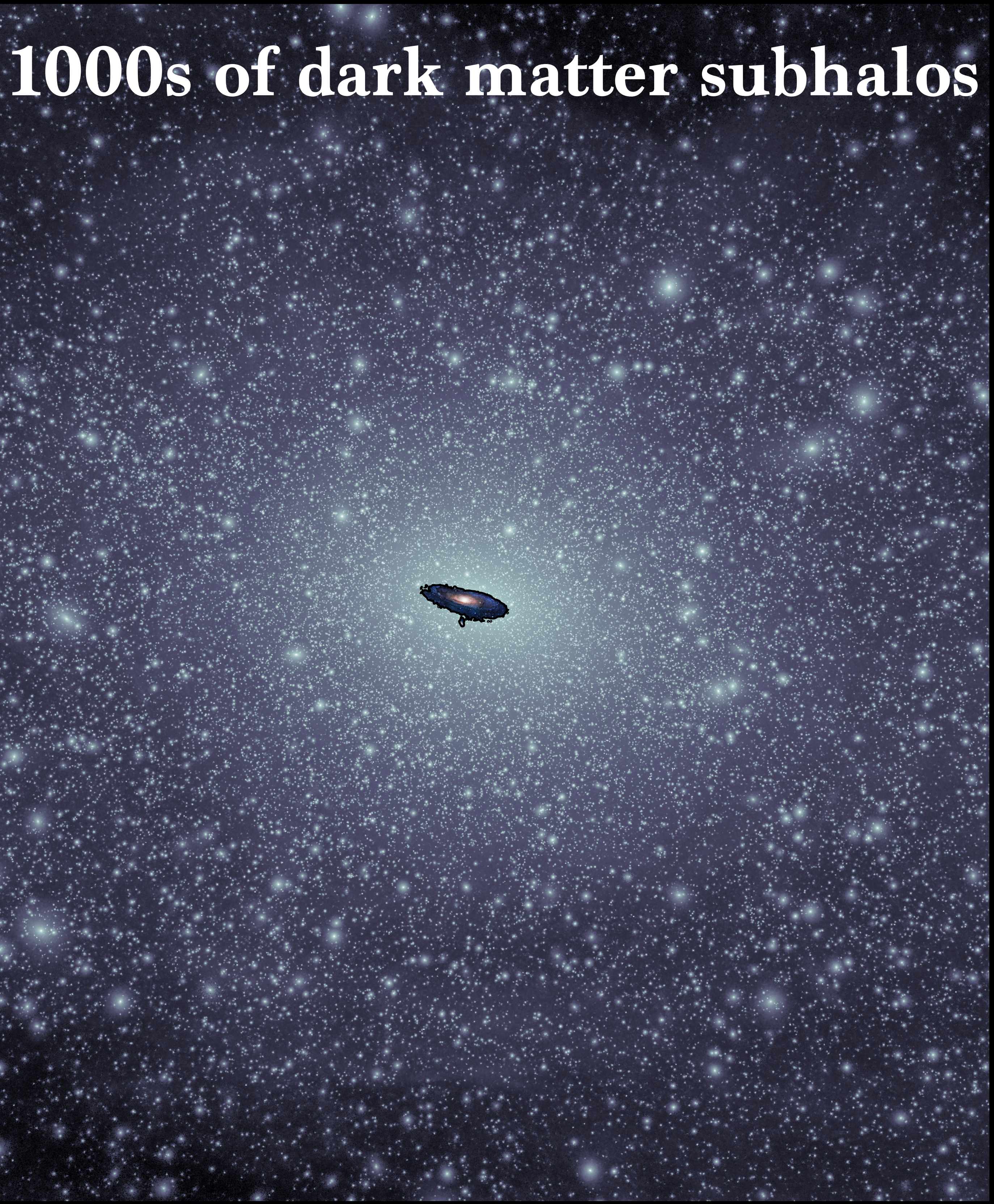
Dwarf galaxies can teach us about dark matter



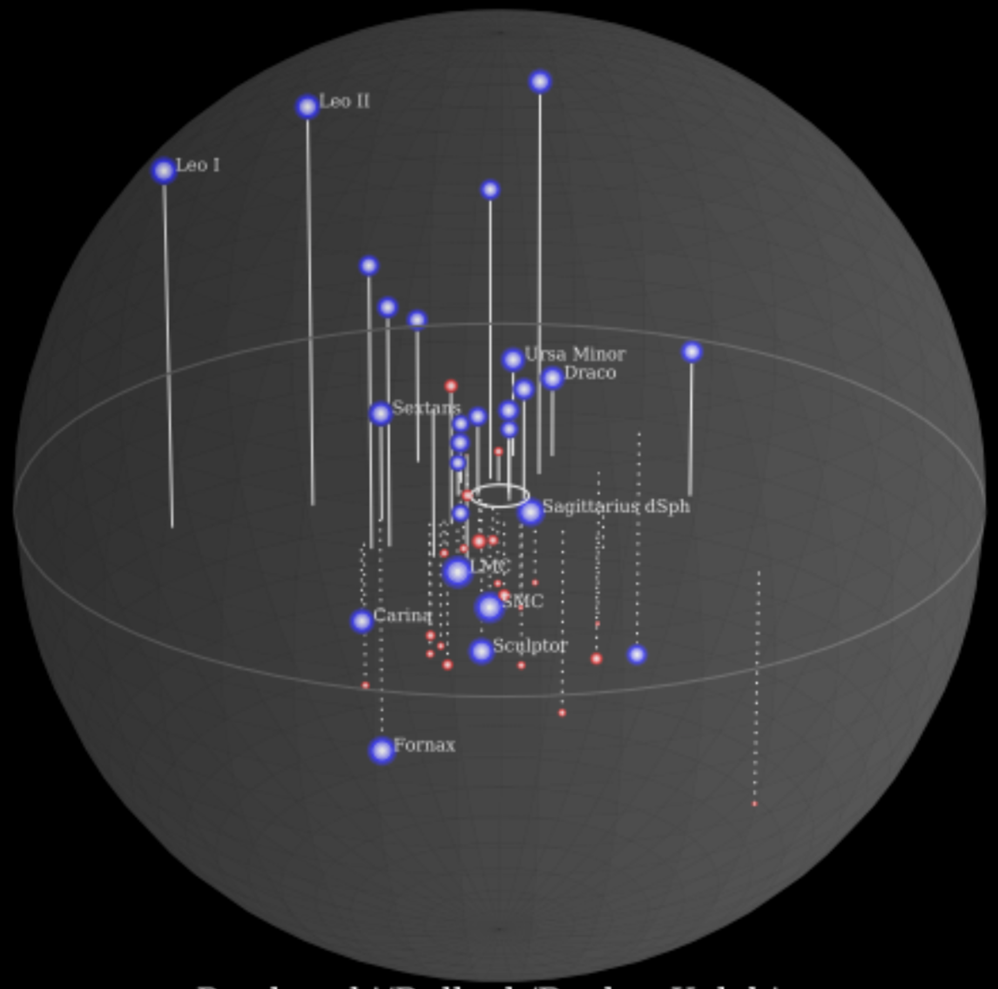
Dwarf galaxies can teach us about reionization

Dwarf galaxies can teach us about star formation and feedback

1000s of dark matter subhalos



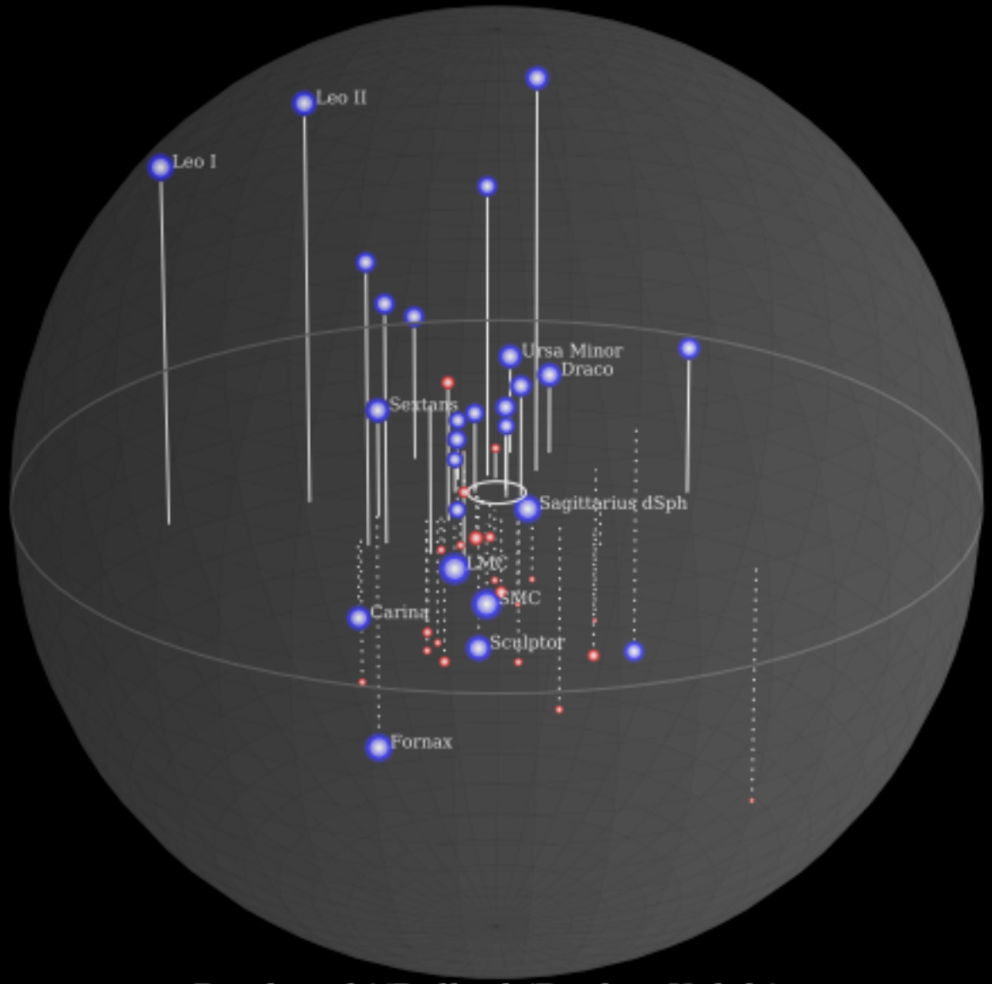
~ 50 dwarf satellite galaxies



Pawlowski/Bullock/Boylan-Kolchin

1000s of dark matter subhalos ~ 50 dwarf satellite galaxies

MSP: Missing Satellites Problem



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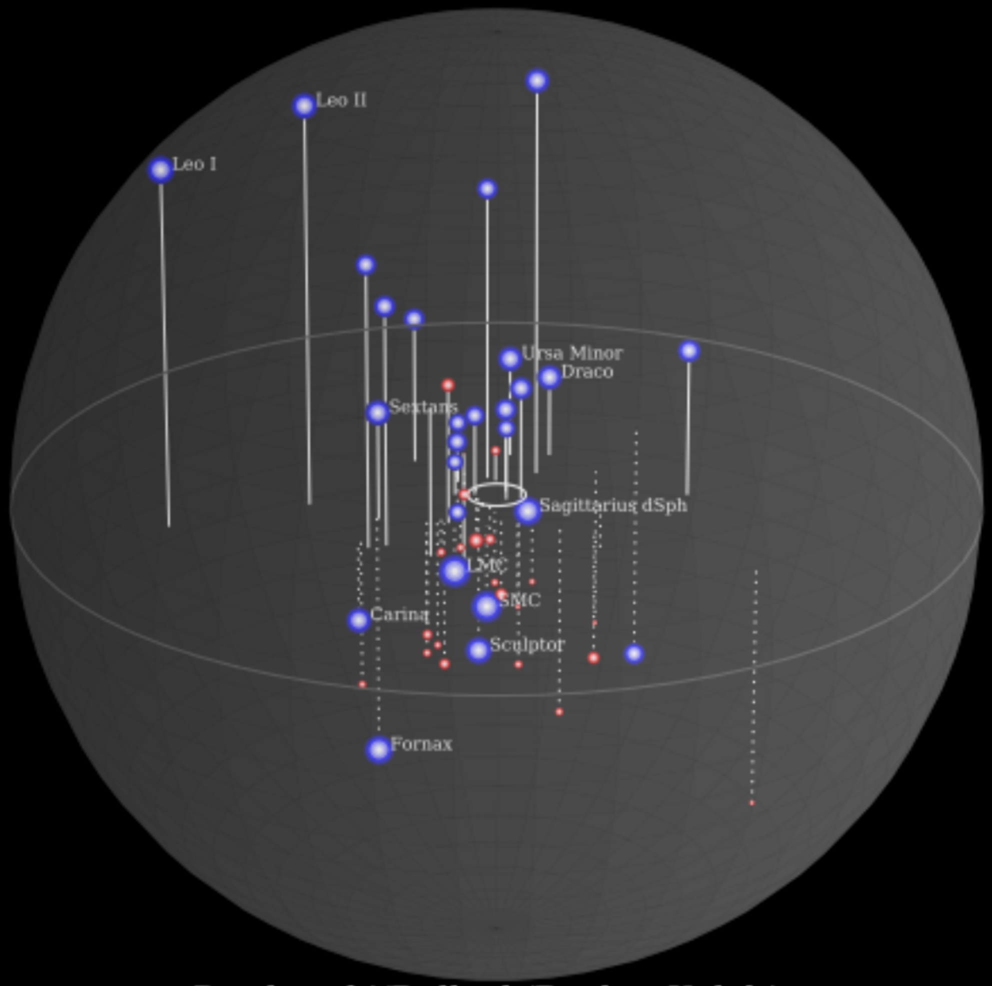


Pawlowski/Bullock/Boylan-Kolchin

“If I ever hear anyone mention the missing satellites problem again, I’ll leave the room” - Carlos Frenk

Missing Satellites Problem solved to M* ~ 10^5 M$_\odot$

Bright Dwarfs:

$M_\star \approx 10^8 M_\odot$

$M_{\rm vir} \approx 10^{11} M_\odot$

Classical Dwarfs:

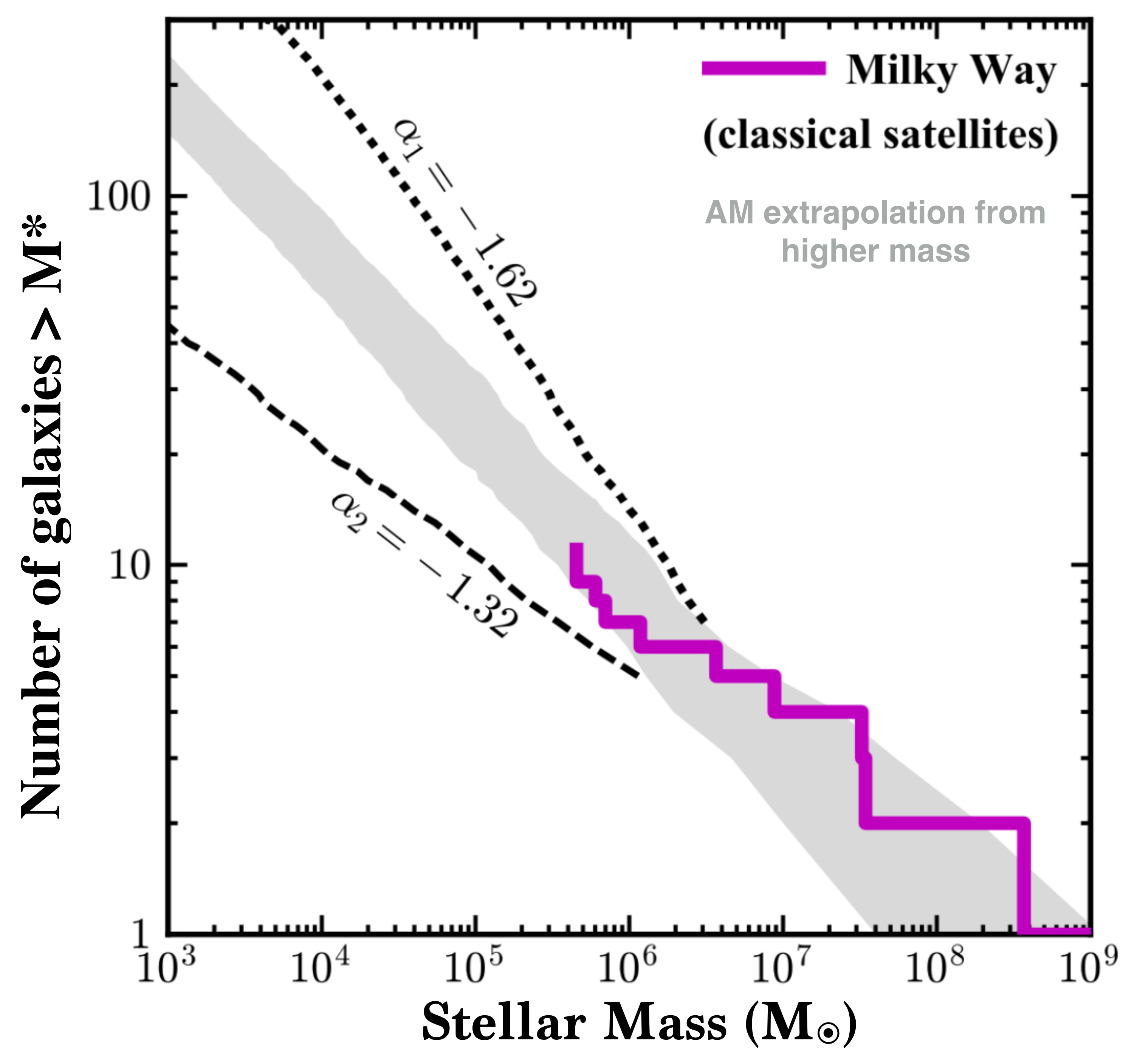
$M_\star \approx 10^6 M_\odot$

$M_{\rm vir} \approx 10^{10} M_\odot$

Ultra-faint Dwarfs:

$M_\star \approx 10^4 M_\odot$

$M_{\rm vir} \approx 10^9 M_\odot$



Bullock & Boylan-Kolchin 2017

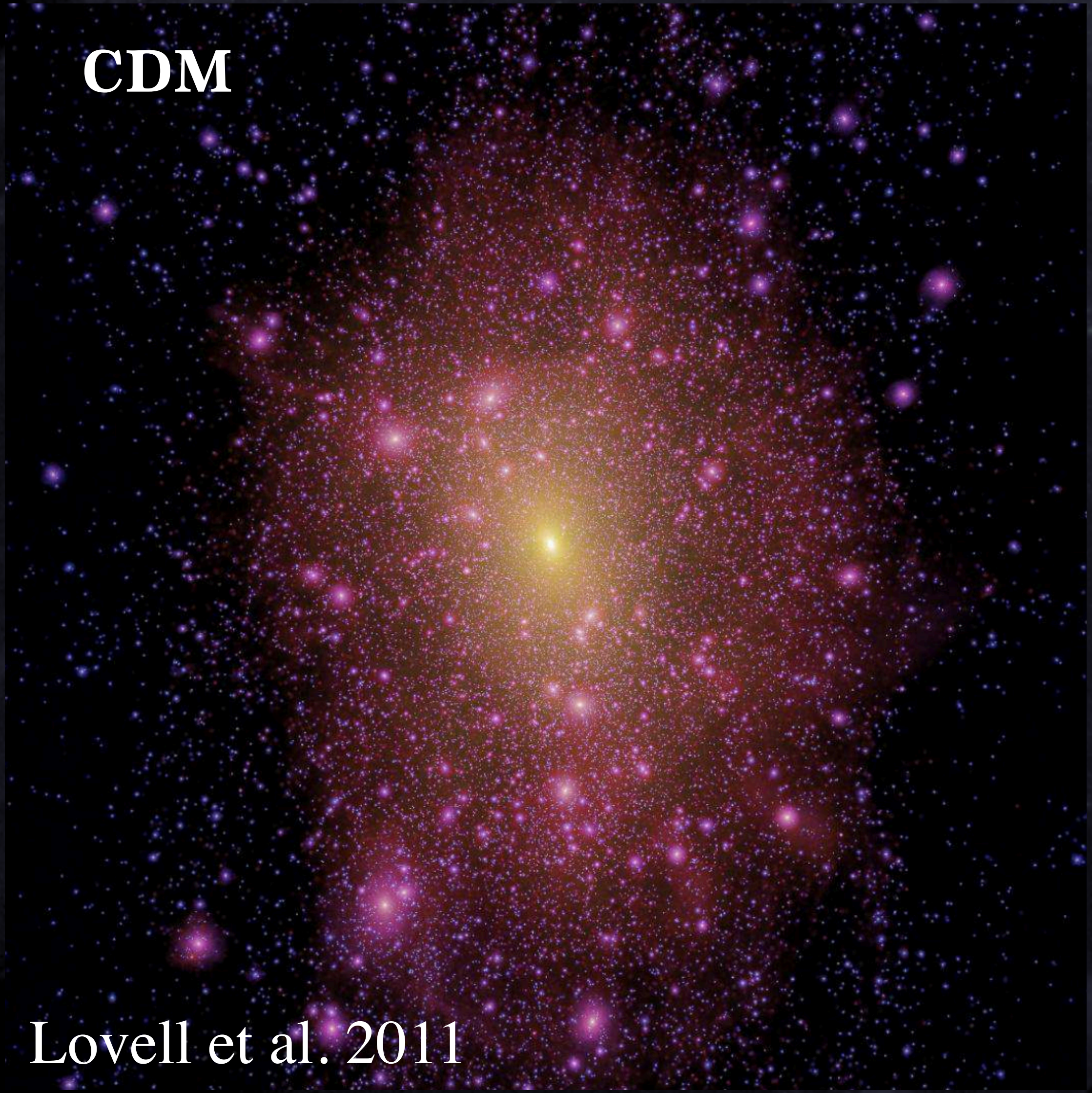
Dwarf galaxies can teach us about dark matter

MSP: Missing Satellites Problem: why are there so few Galactic satellites?

Dwarf galaxies can teach us about dark matter

MSP: Missing Satellites Problem: why are there so few Galactic satellites?

LCDM solution: something prevents small halos from forming galaxies, or can't see them



Lovell et al. 2011

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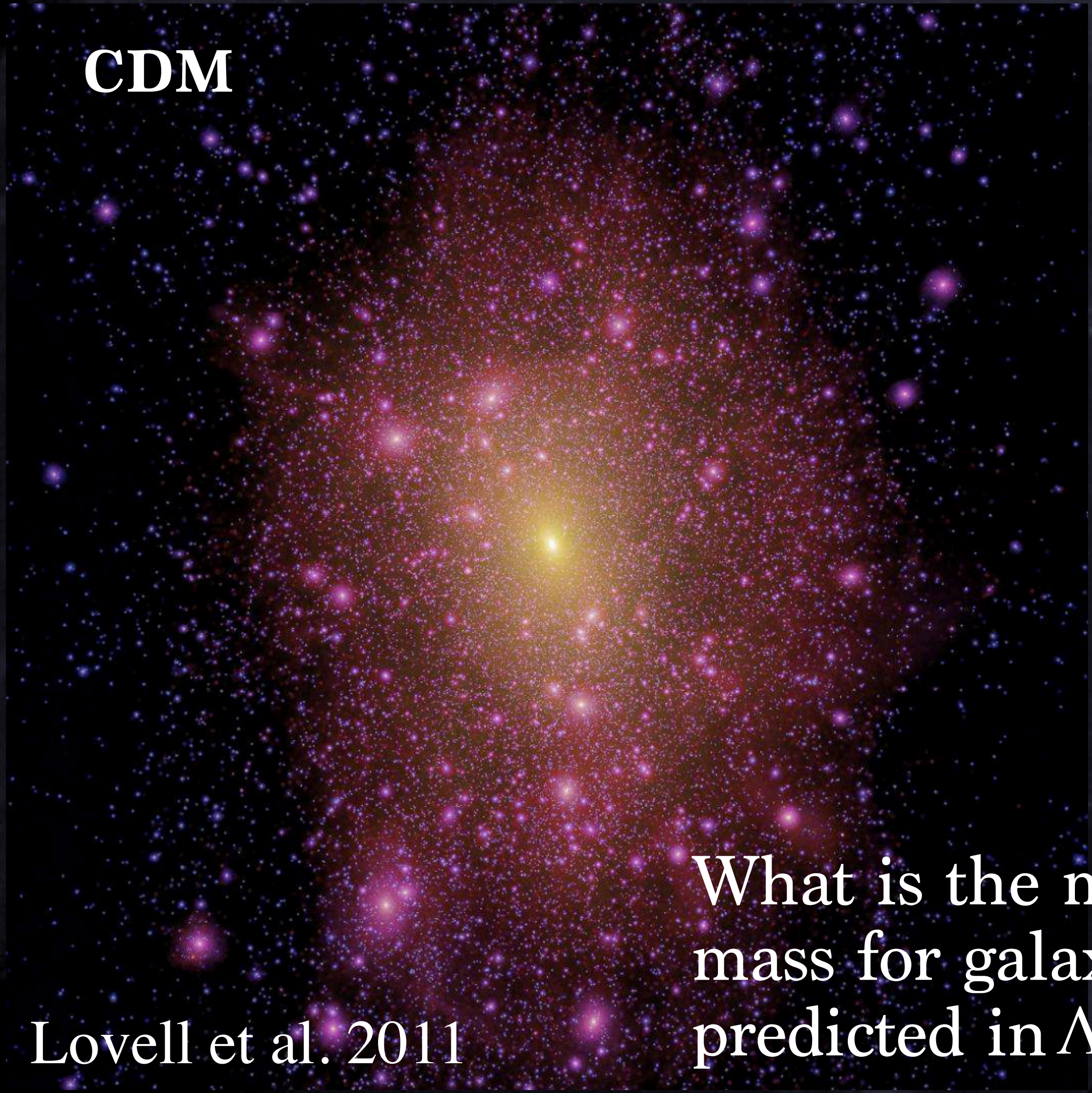


Lovell et al. 2011

What is the minimum mass for galaxy formation predicted in $\Lambda - \mathrm{CDM}$?

Dwarf galaxies can teach us about dark matter

MSP: Missing Satellites Problem: why are there so few Galactic satellites?

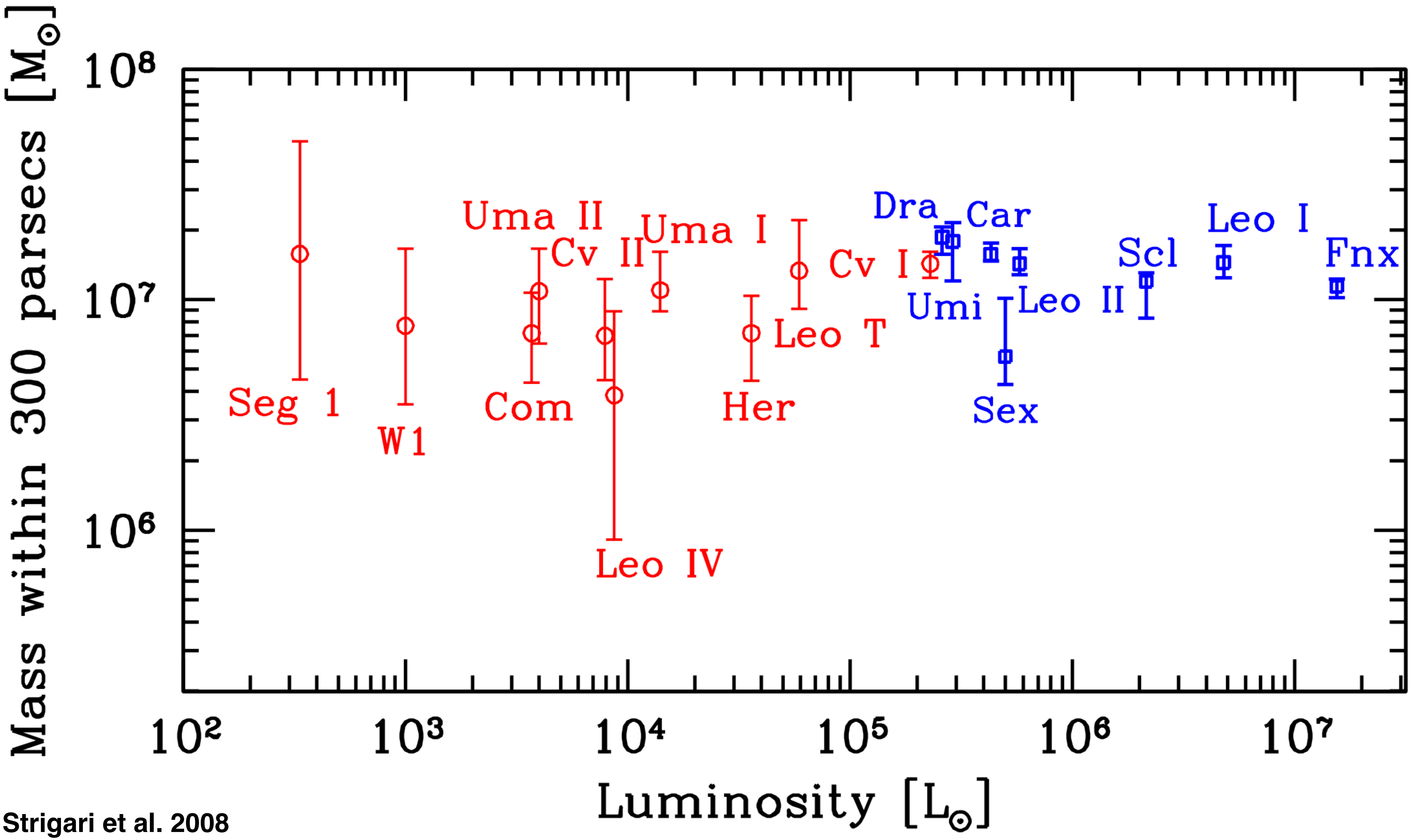
LCDM solution: something prevents small halos from forming galaxies, or can't see them

Alternative solution: Dark matter particle is warmer, so small halos themselves do not exist

Lovell et al. 2011

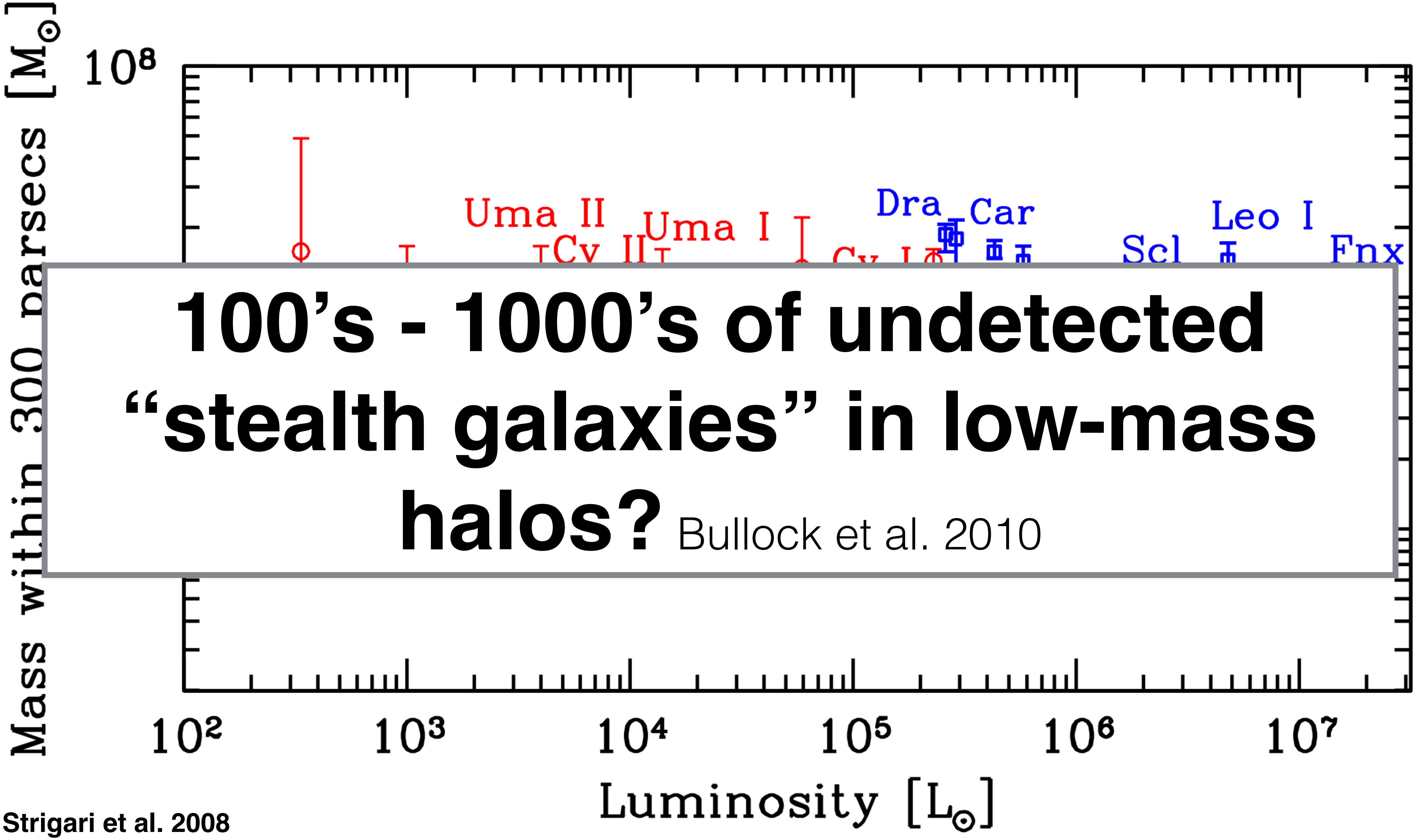
What is the minimum mass for galaxy formation predicted in $\Lambda - \mathrm{CDM}$?

Dwarfs with luminosities over nearly 5 orders of magnitude occupy halos of strikingly similar mass: ~3 x 10^9 $M_\odot$



Strigari et al. 2008

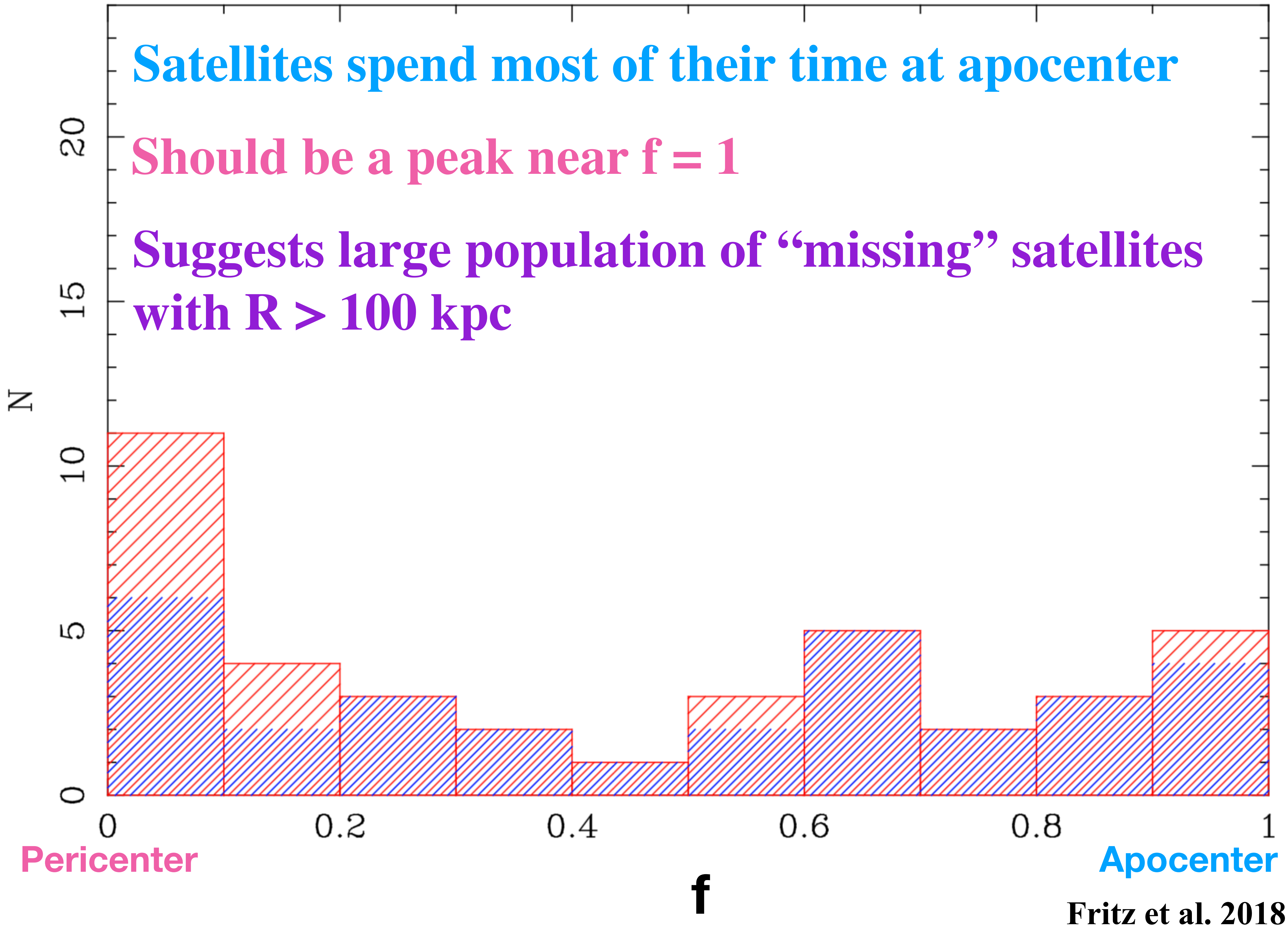
Selection Effect?



100’s - 1000’s of undetected “stealth galaxies” in low-mass halos? Bullock et al. 2010

Strigari et al. 2008

Gaia and the Missing Satellites Problem

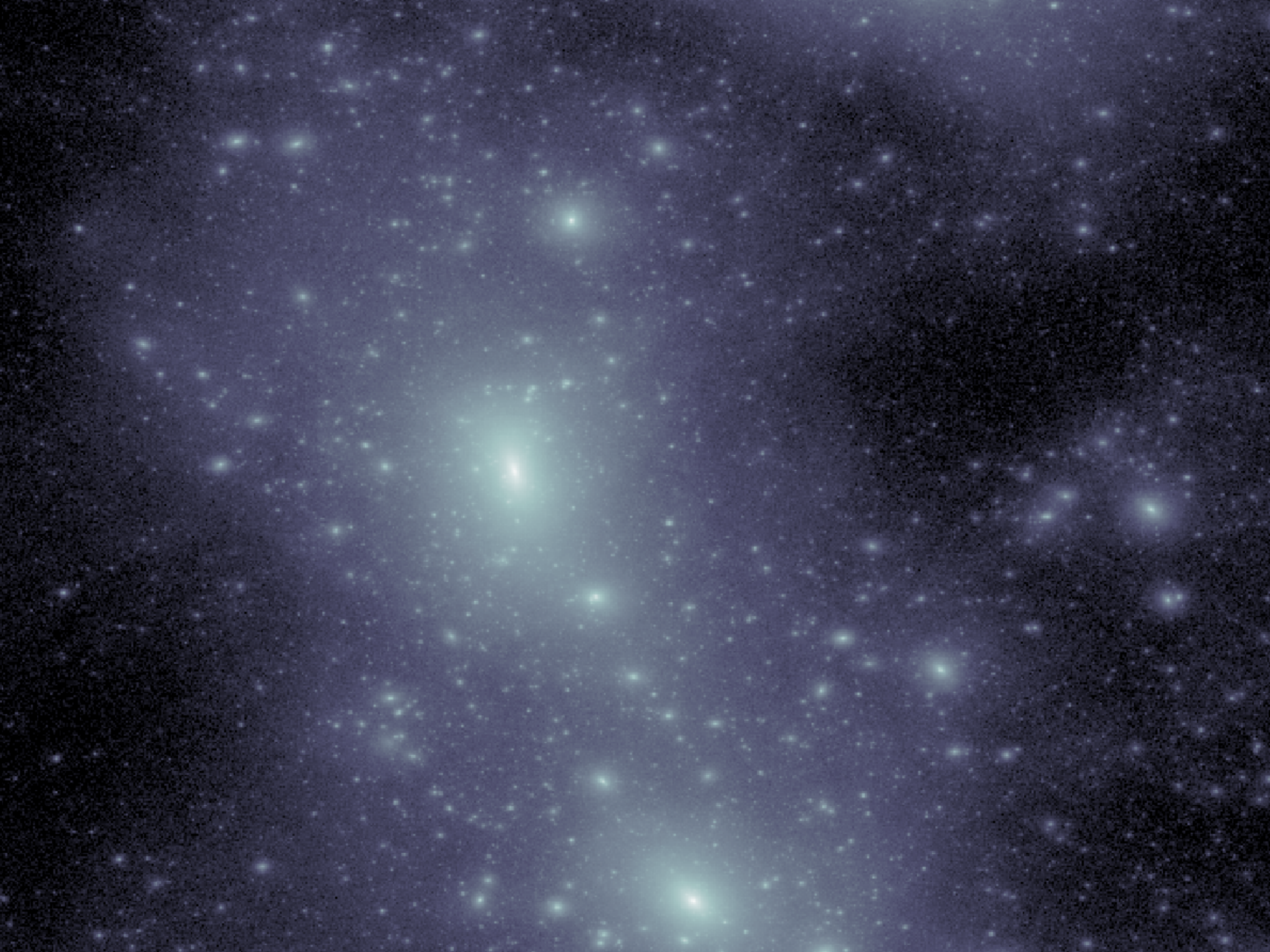


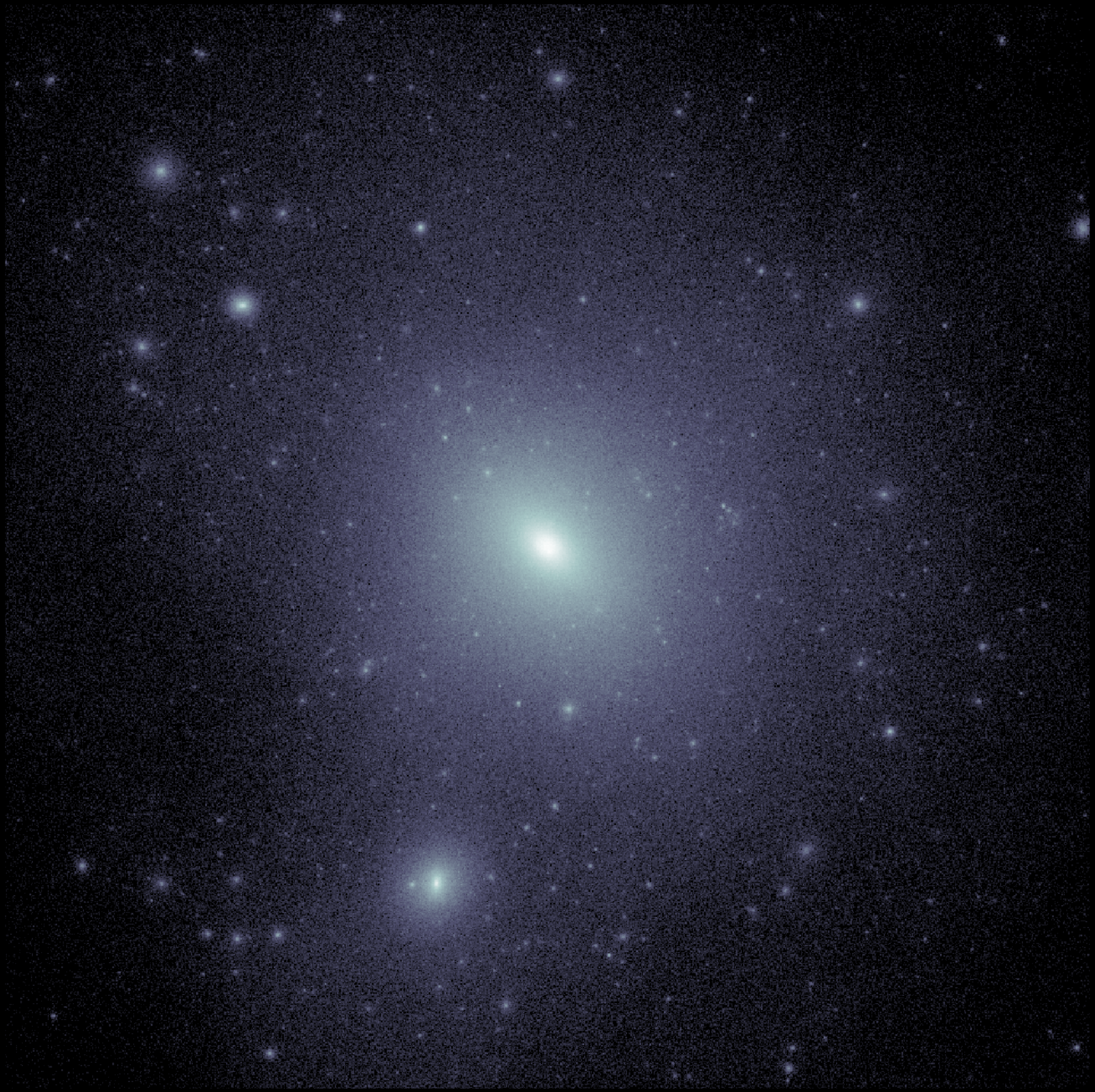
Satellites spend most of their time at apocenter

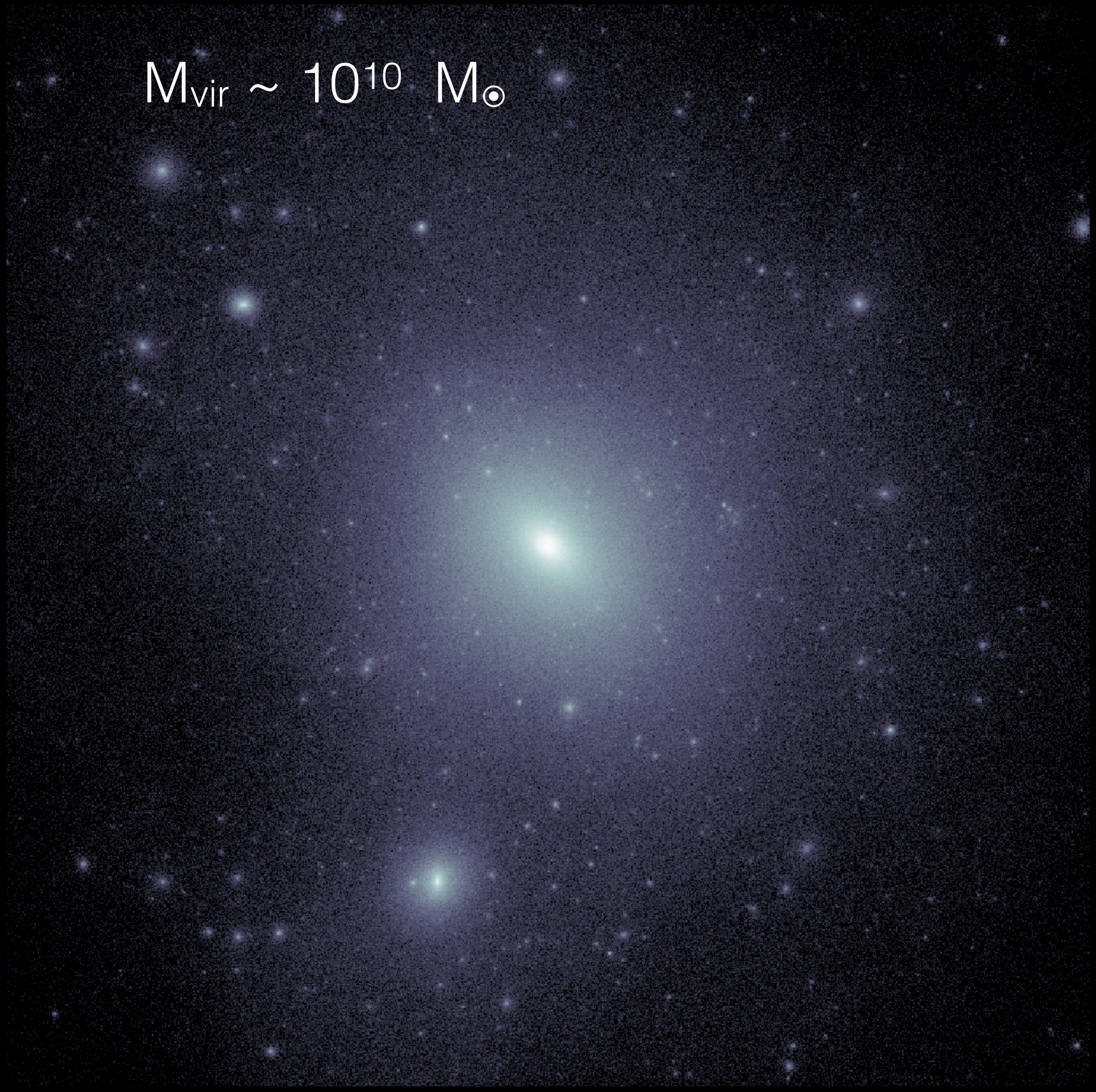
Should be a peak near f = 1

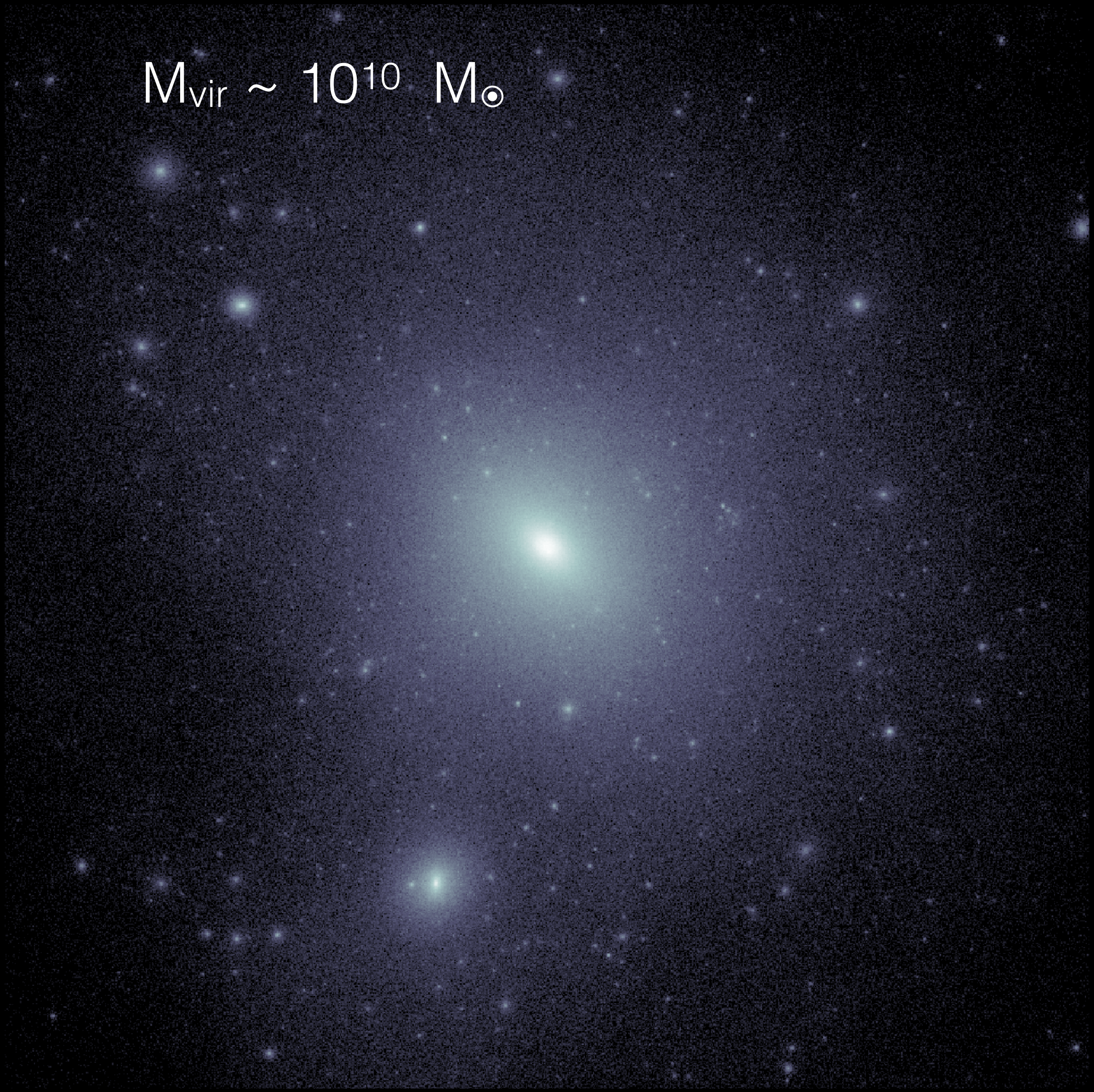
Suggests large population of “missing” satellites with R > 100 kpc

Fritz et al. 2018






$M_{vir} \sim 10^{10}\ M_\odot$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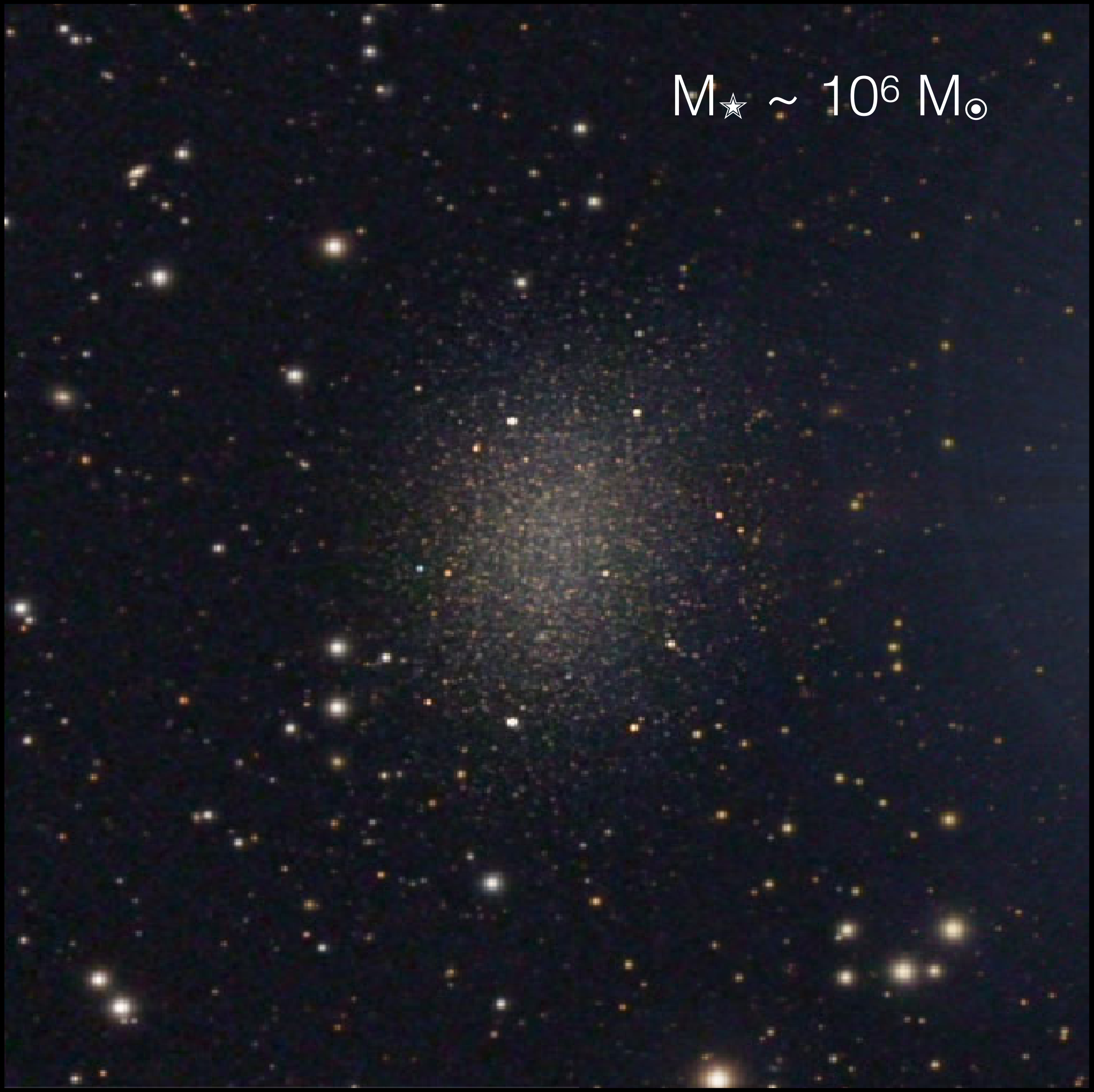
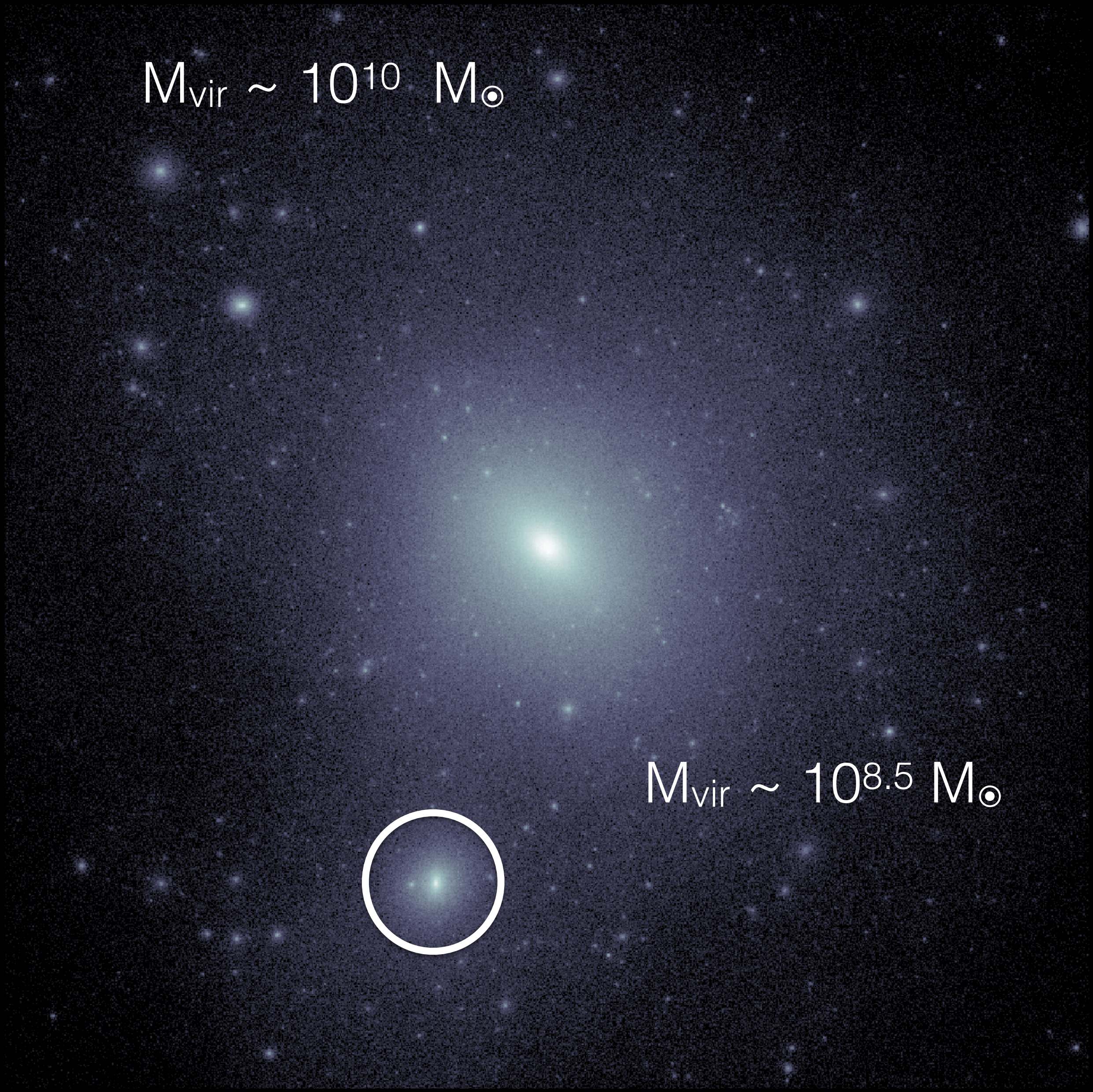
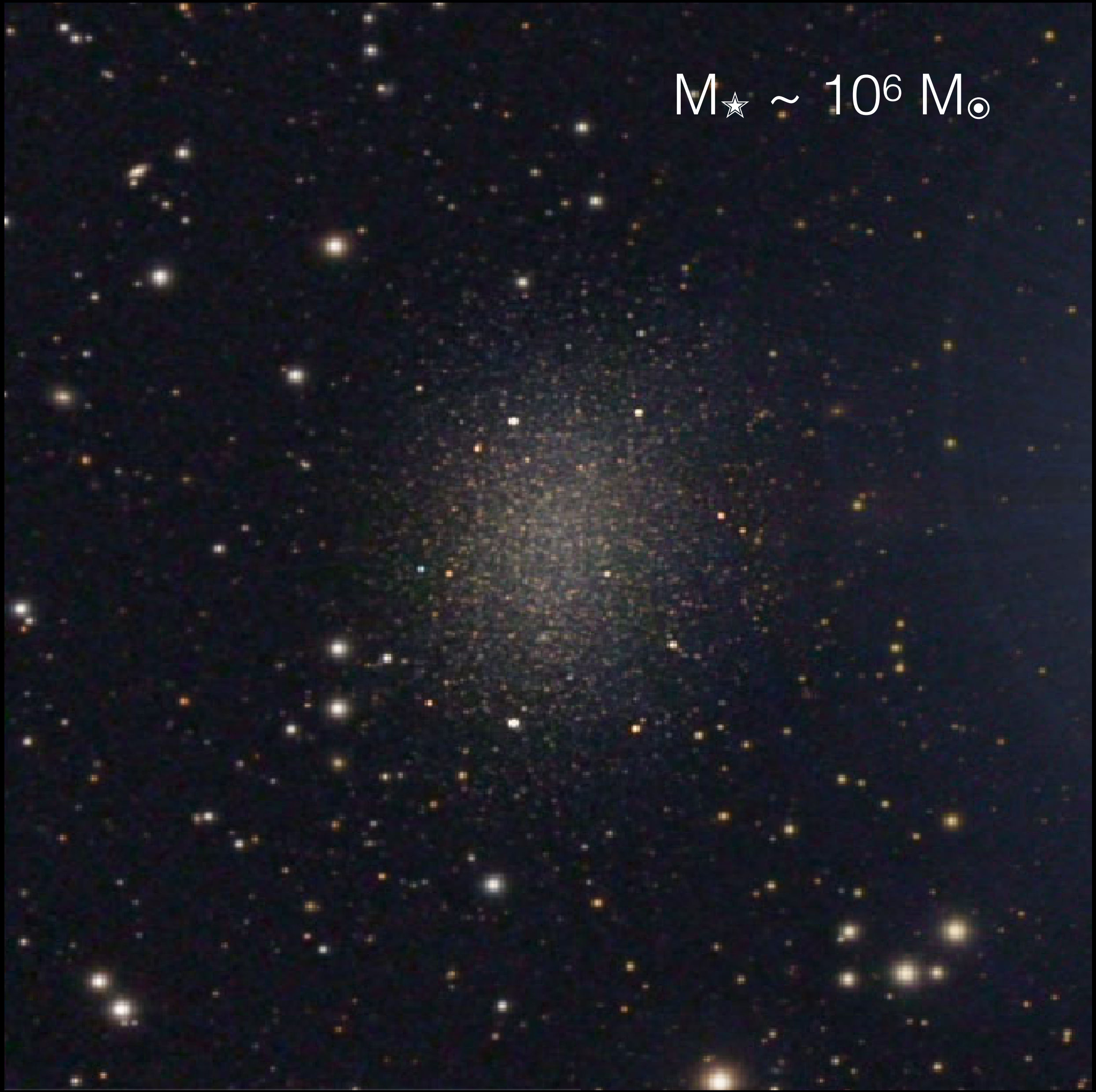

$M_\star \sim 10^6\ M_\odot$


$M_{vir} \sim 10^{10}\ M_\odot$
$M_{vir} \sim 10^{8.5}\ M_\odot$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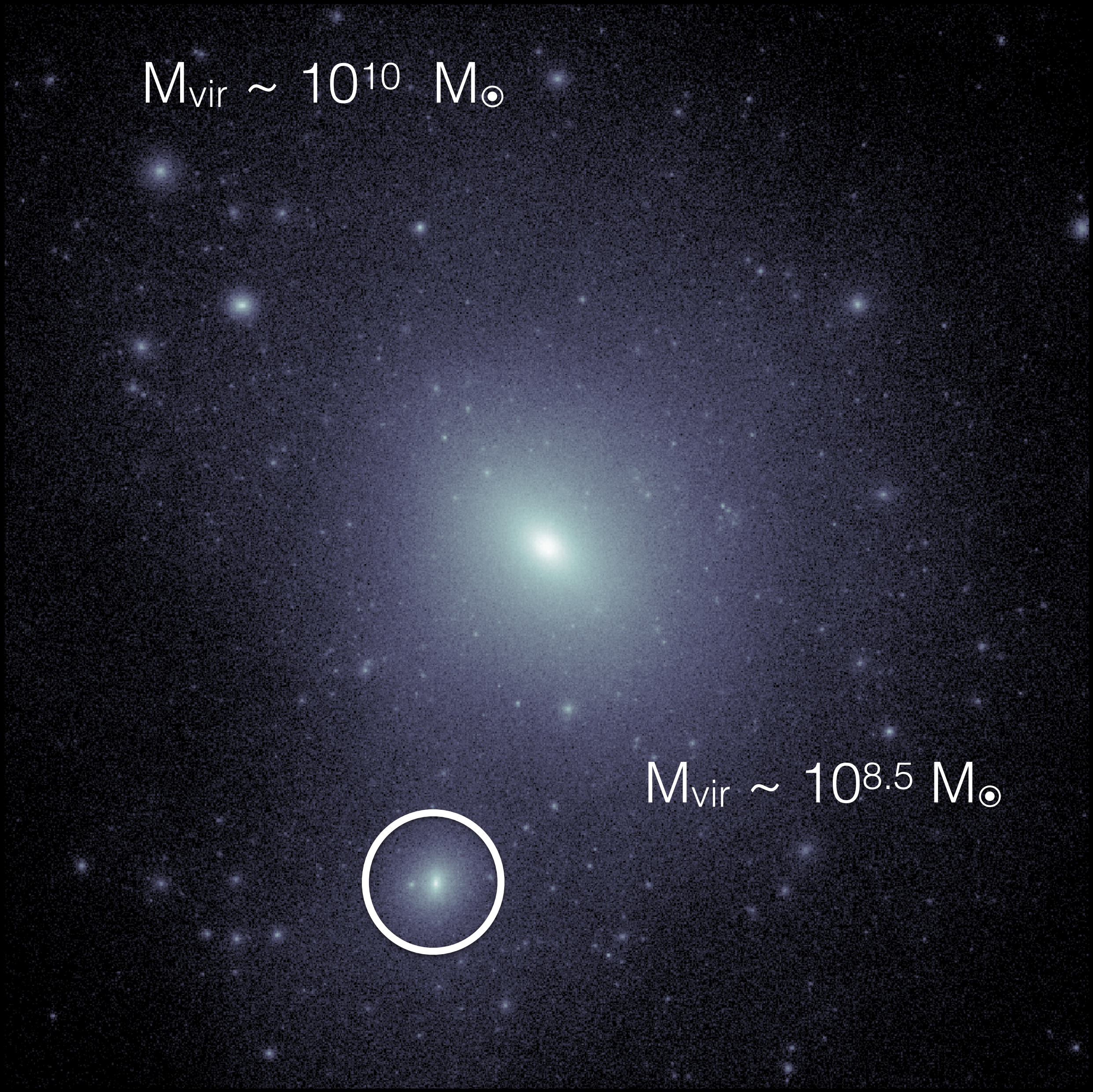
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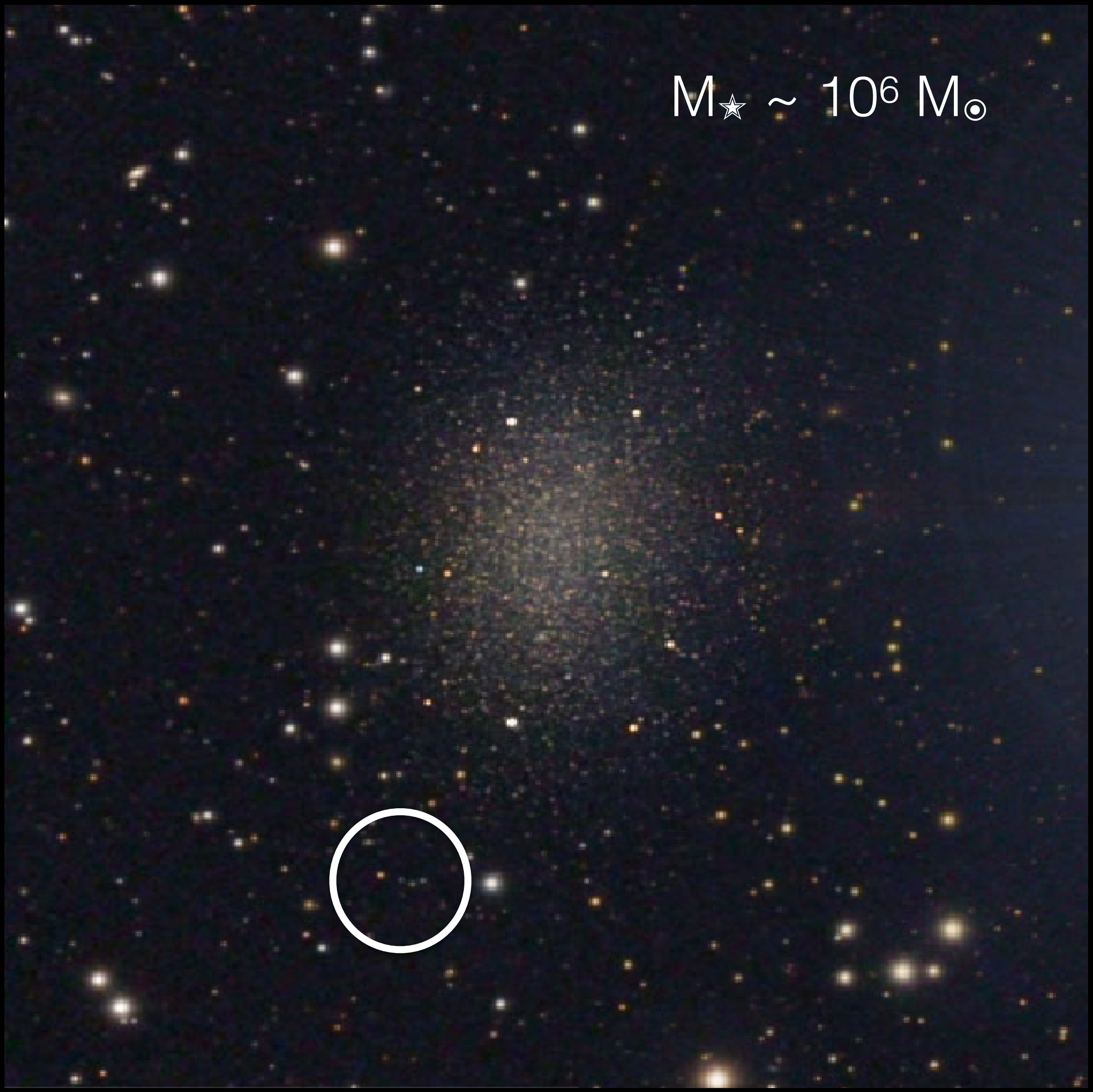
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DWARF GALAXIES ON FIRE

"Feedback In Realistic Environments"

Hopkins et al. 2014
Wheeler et al. 2015
Wheeler et al. 2018b

Radiation pressure

Stellar winds

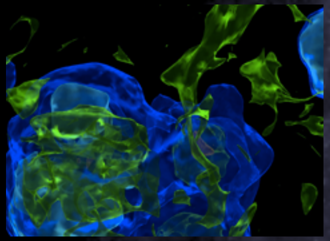
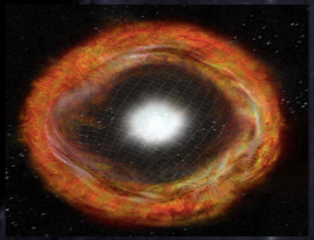
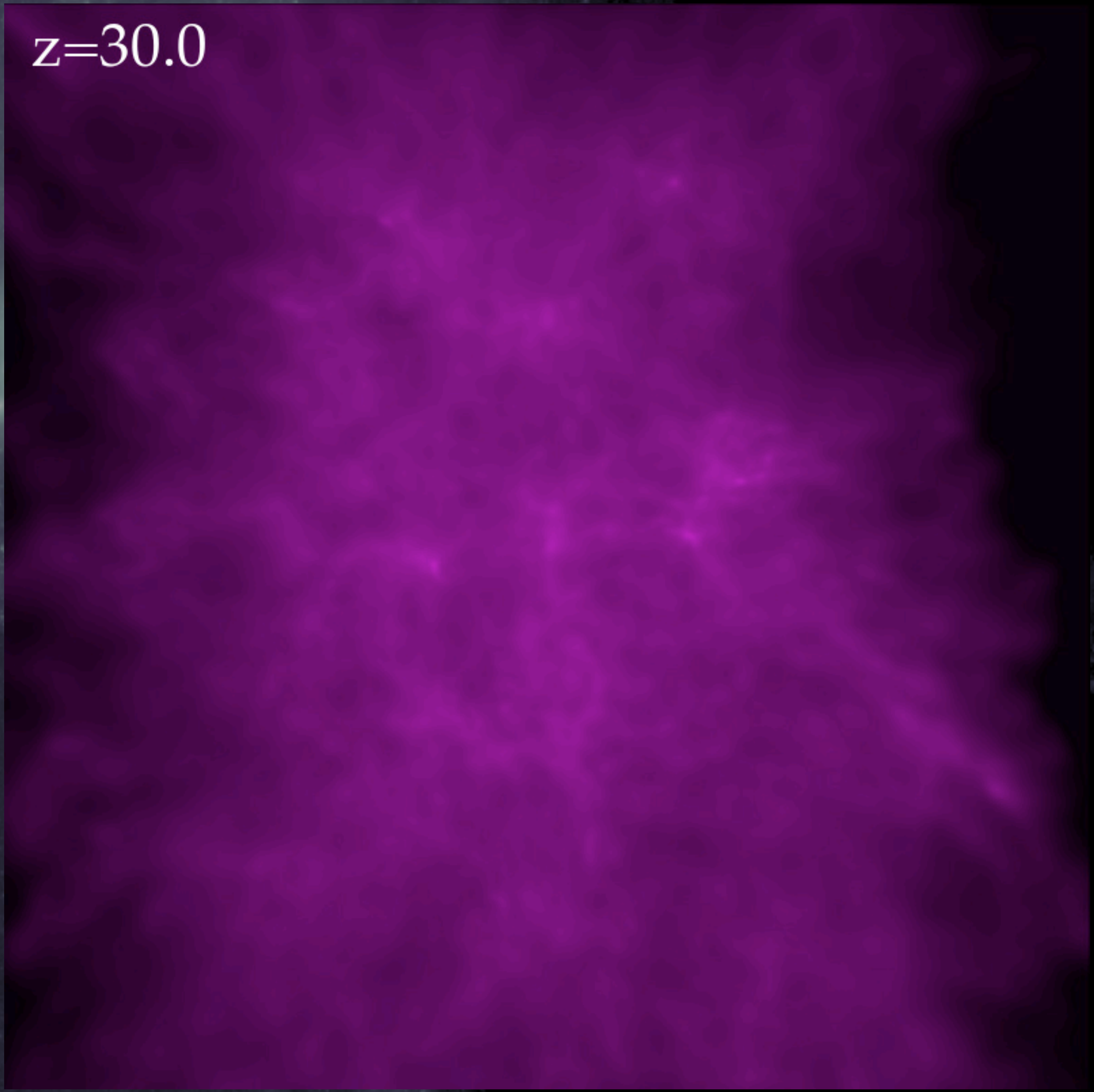


Photo-Ionization



Supernovae Type I and II



NEUTRAL GAS IONIZED GAS HOT GAS

arXiv:1812.02749

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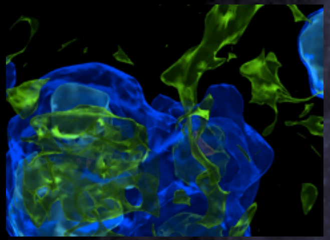

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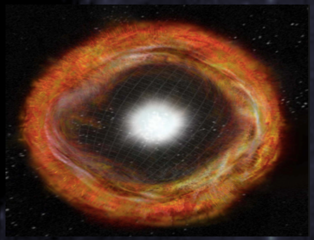

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Typical (pre-FIRE) resolution:

DM particle mass = $10^5\ M_\odot$

Star particle mass ~ $10^4\ M_\odot$

Spatial resolution = 100pc

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High Resolution (Wheeler 2015):

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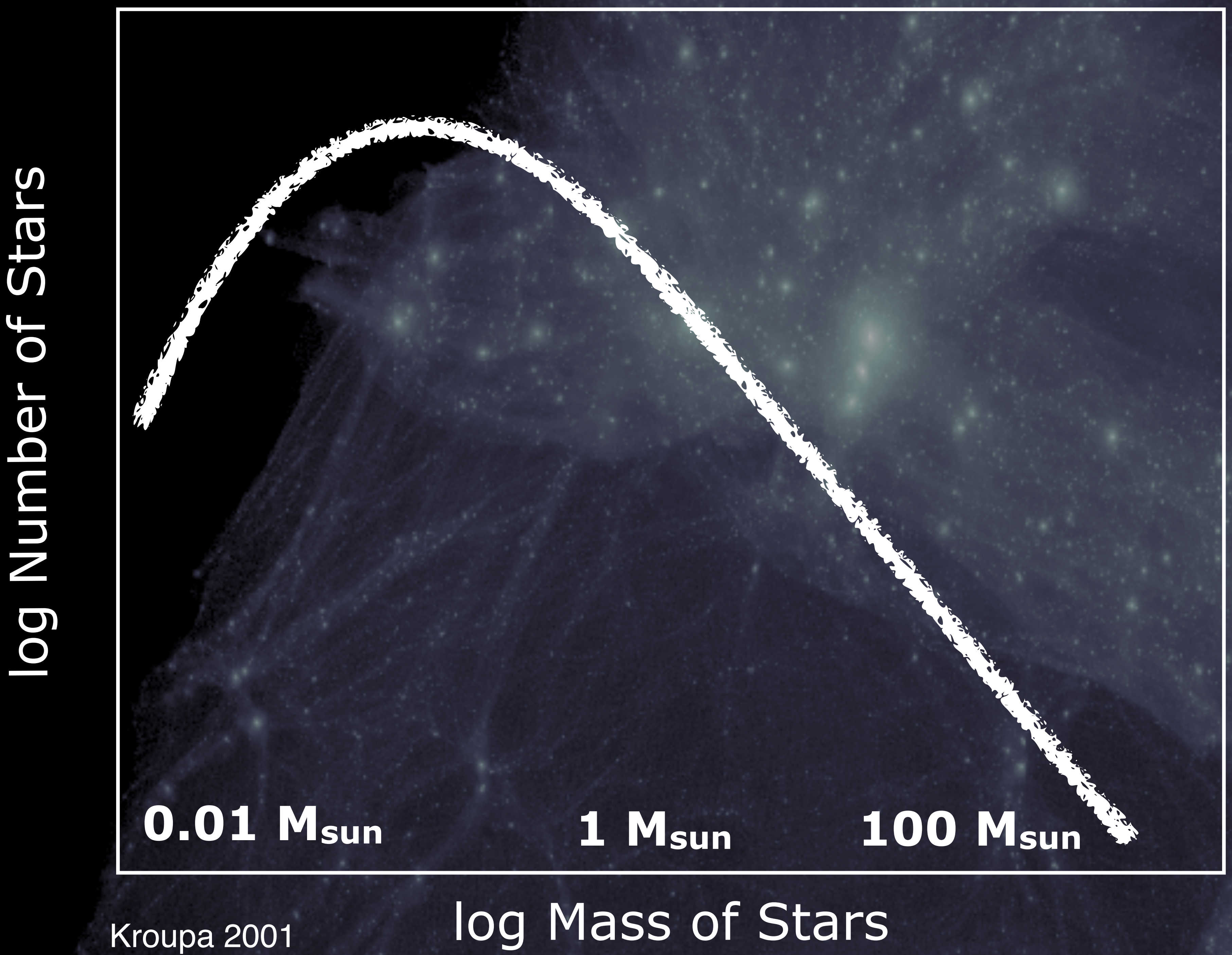
Spatial resolution = 1pc

Highest Resolution (Wheeler 2018):
DM particle mass = $160\ M_\odot$
Star particle mass ~ $30\ M_\odot$
Spatial resolution = 0.1-0.4pc

arXiv:1812.02749

Trouble with High Resolution: IMF Sampling

Massive star particle treated as single stellar population with Kroupa 2001 IMF



Kroupa 2001

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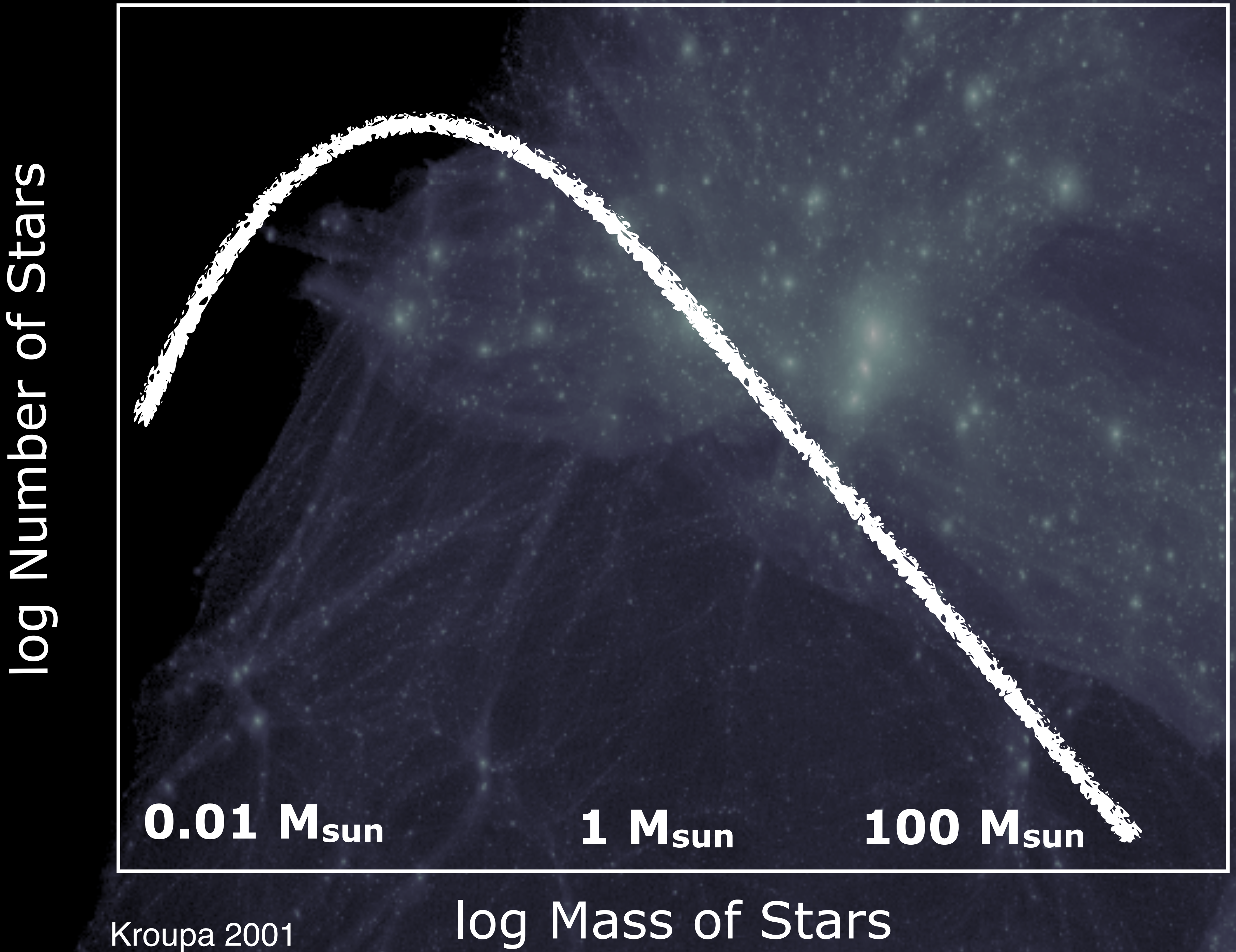

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Star particles < ~100 M_{sun} can no longer represent complete stellar population

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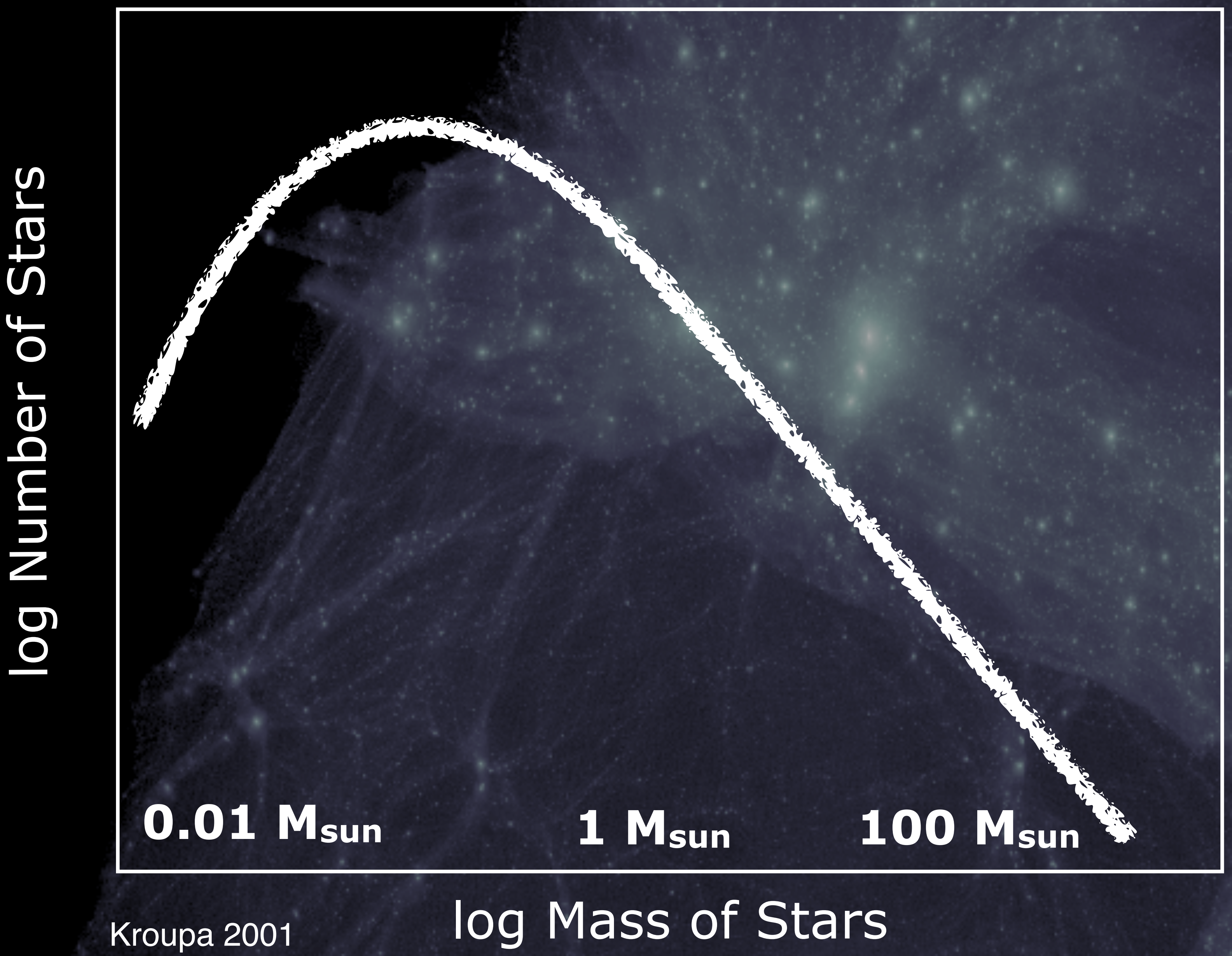


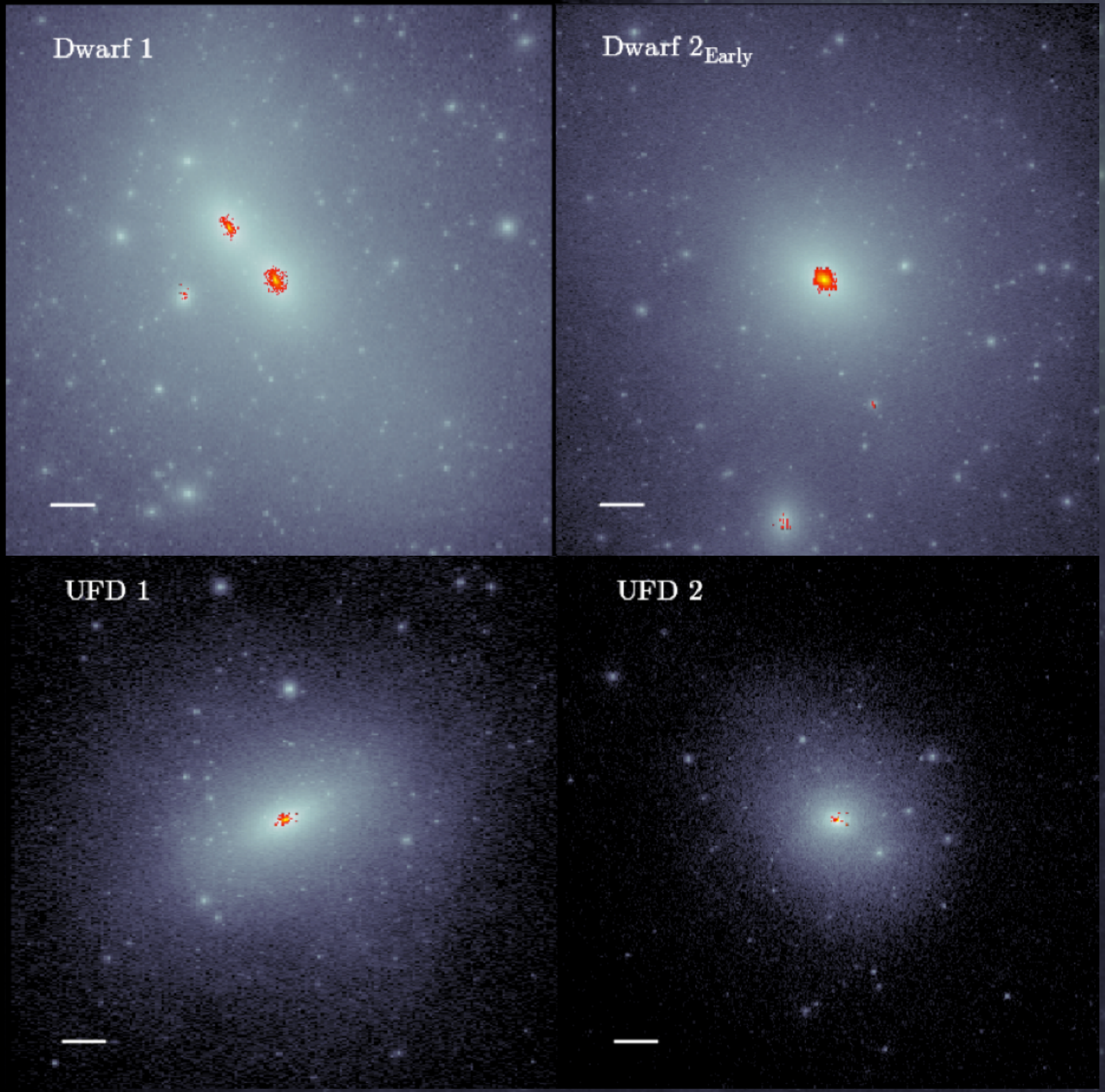
Kroupa 2001

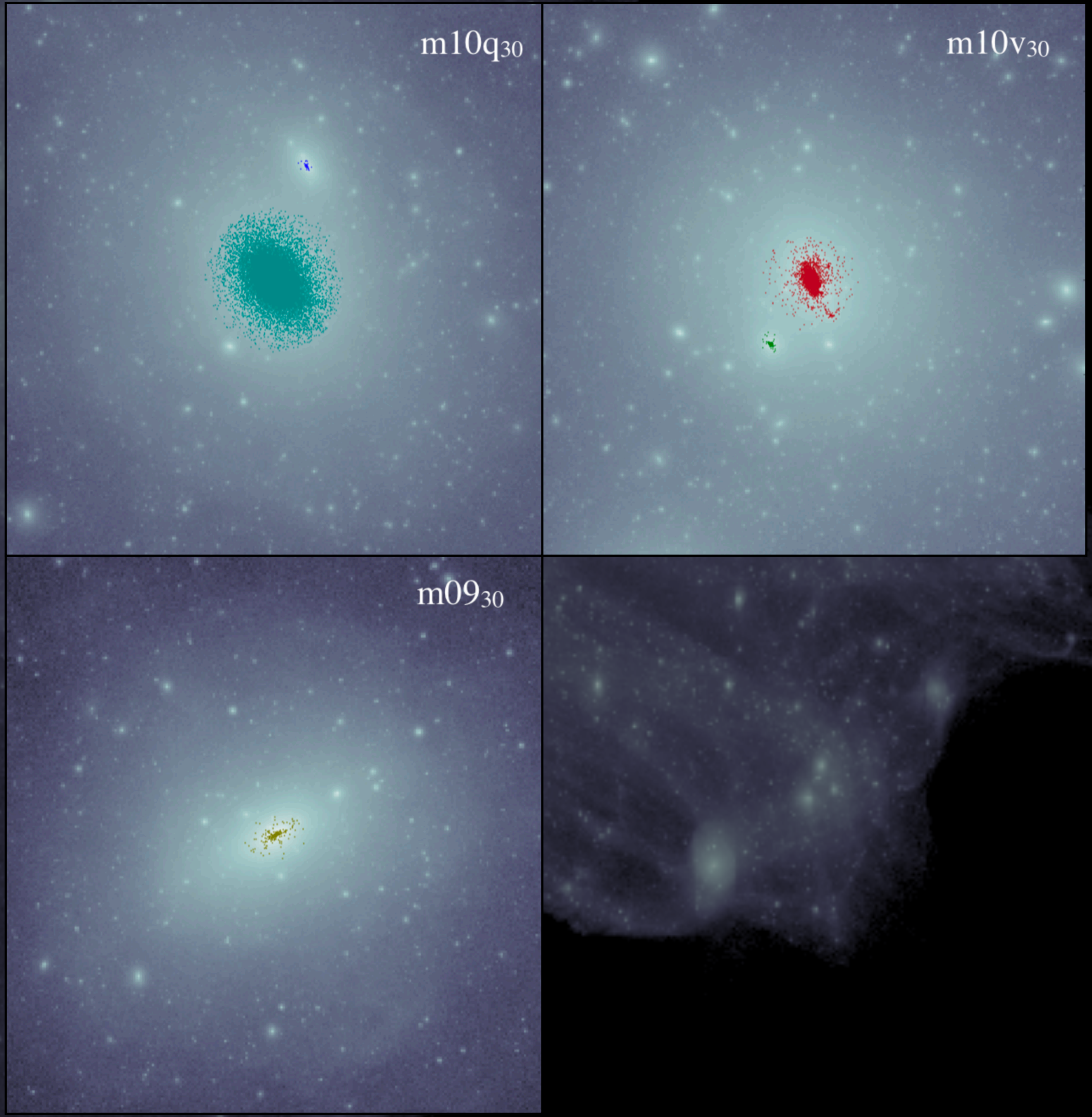
Massive star particle treated as single stellar population with Kroupa 2001 IMF

Star particles < ~100 M_{sun} can no longer represent complete stellar population

Must stochastically sample IMF, allowing small fraction of particles to represent a discrete integer number of massive stars

Prediction: Galaxies in all halos with $M_{halo} > 5\text{x}10^8\ M_\odot$





Wheeler et al. 2015

Wheeler et al. 2018b

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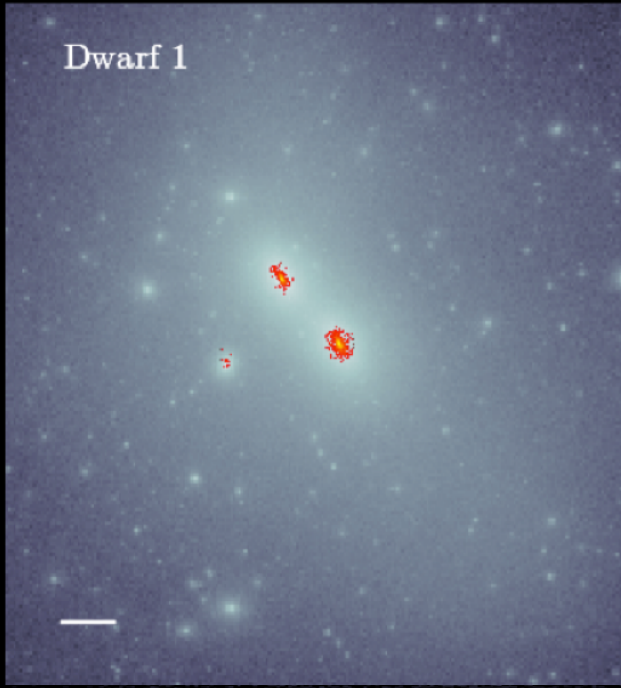

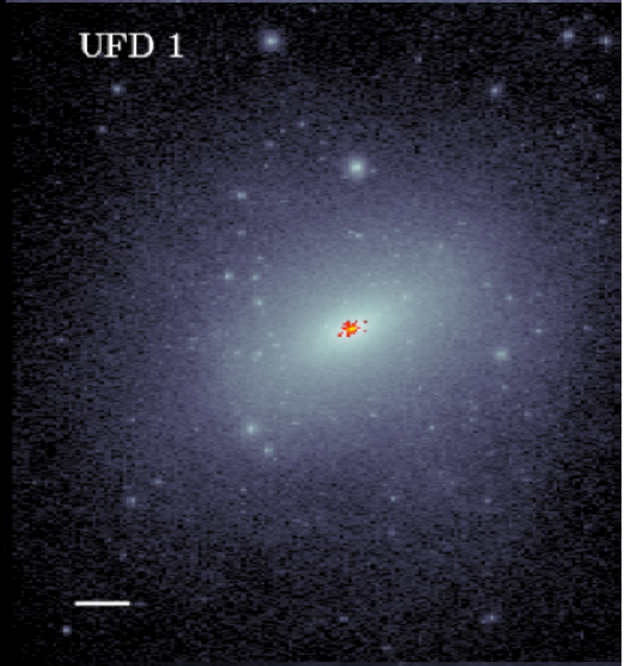

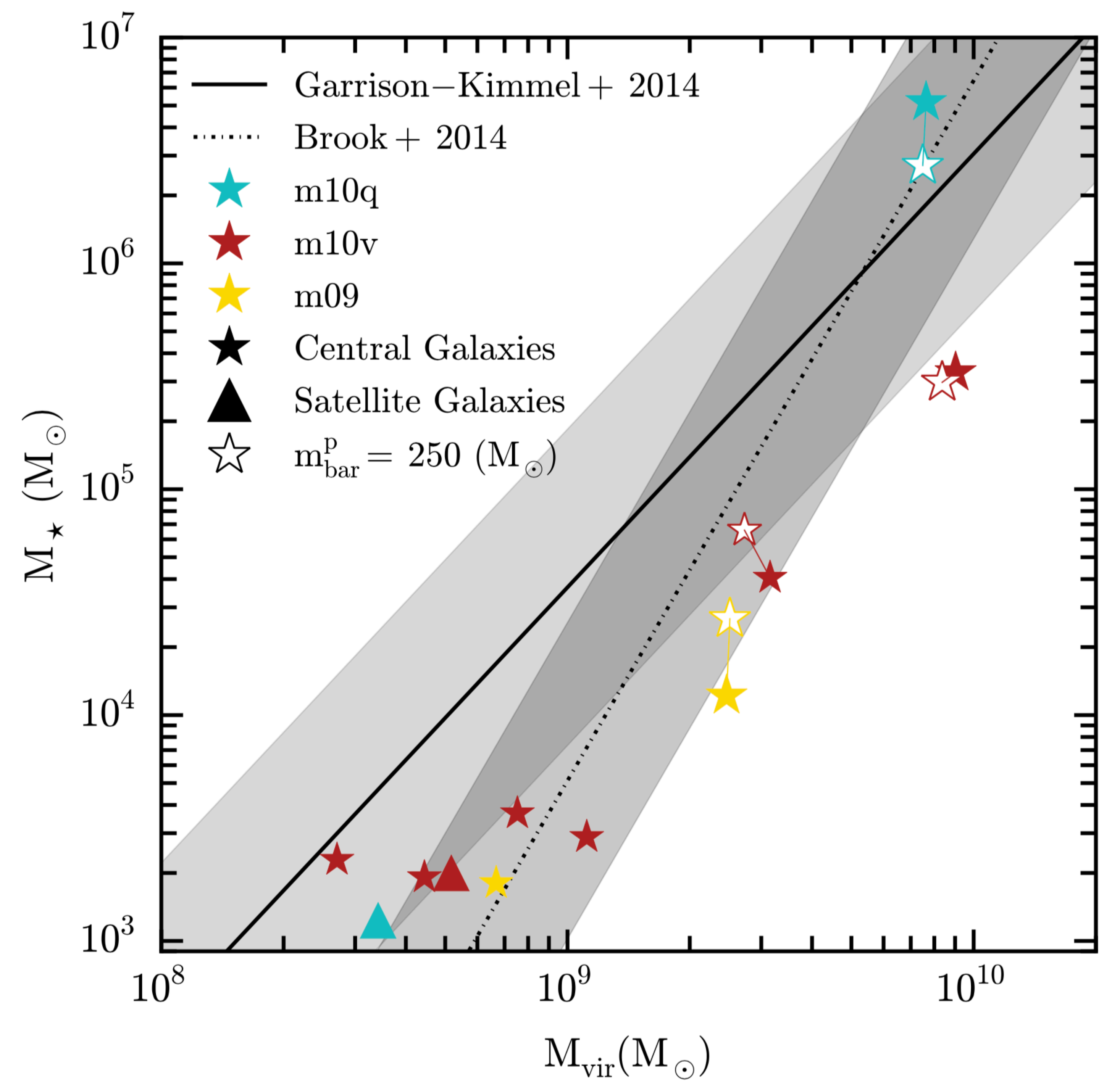

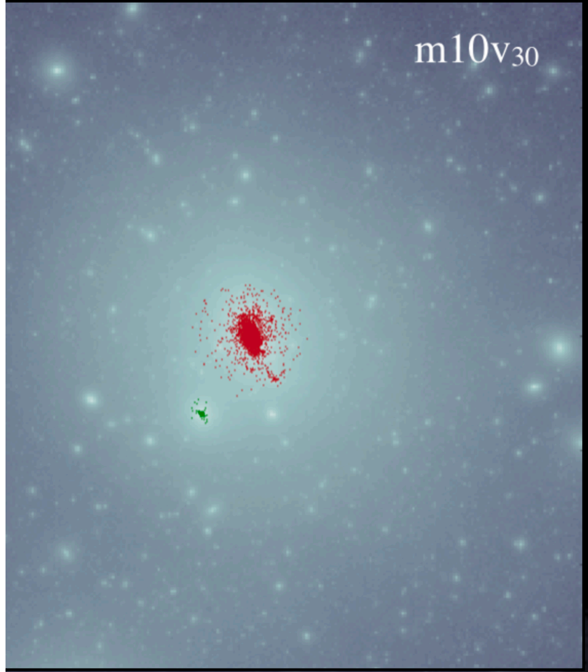

Wheeler et al. 2015

Wheeler et al. 2018b

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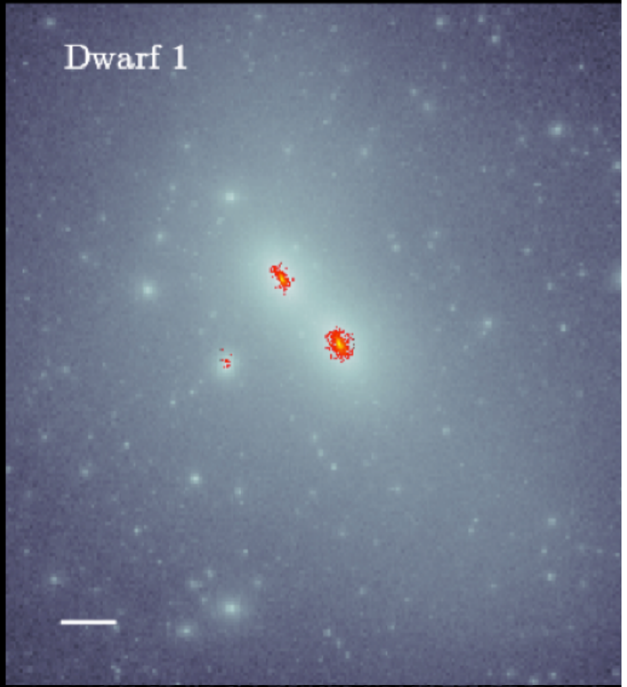
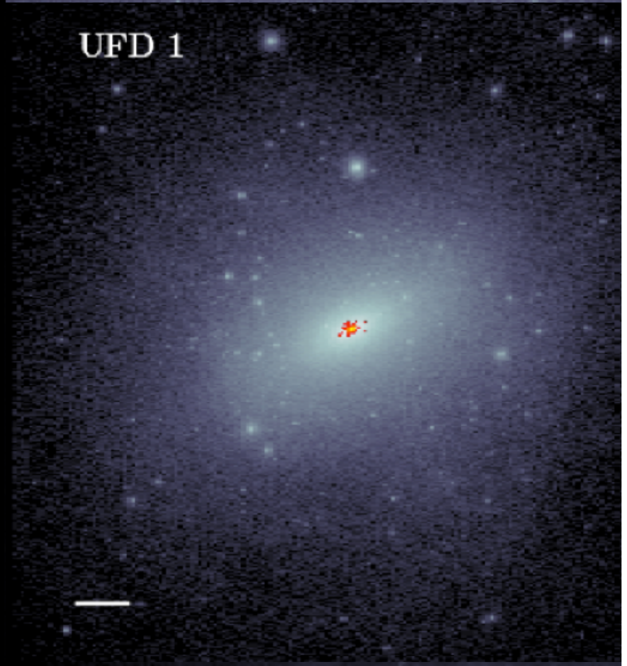
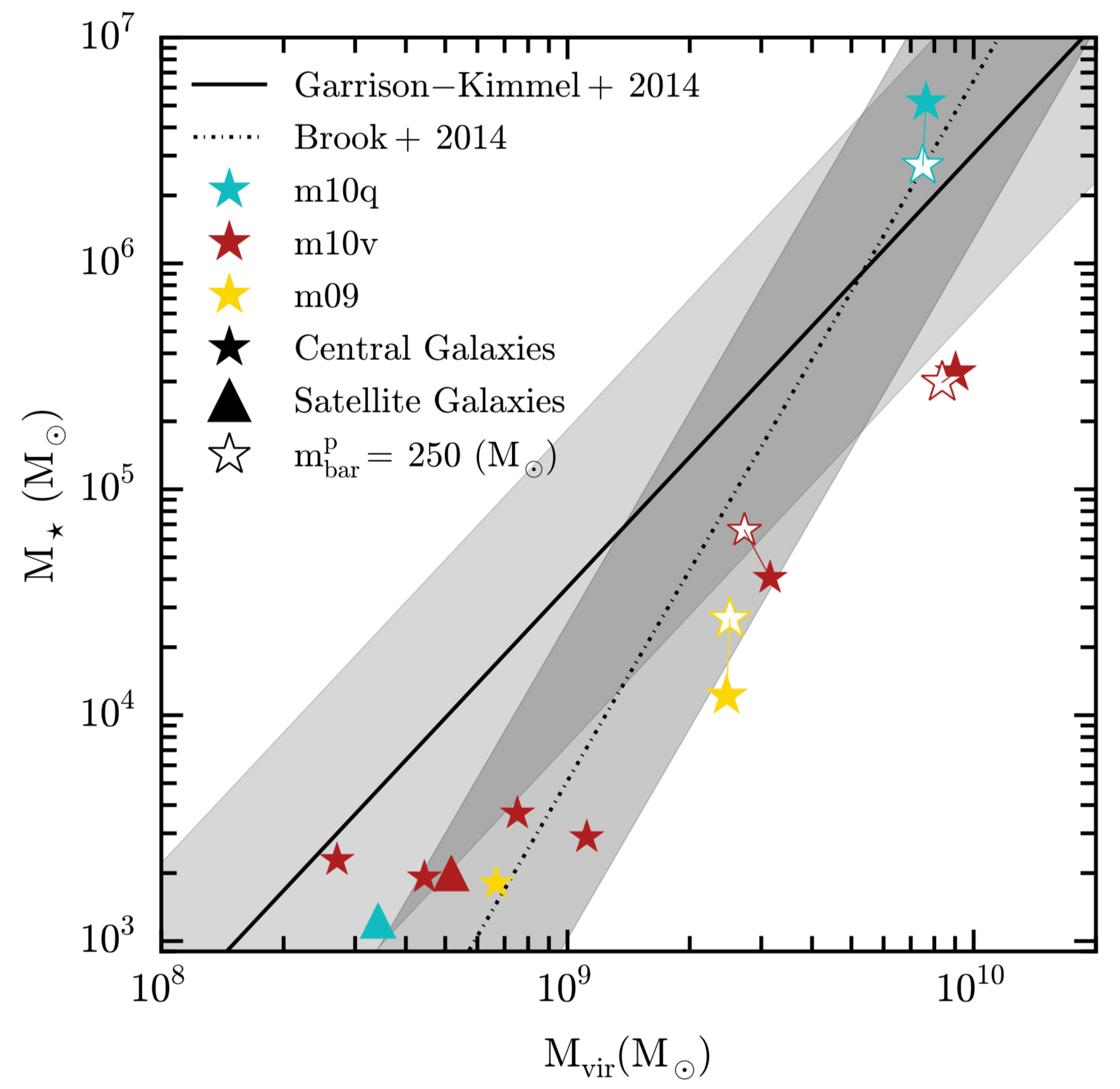
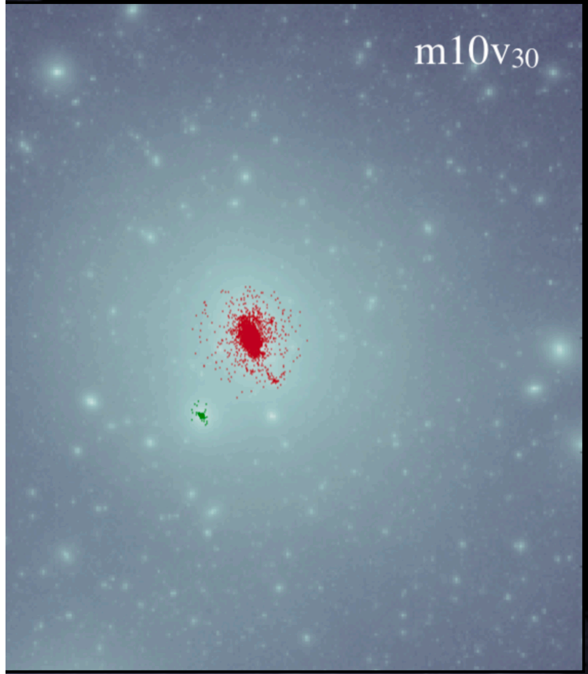
Testable prediction: Isolated classical dwarfs have their own ultra-faint satellites









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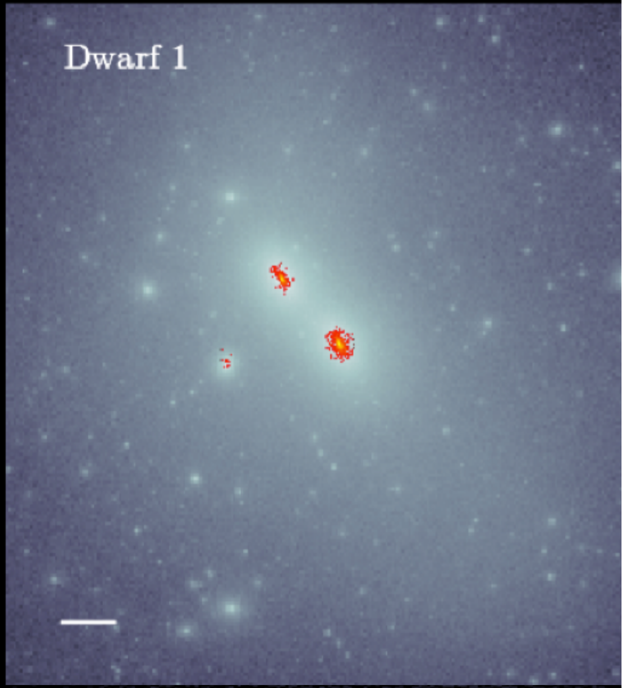
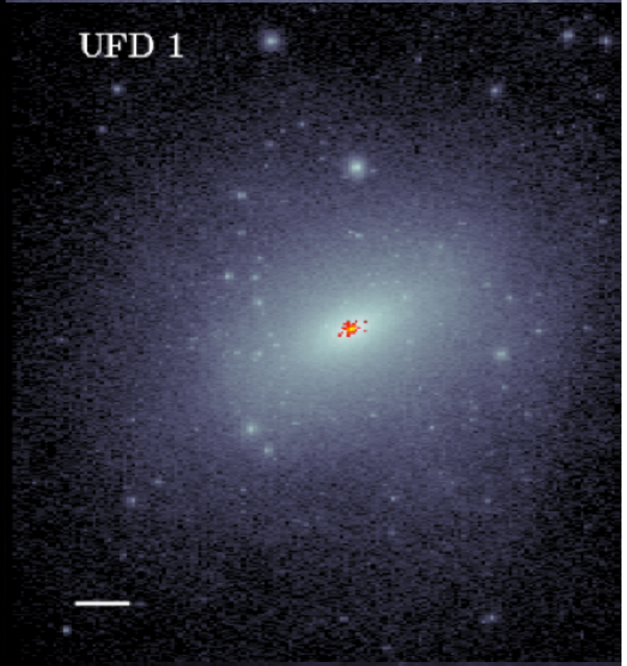
Testable prediction: should be ubiquitous in the field - 100s around the MW!





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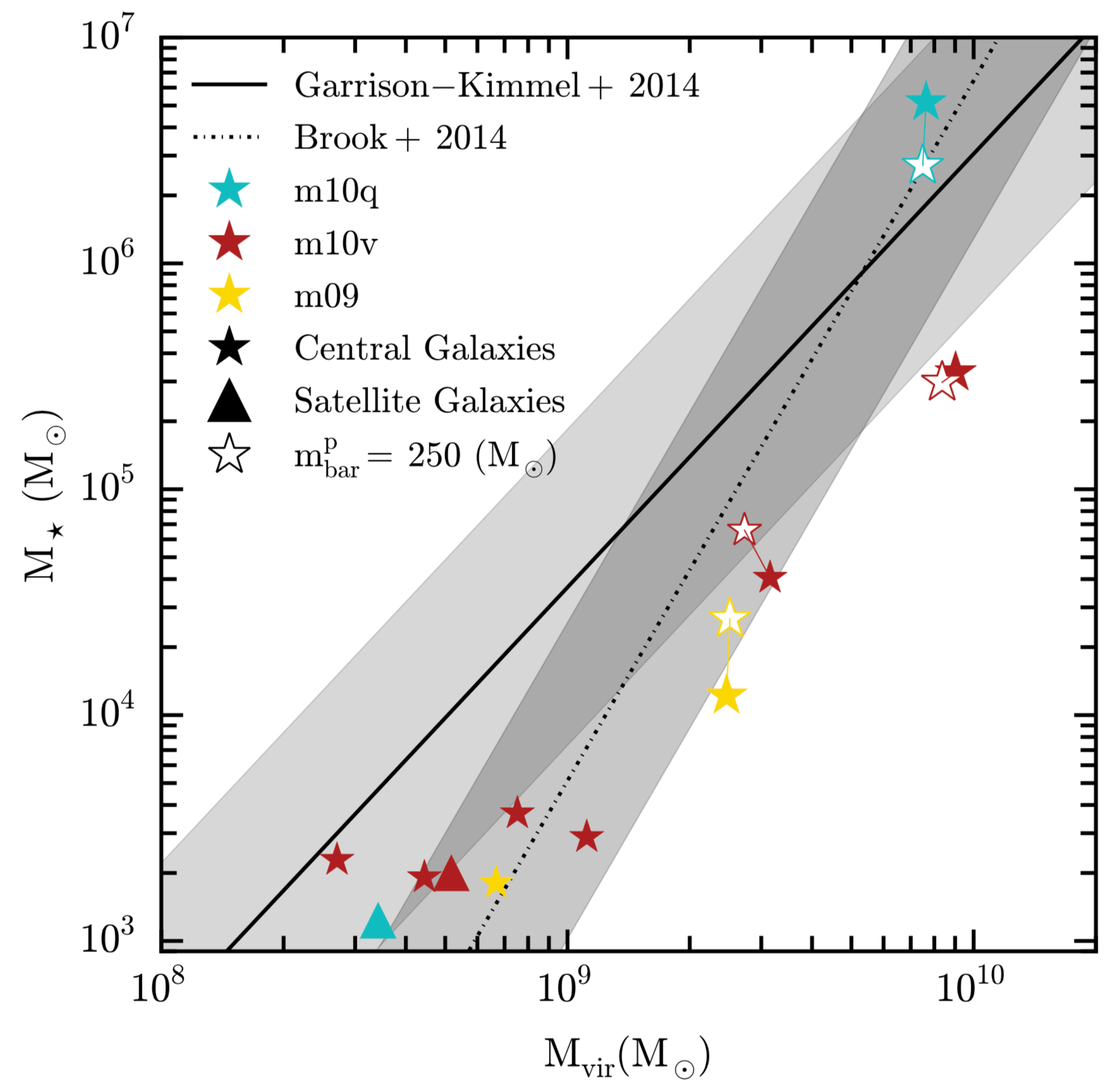

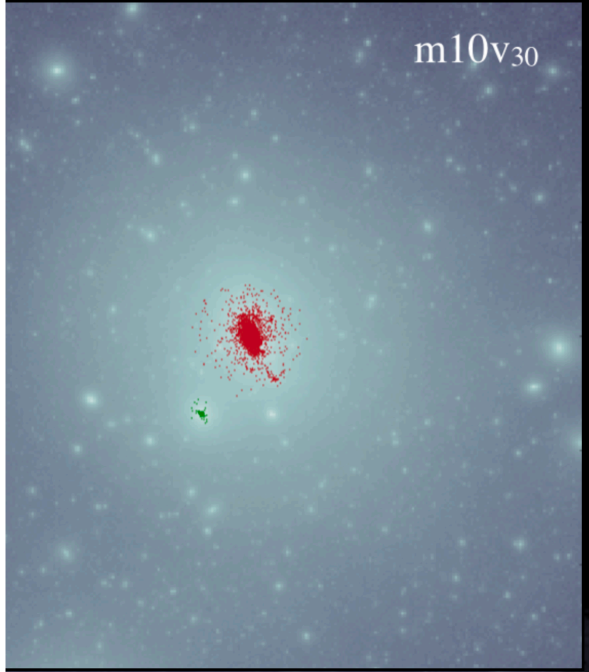

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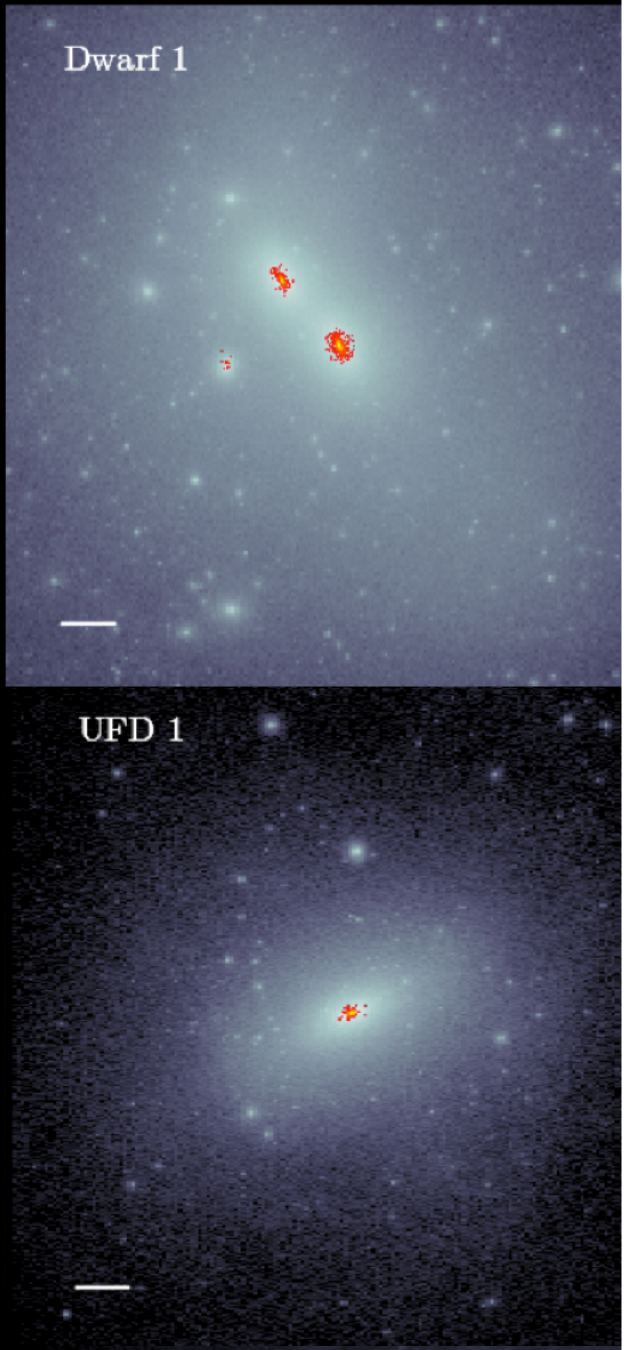

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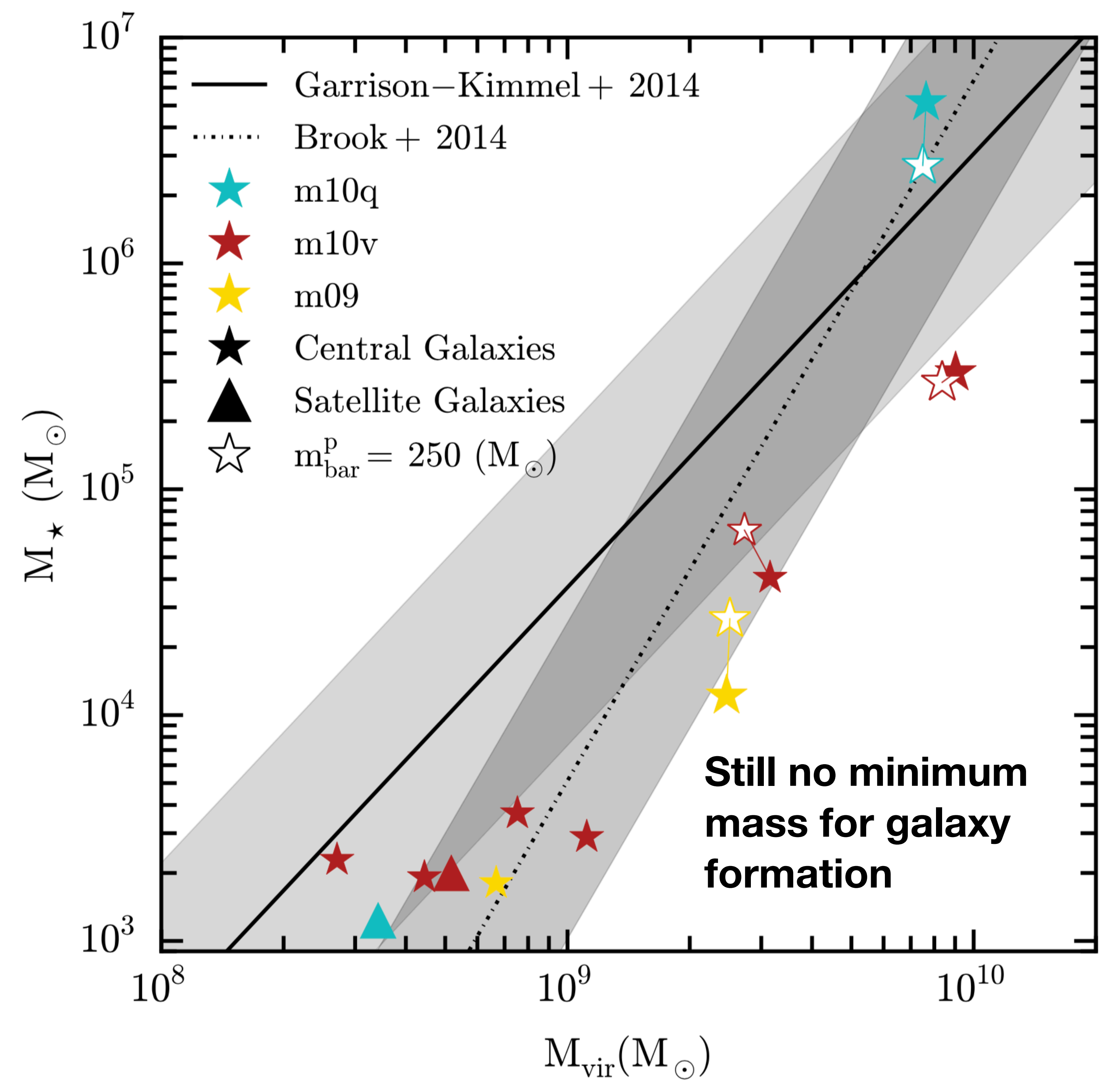
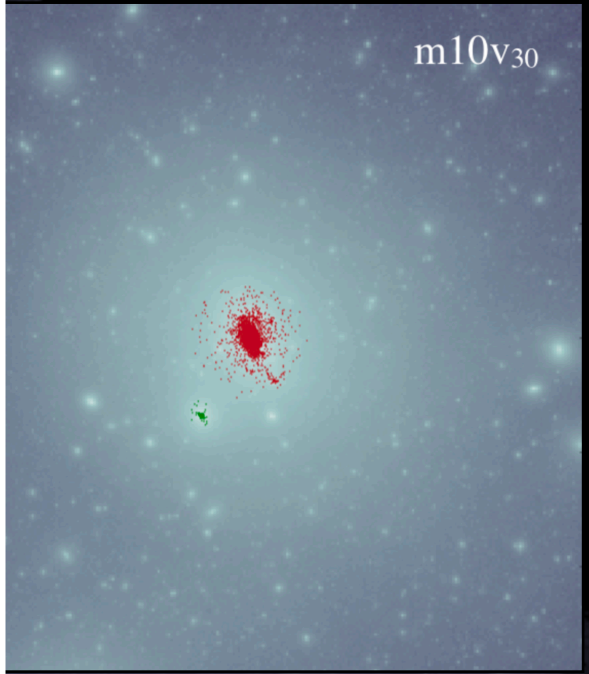
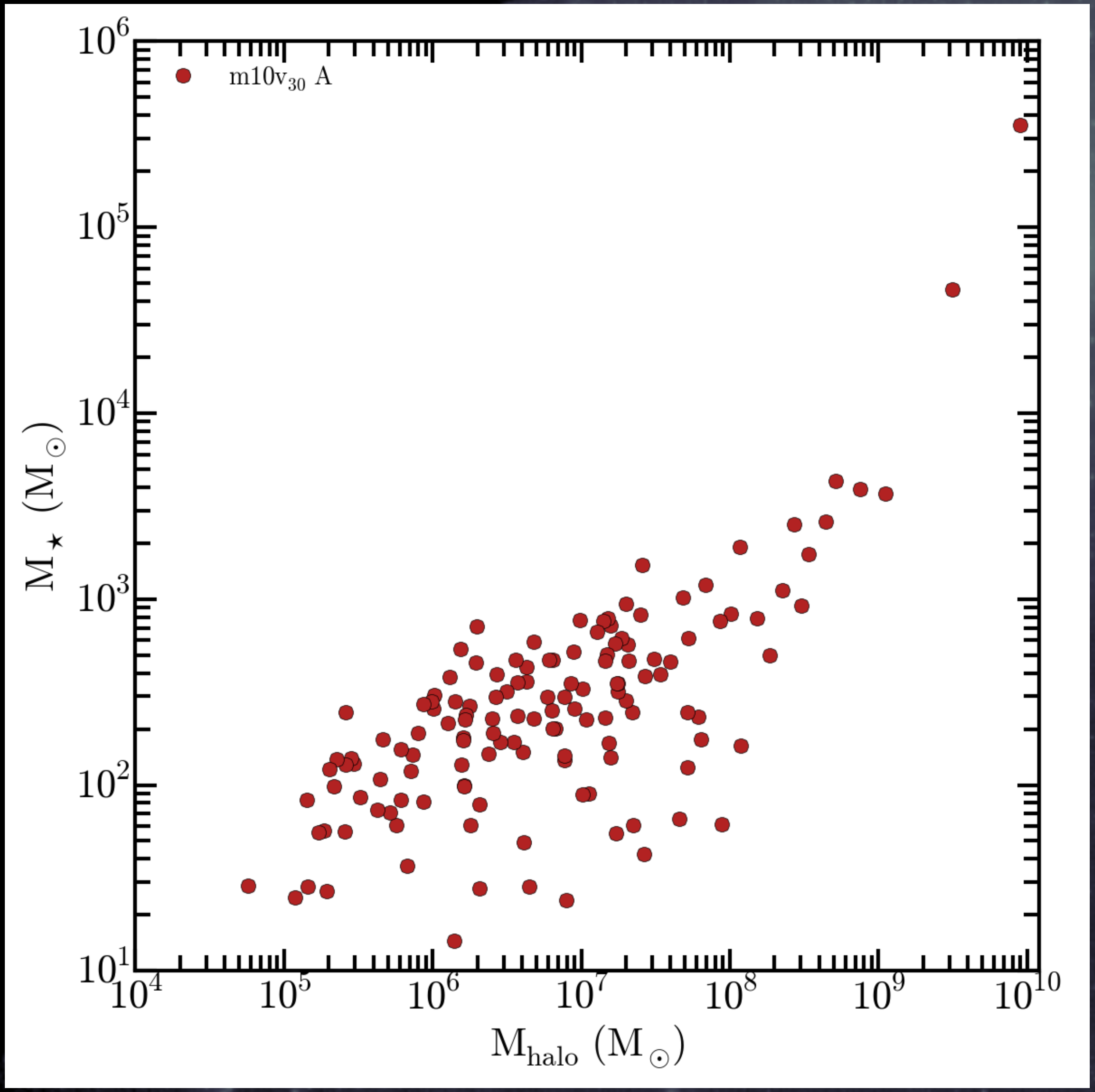


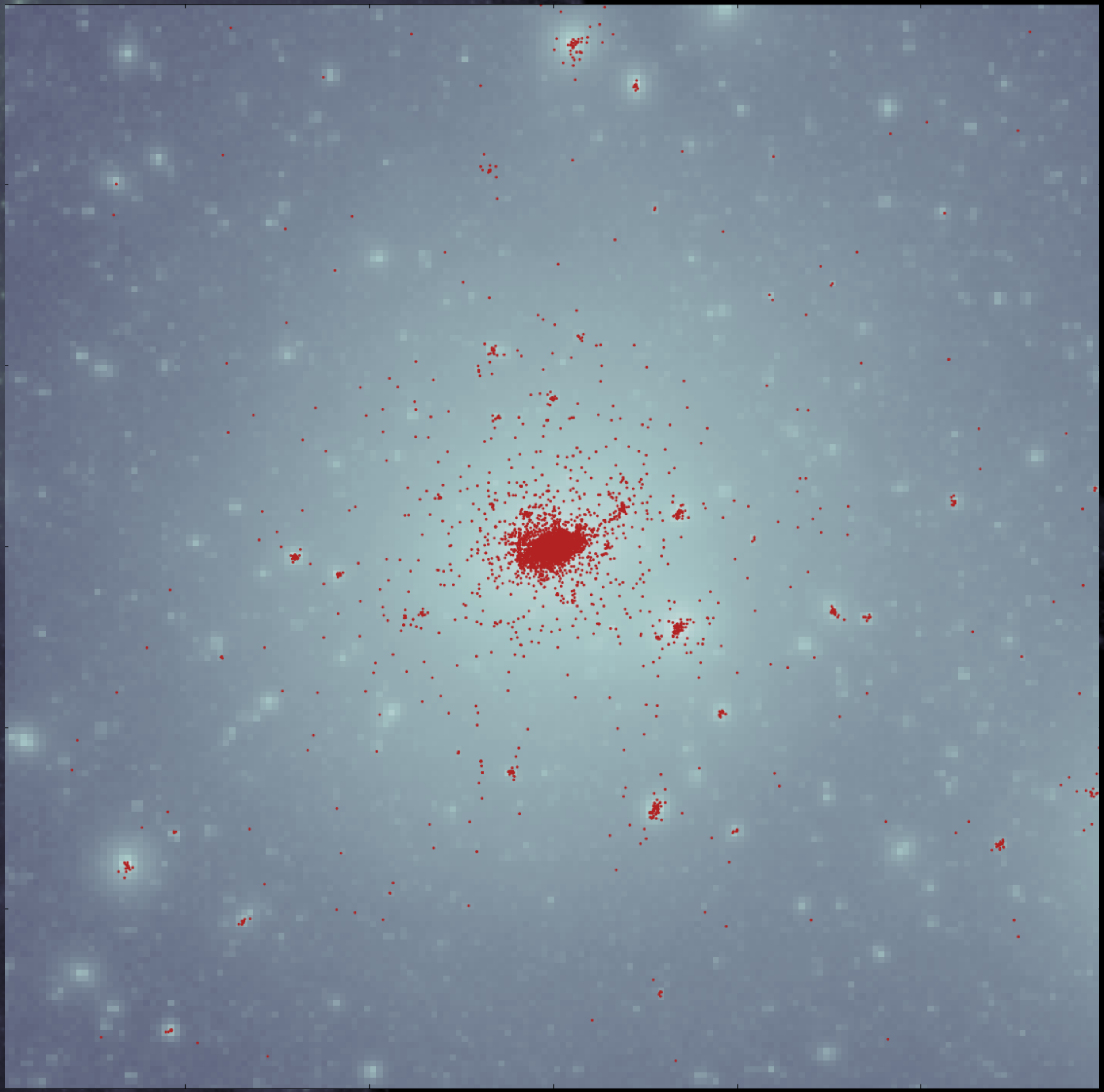
Still no minimum mass for galaxy formation



Wheeler et al. 2018b

Future Work: lower particle count limit





Wheeler et al. 2018b

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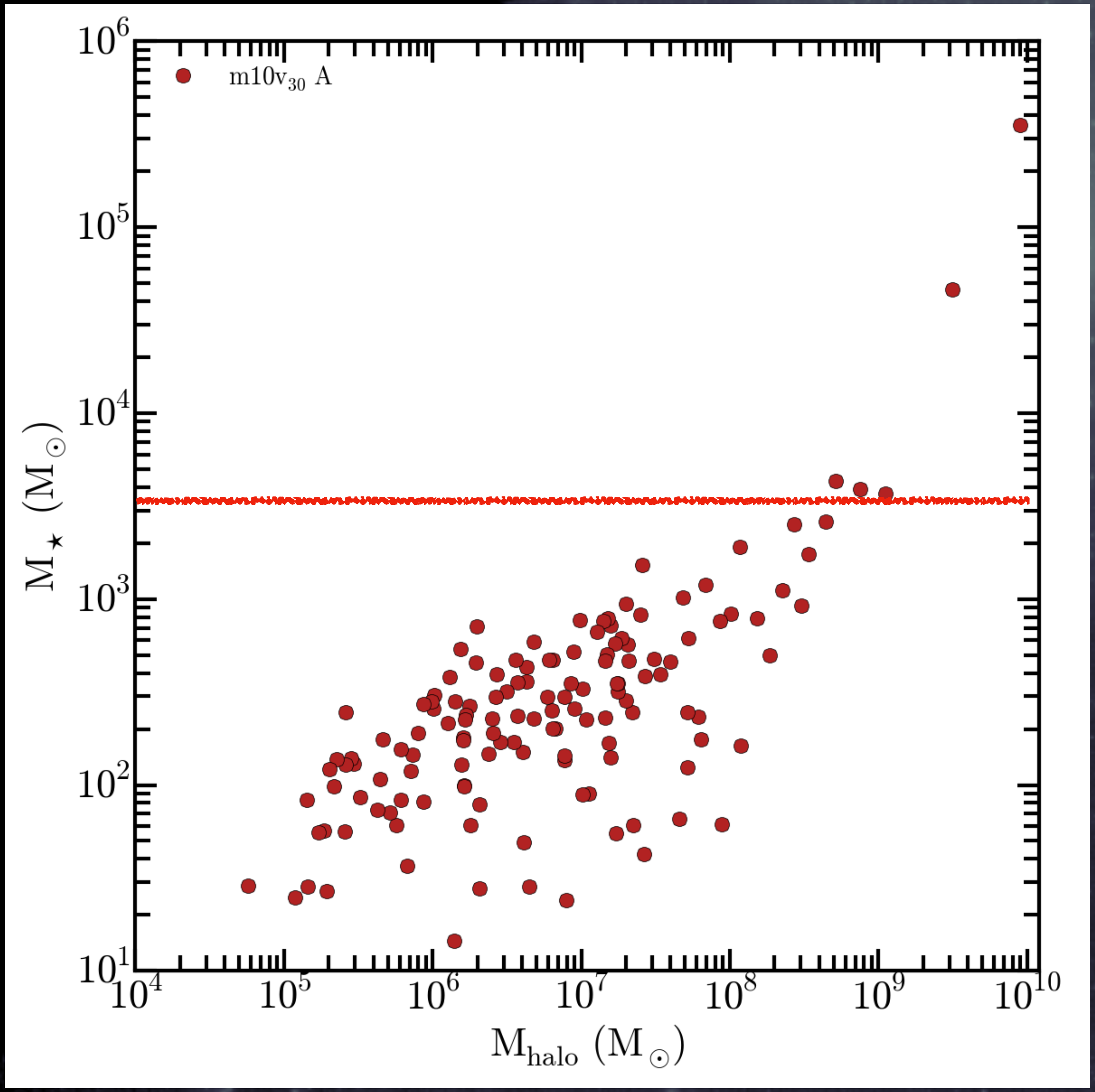

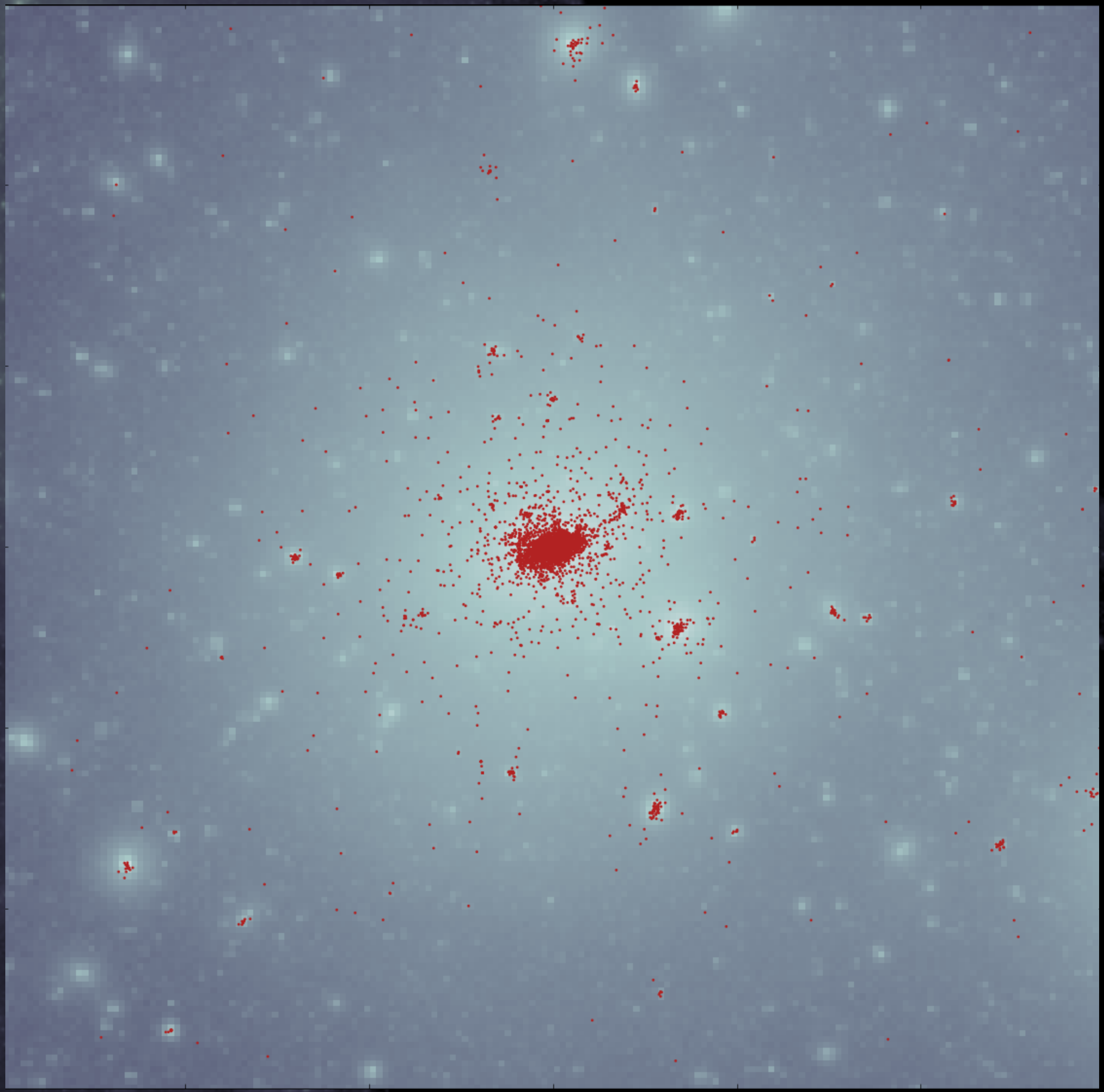

Wheeler et al. 2018b

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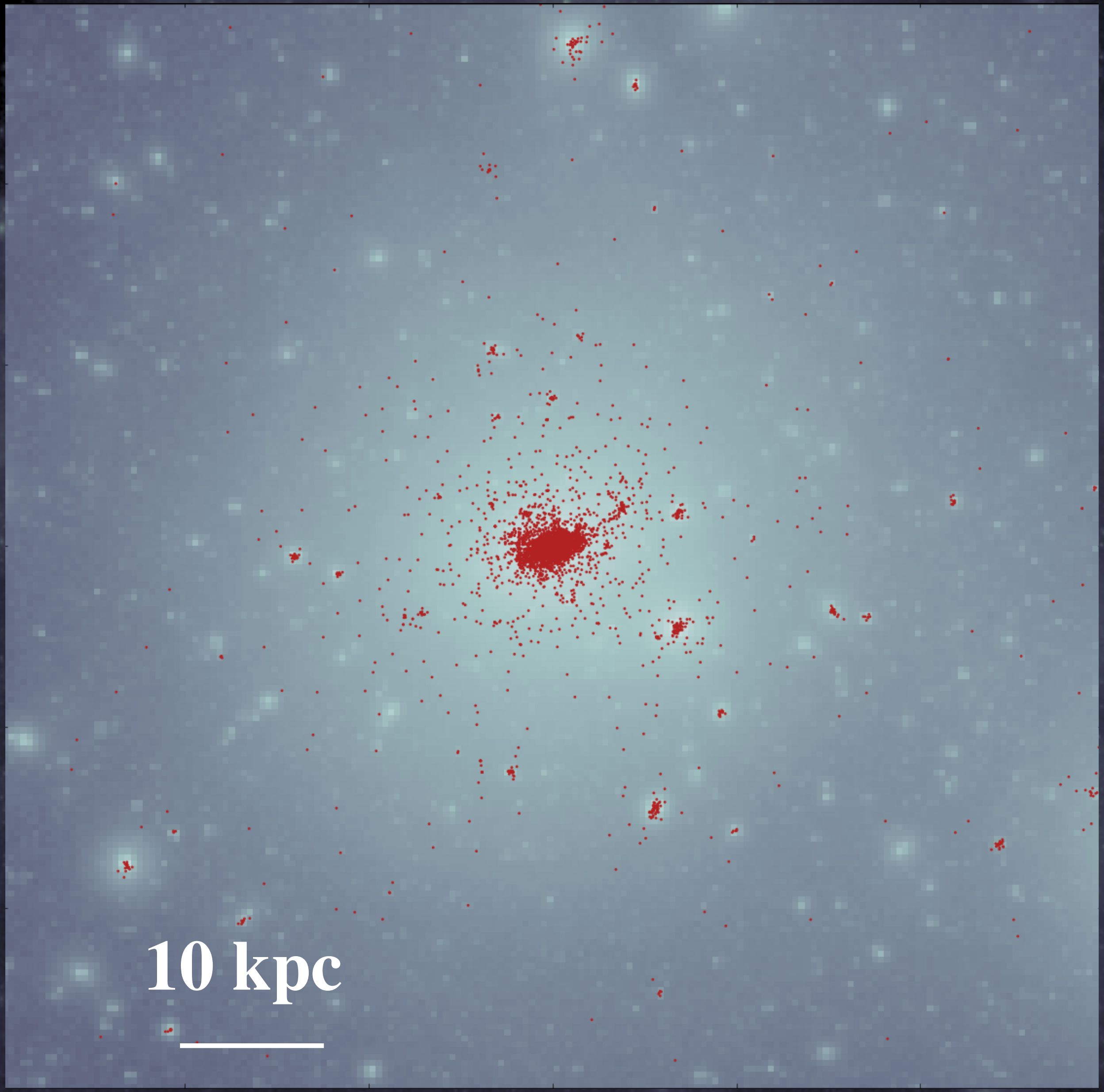

Wheeler et al. 2018b

credit: Garrison-Kimmel

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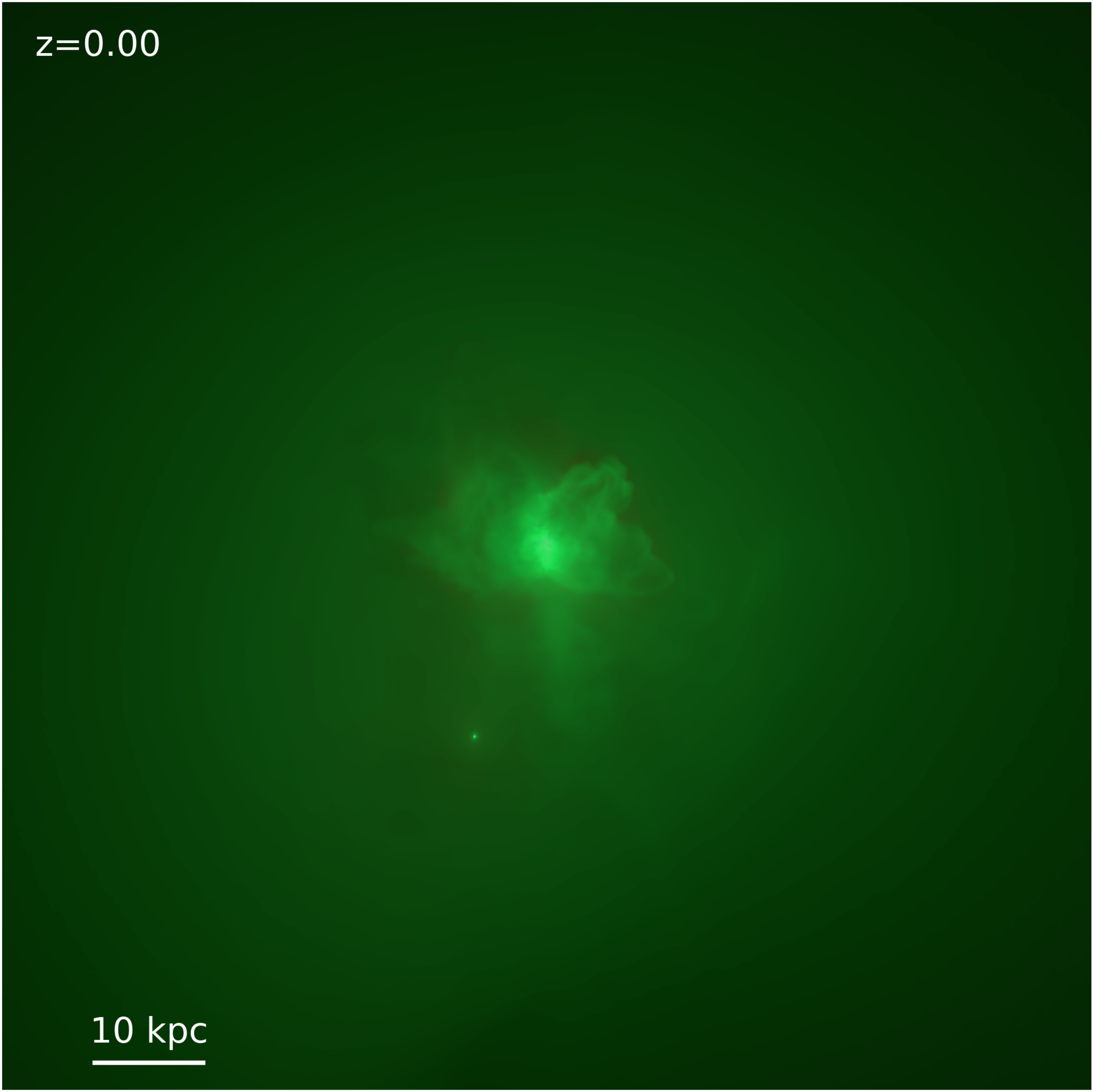
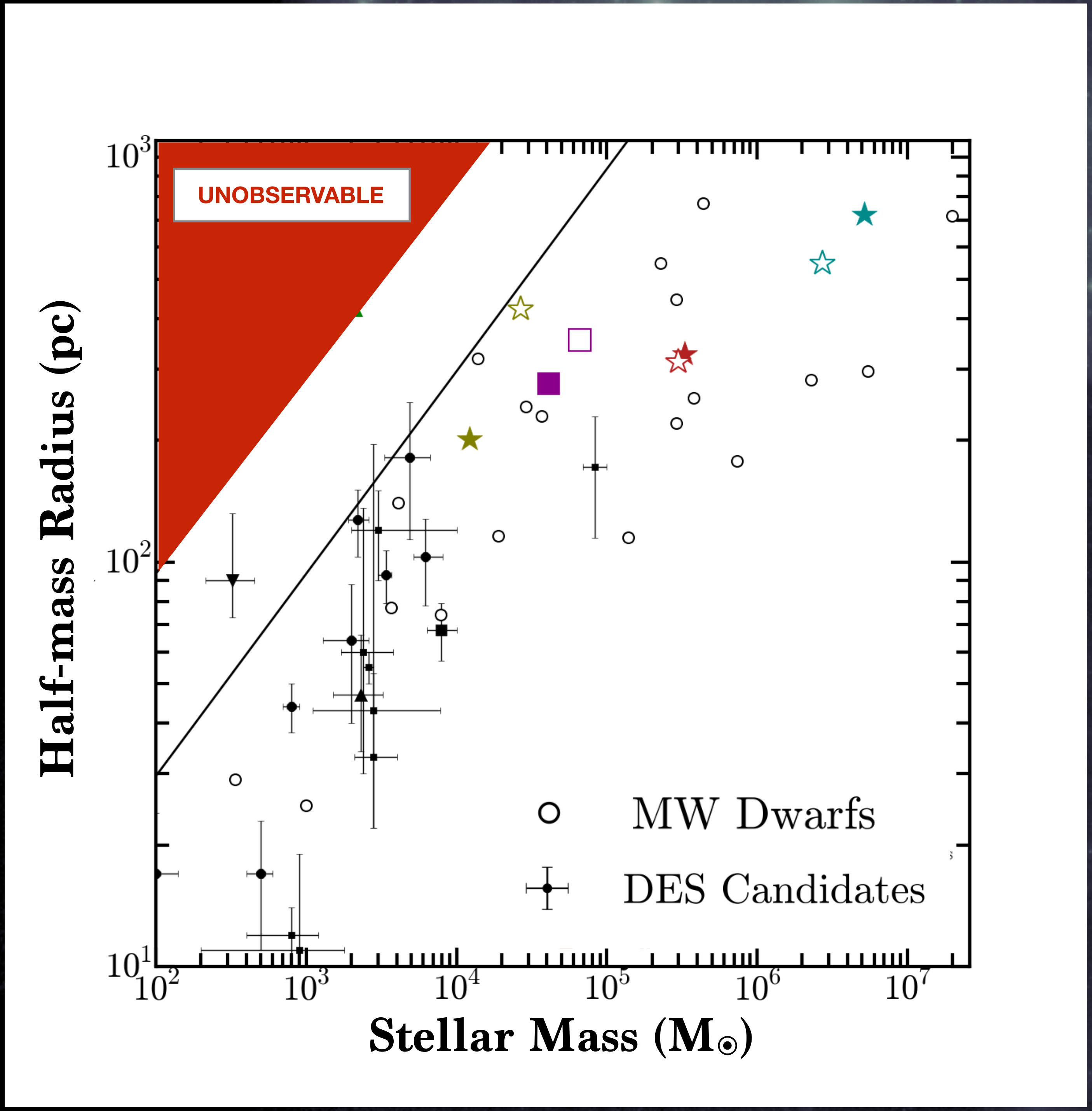


credit: Garrison-Kimmel

Higher mass dwarfs match observations



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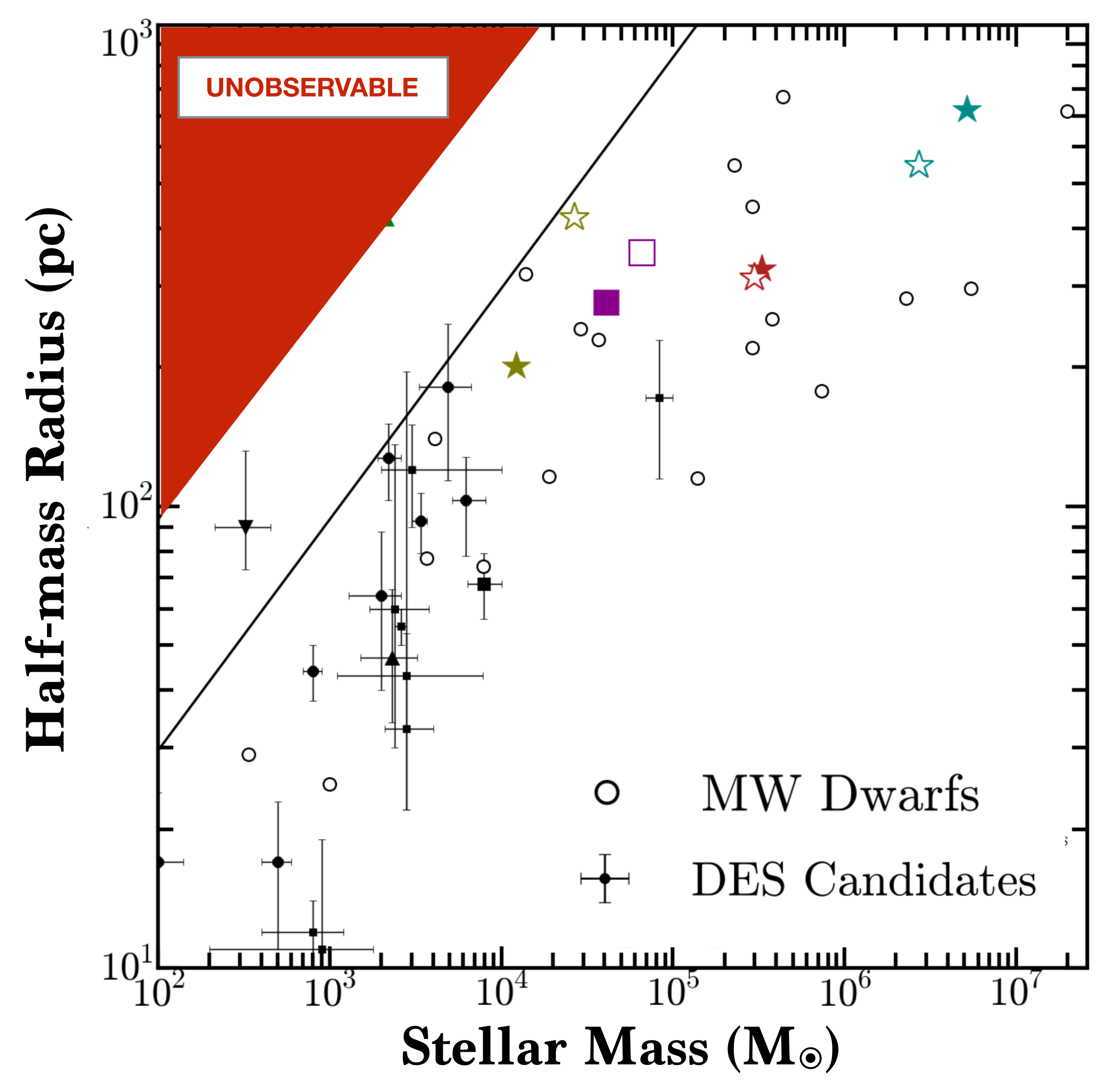

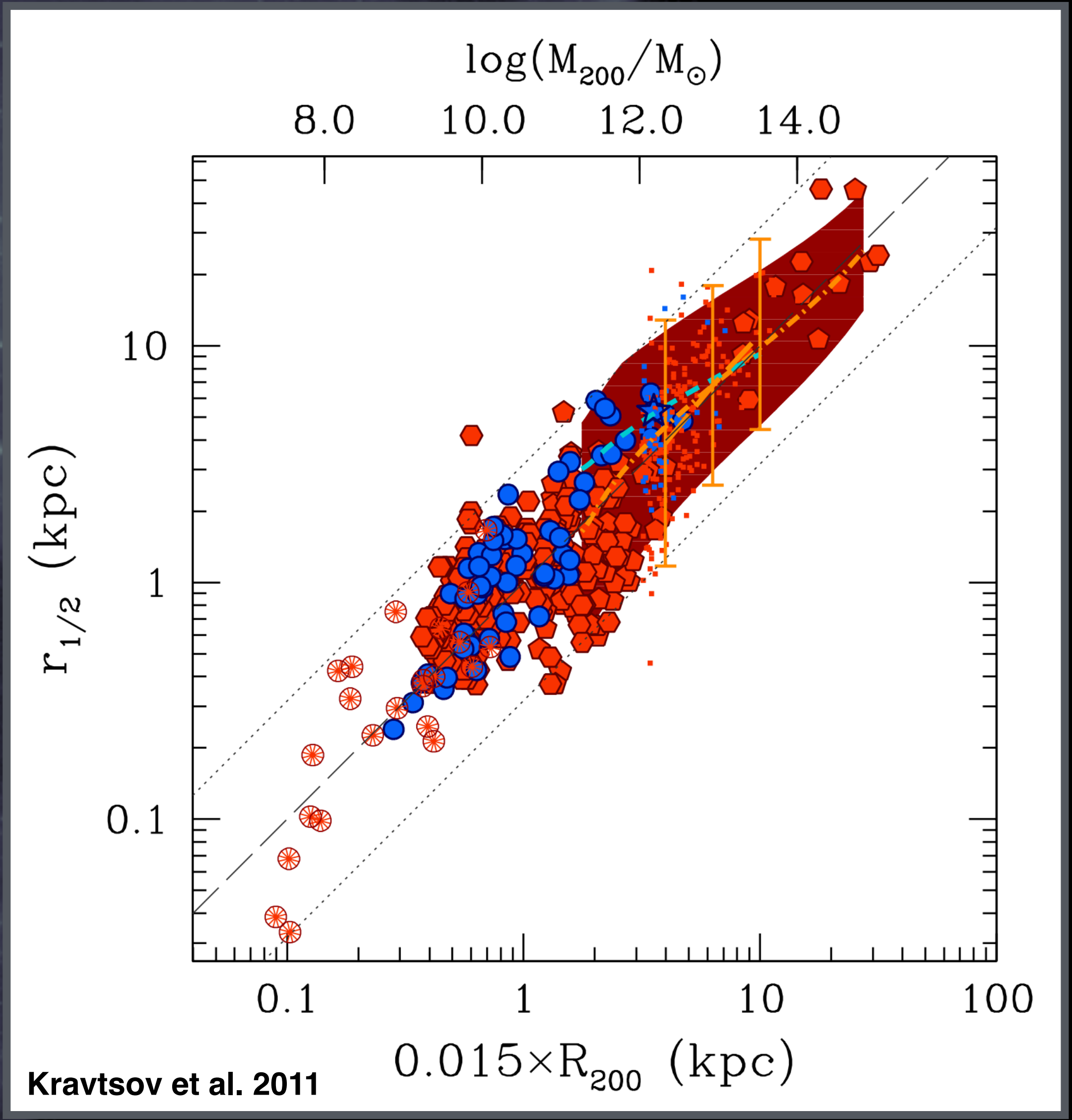

Kravtsov et al. 2011

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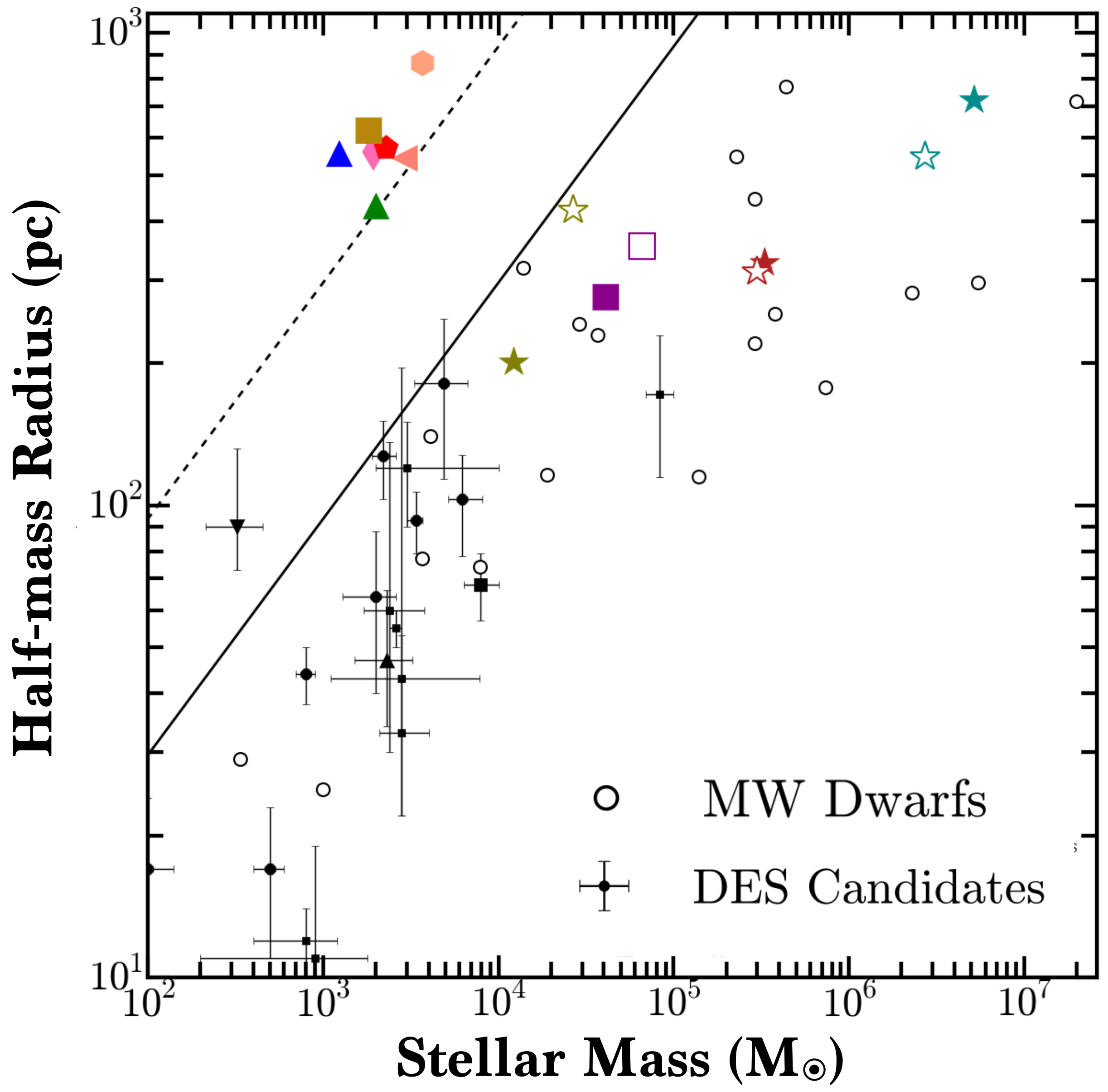
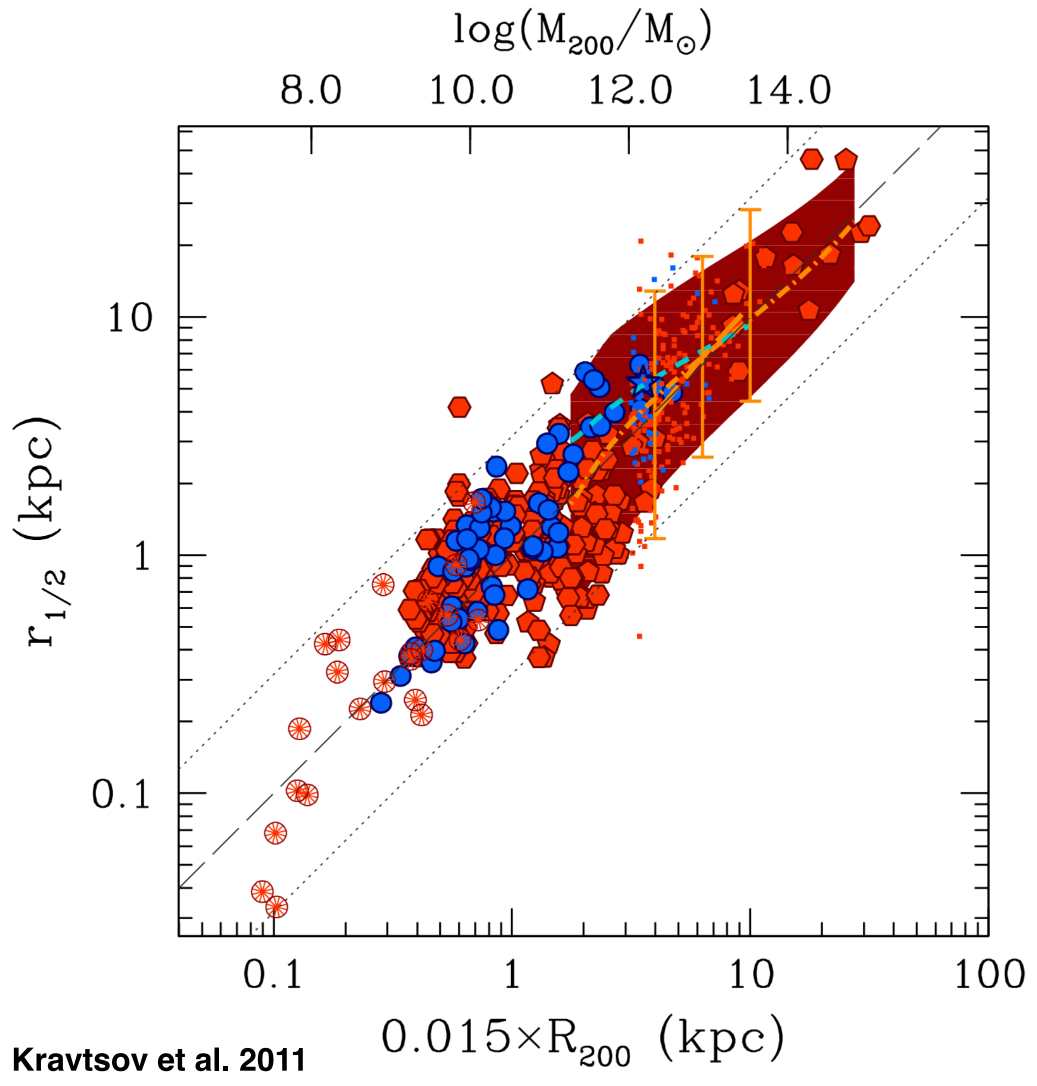
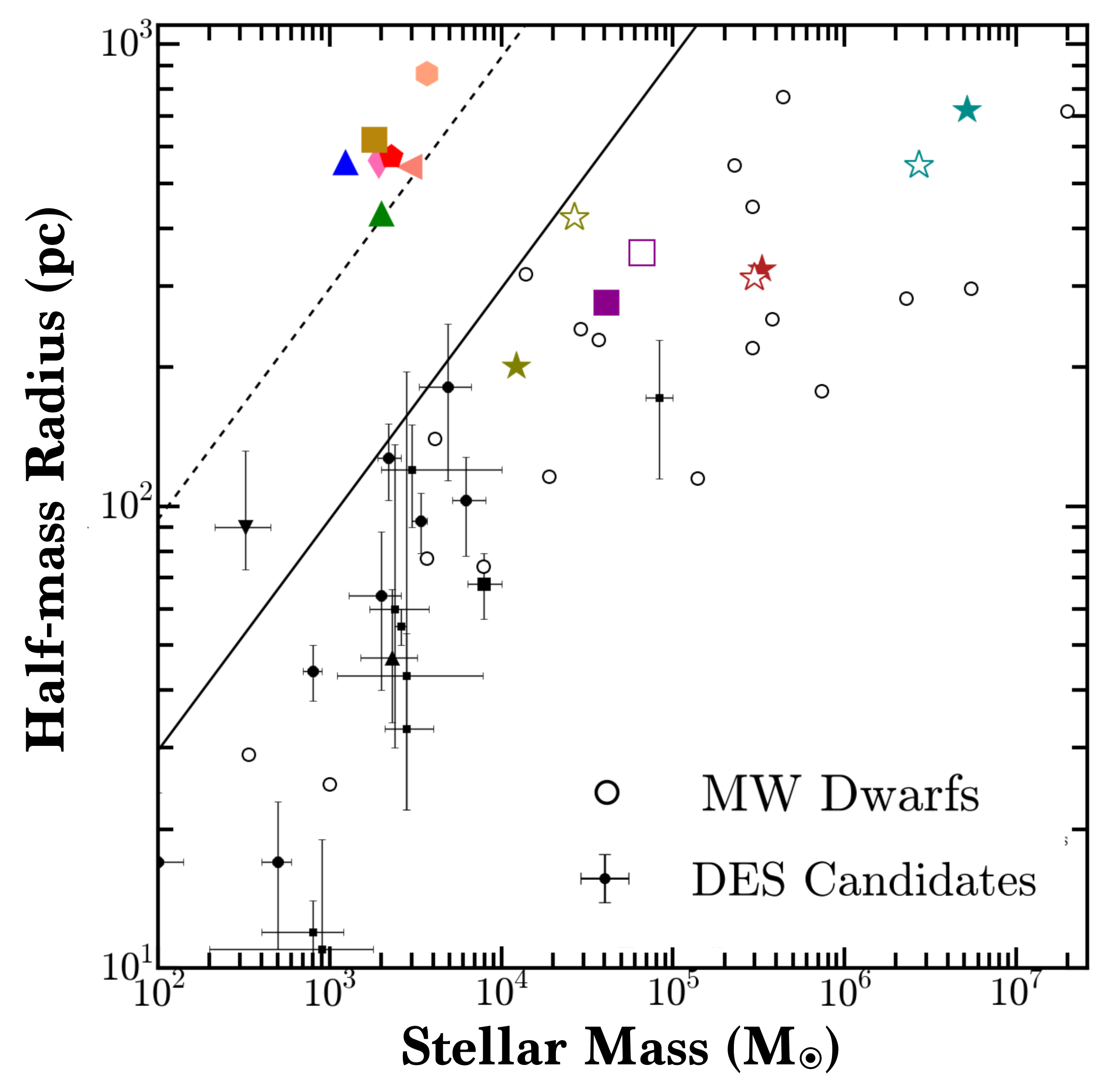




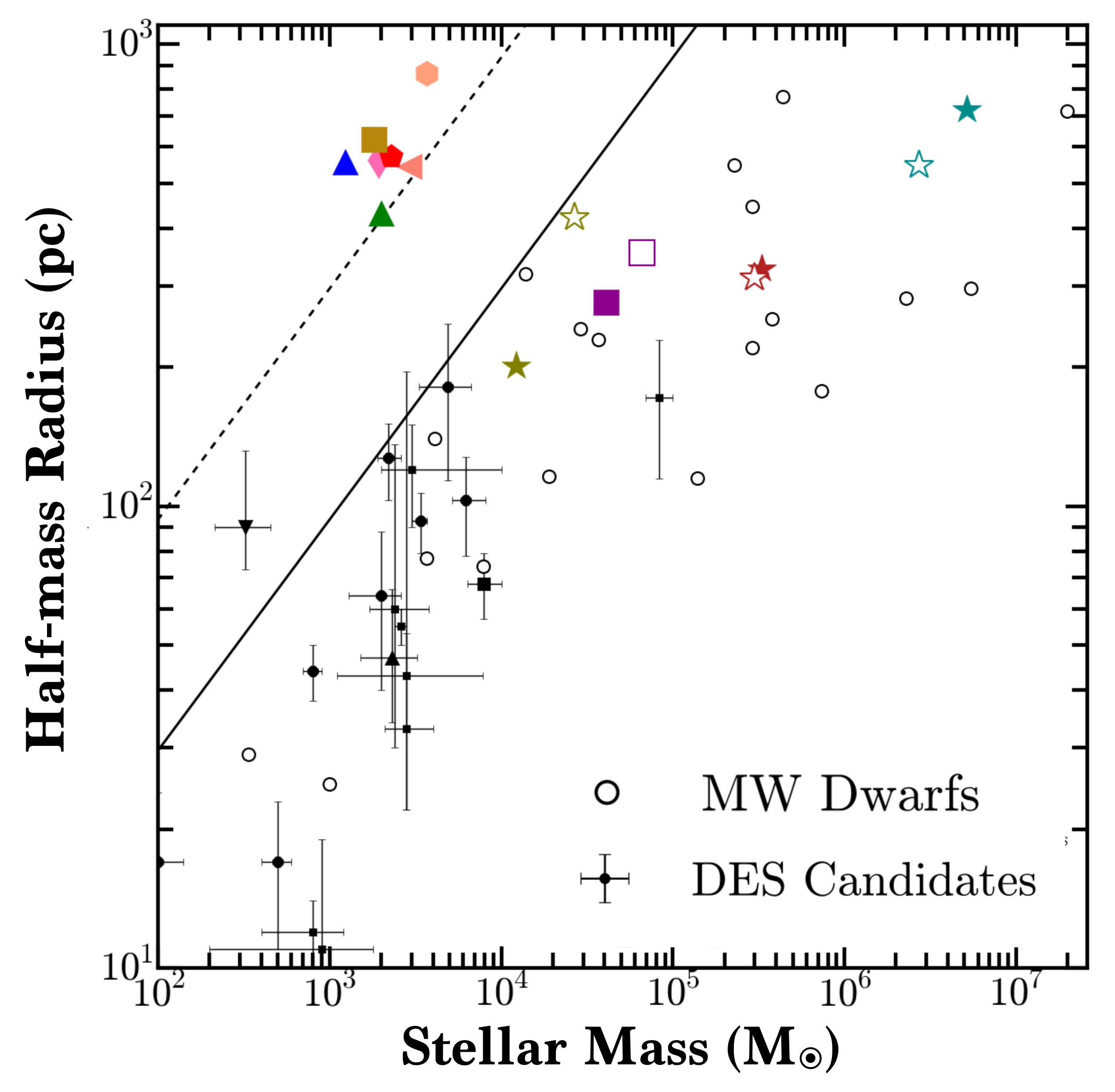
Kravtsov et al. 2011

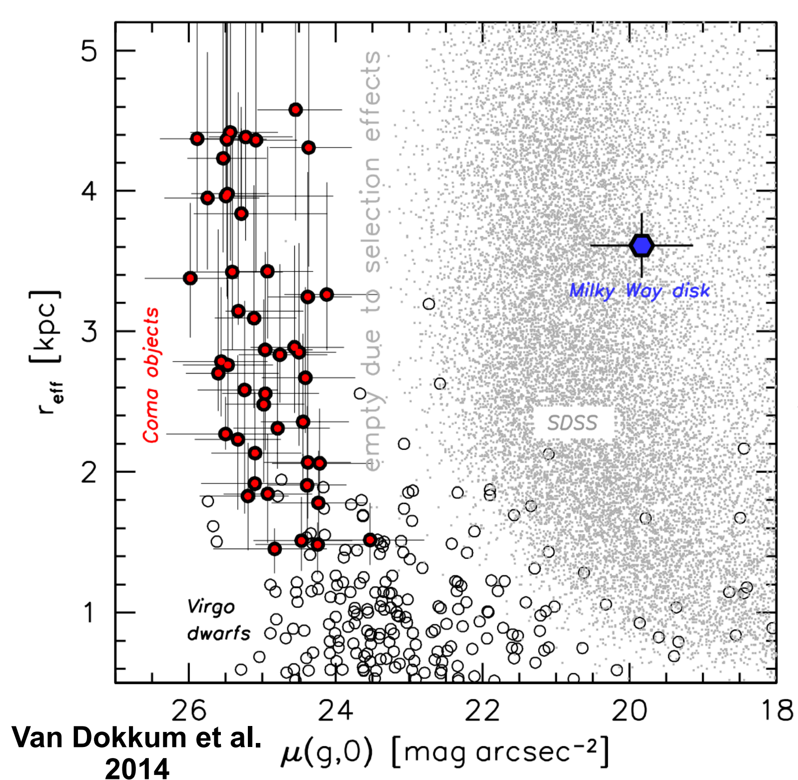
Higher mass dwarfs match observations

Testable prediction: many UFDs have extremely low SB -> Stealth galaxies!



Many new objects at low SB discovered

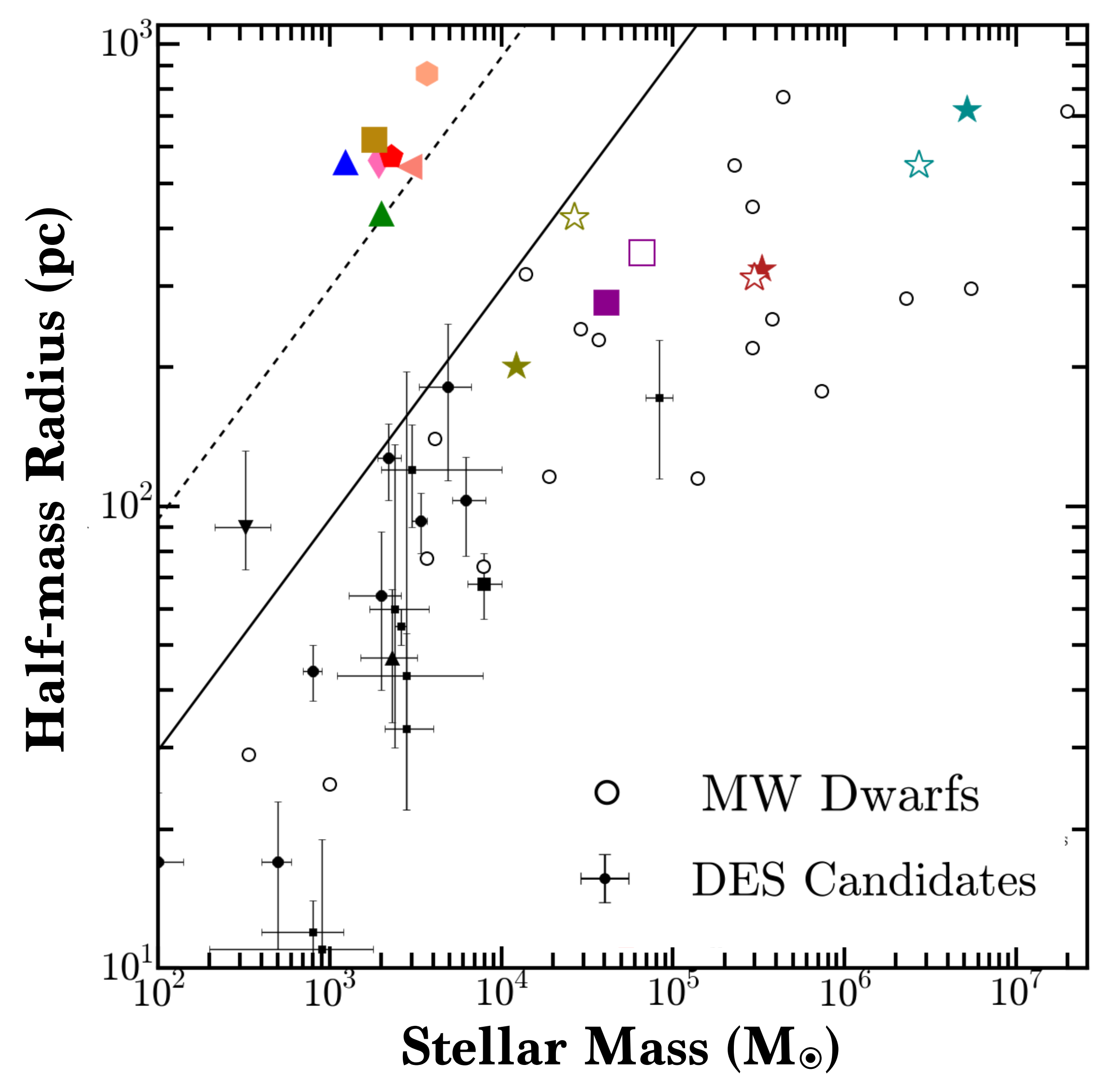


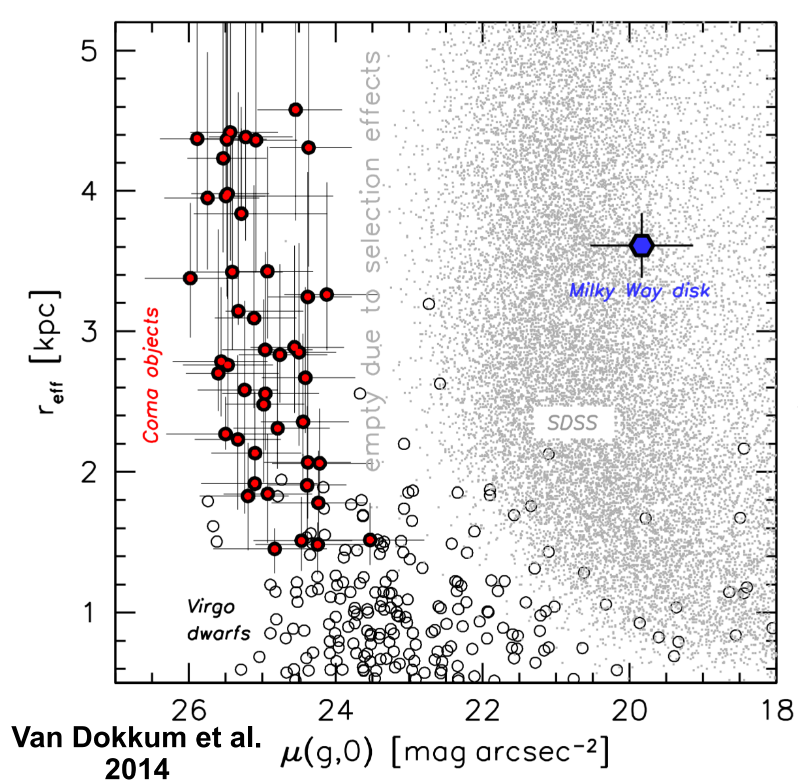


Van Dokkum et al. 2014

Many new objects at low SB discovered

★ Antlia 2





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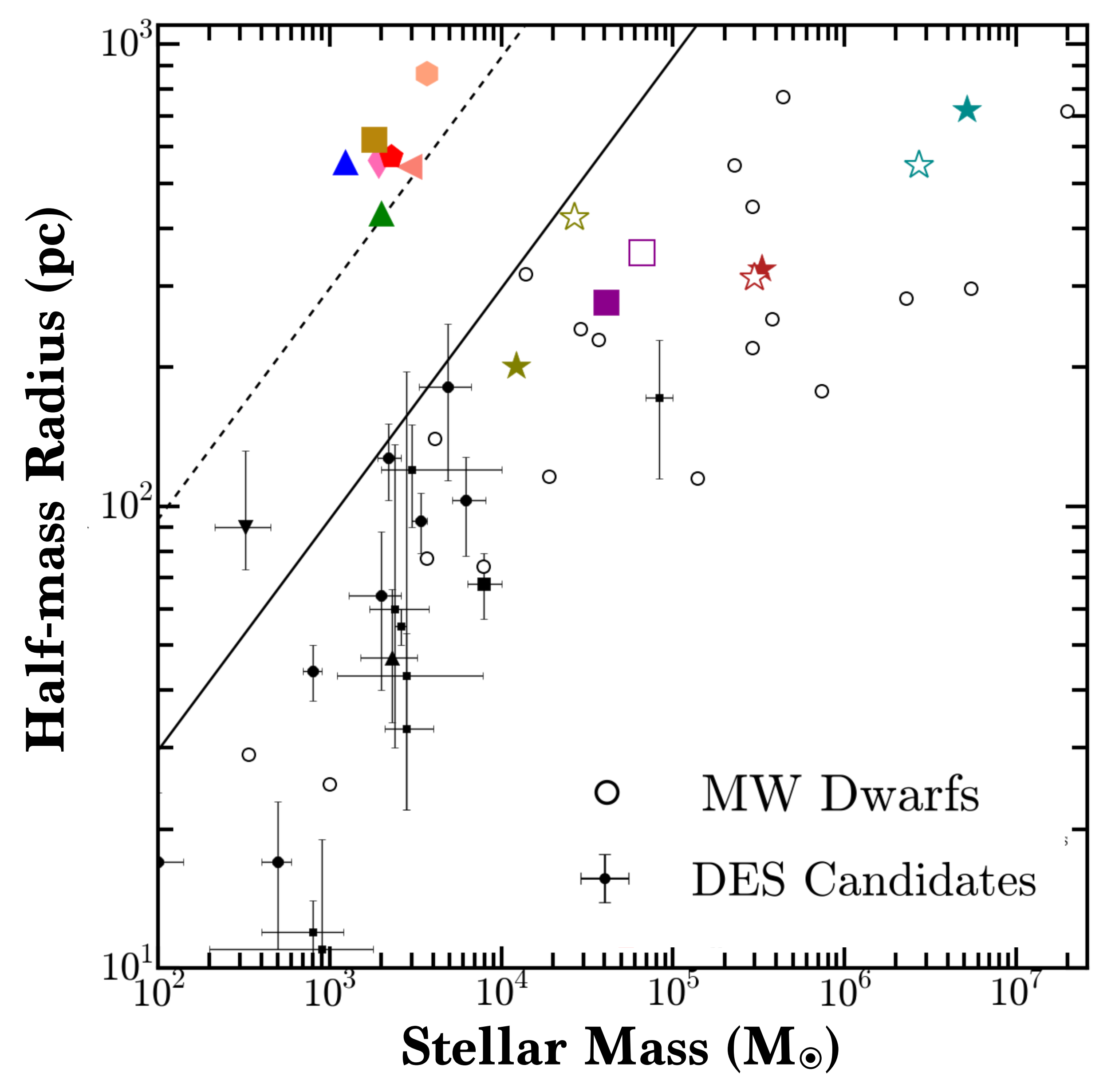

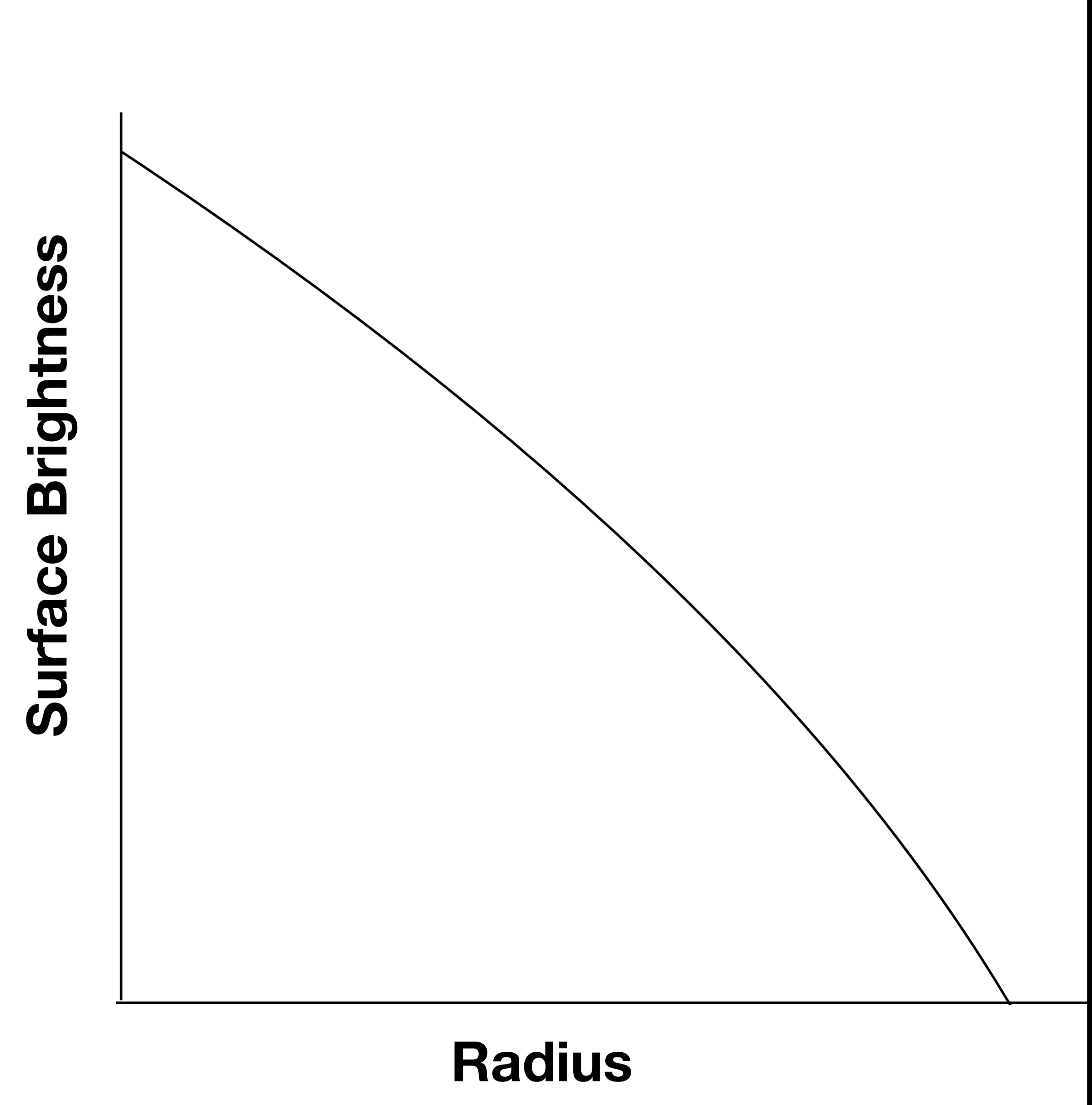

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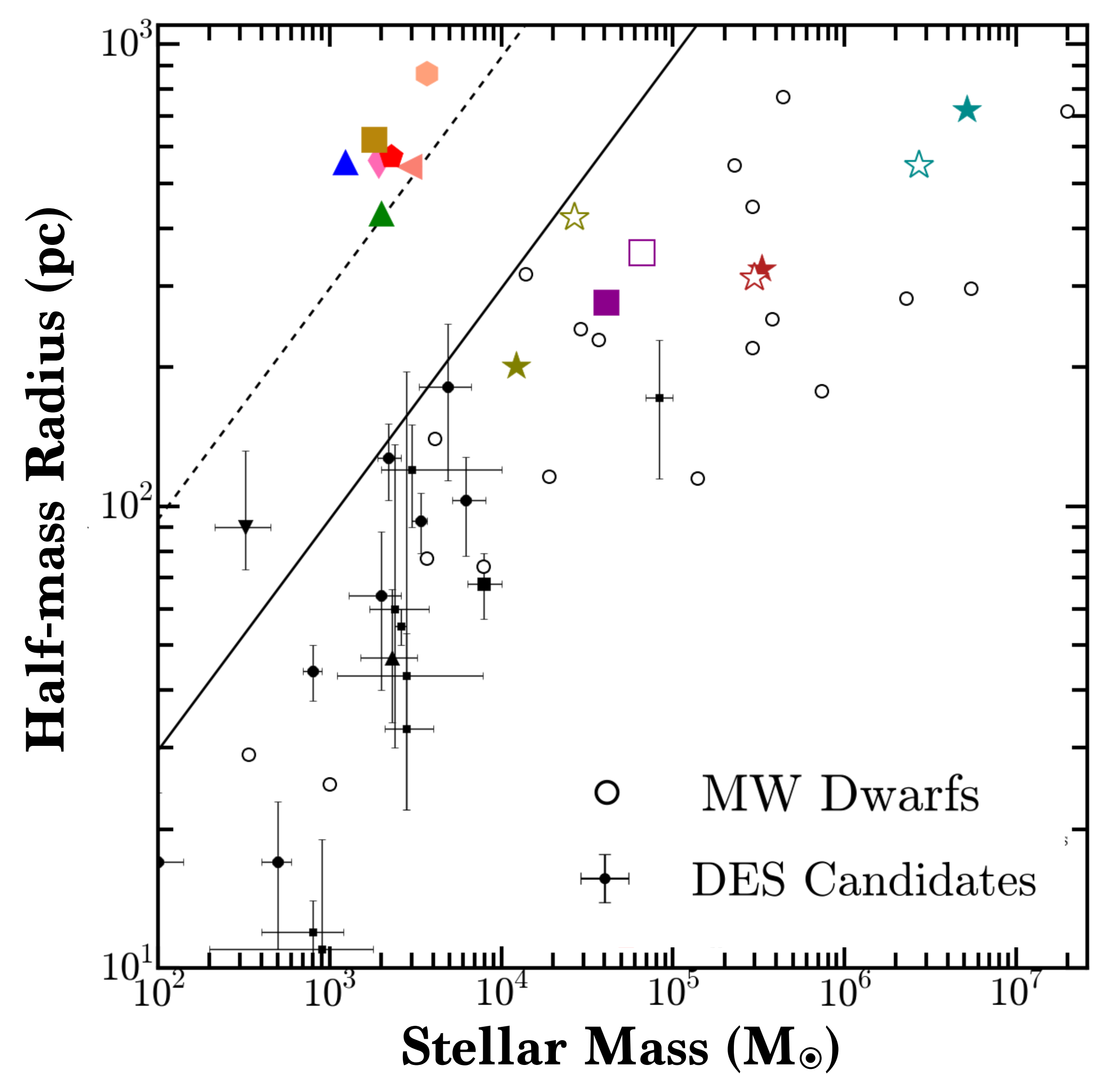

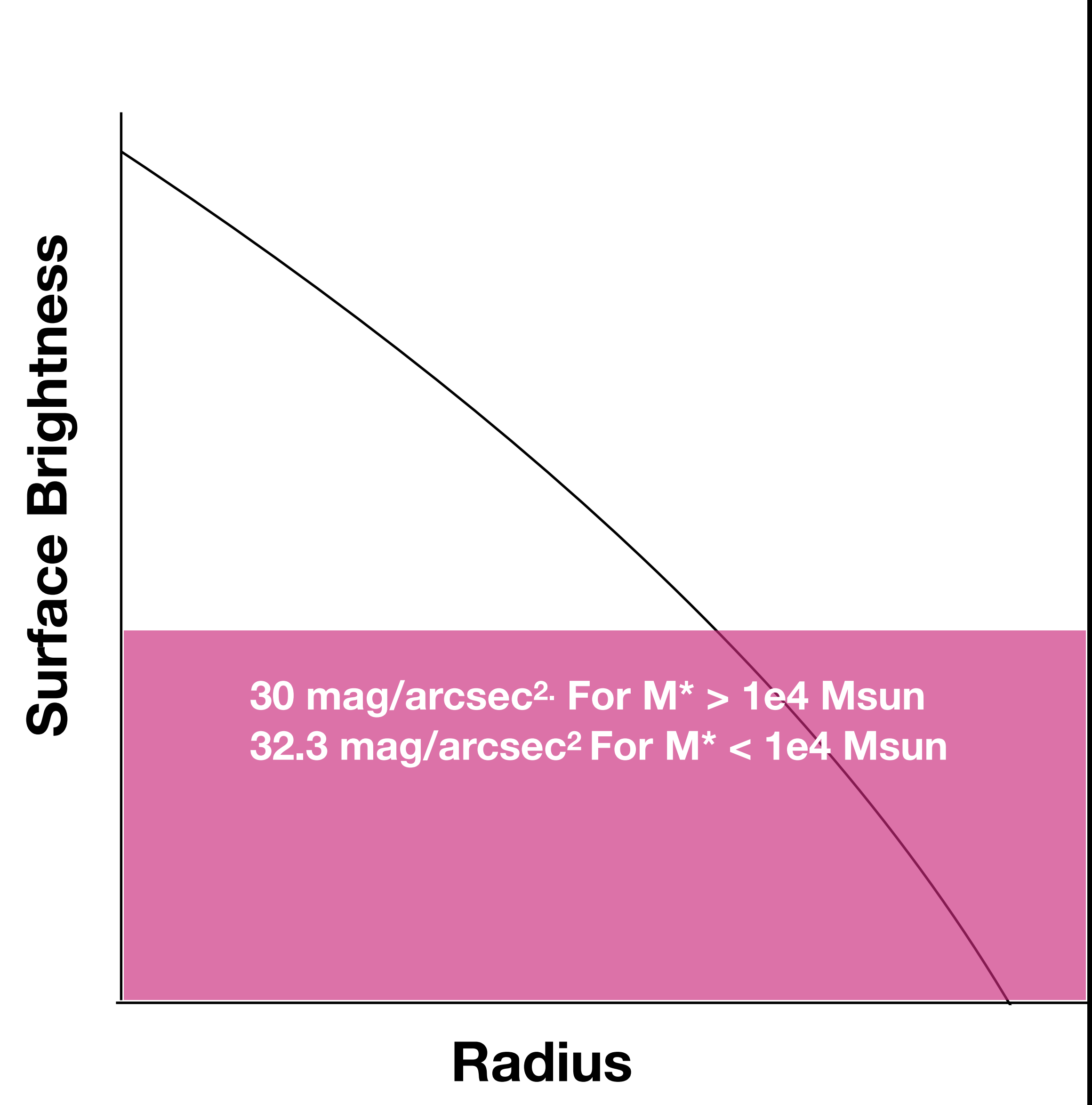

30 mag/arcsec^2. For M* > 1e4 Msun
32.3 mag/arcsec^2 For M* < 1e4 Msun

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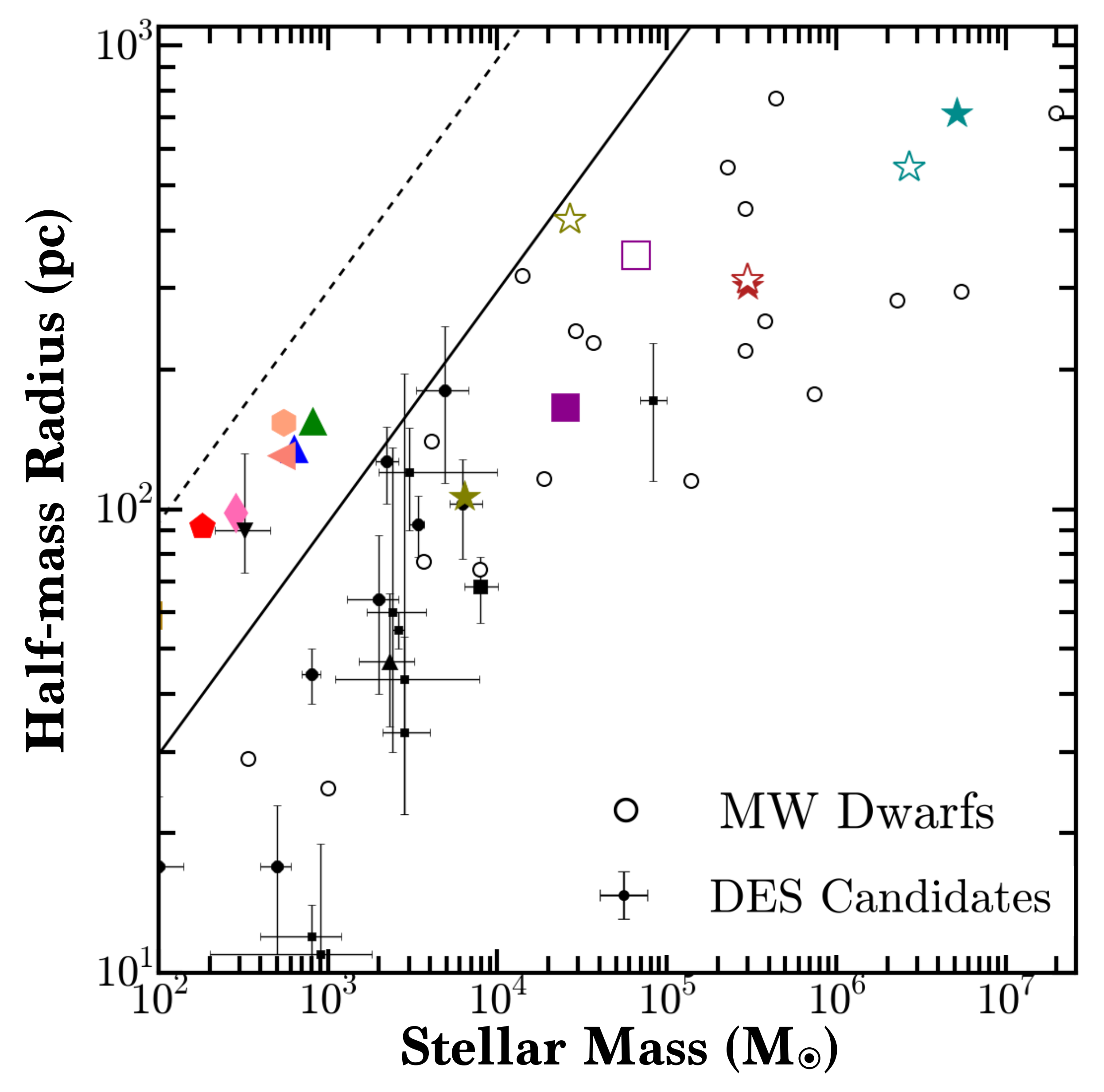
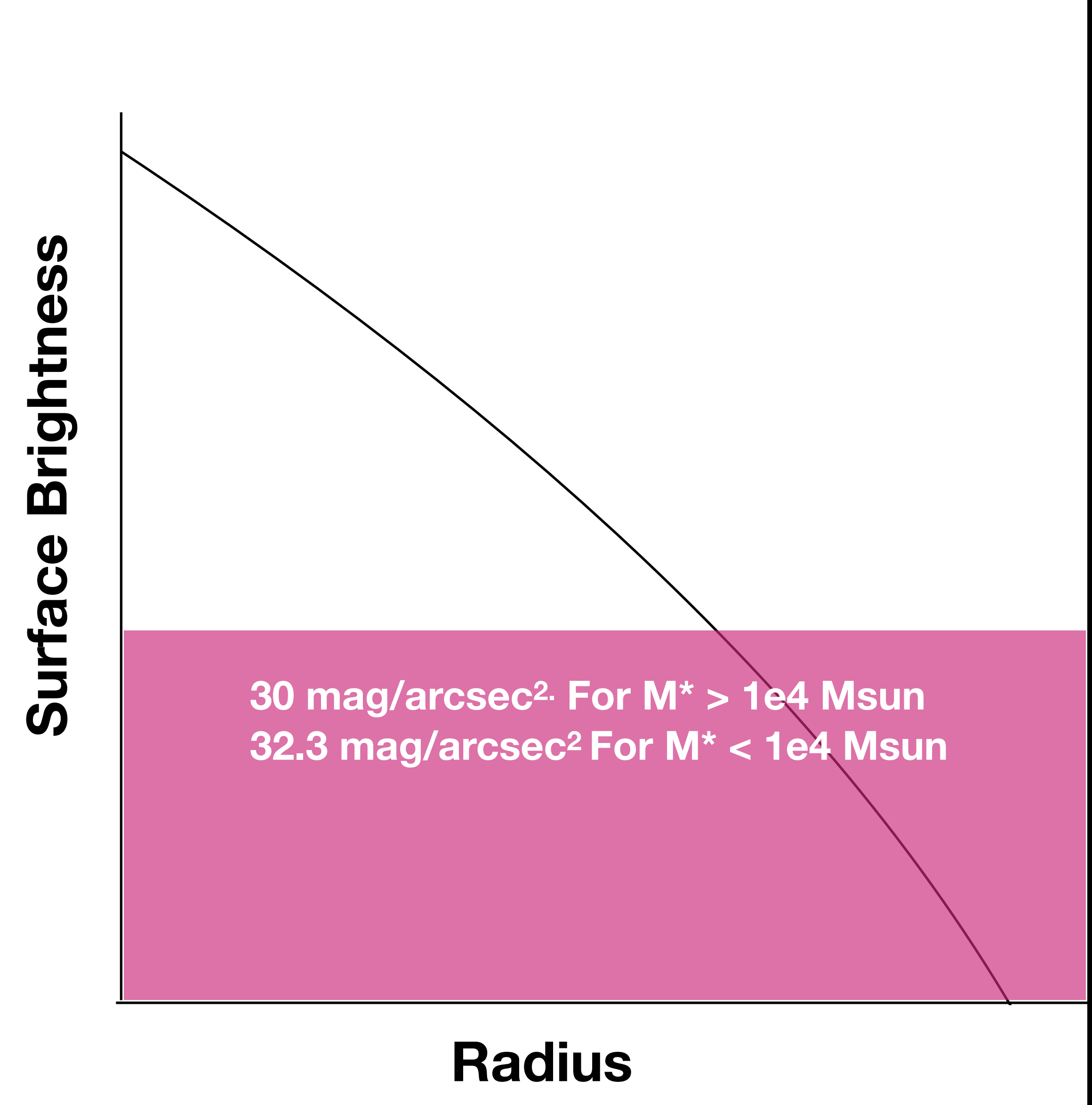
★ Antlia 2

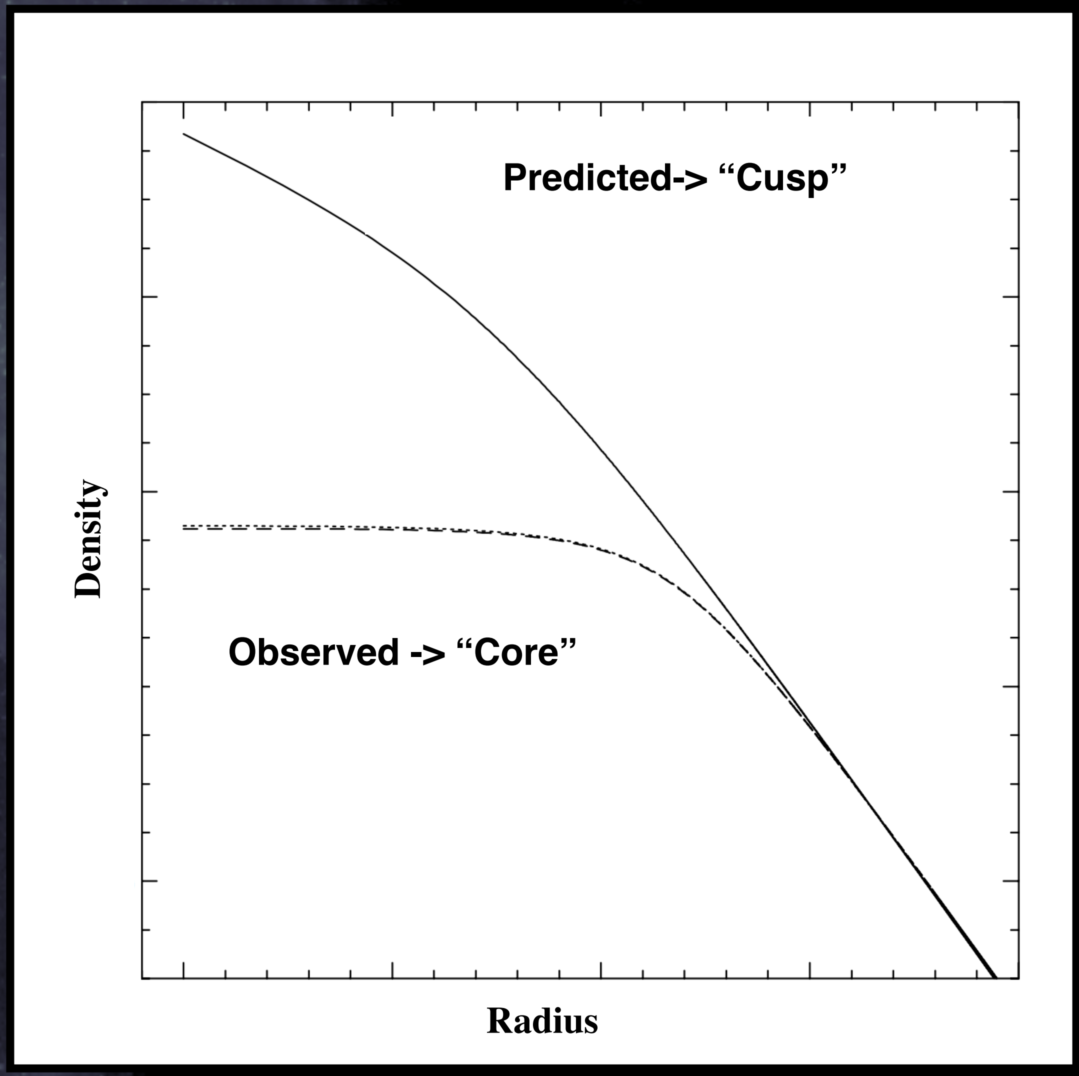




Could some of the DES dwarfs actually be more massive and have undetected stellar halos beyond observational limits?

Dwarf galaxies can teach us about dark matter

CCC: Dark matter-only simulations predict steep central “cusp”, while some dwarf galaxies have instead a flatter “core”



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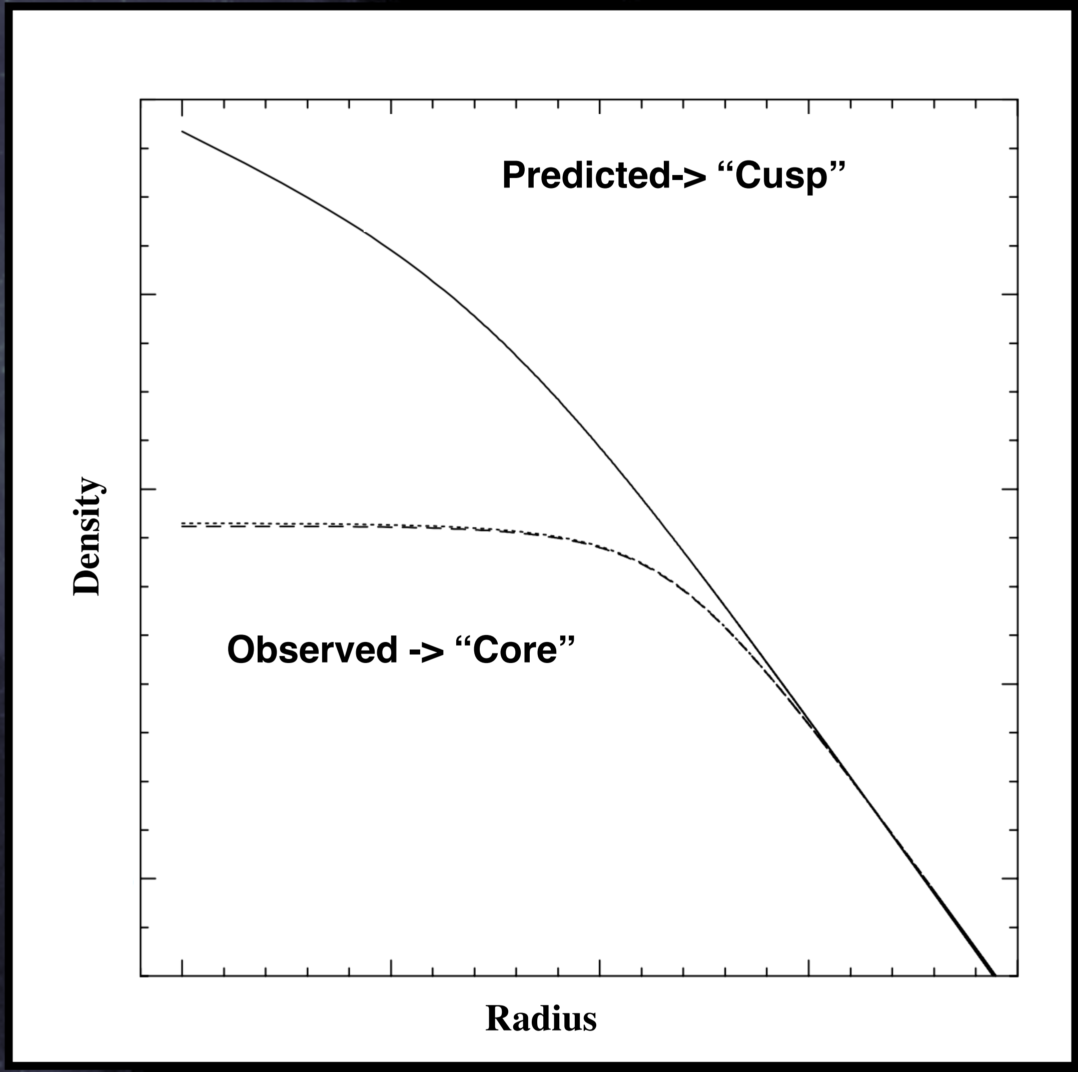

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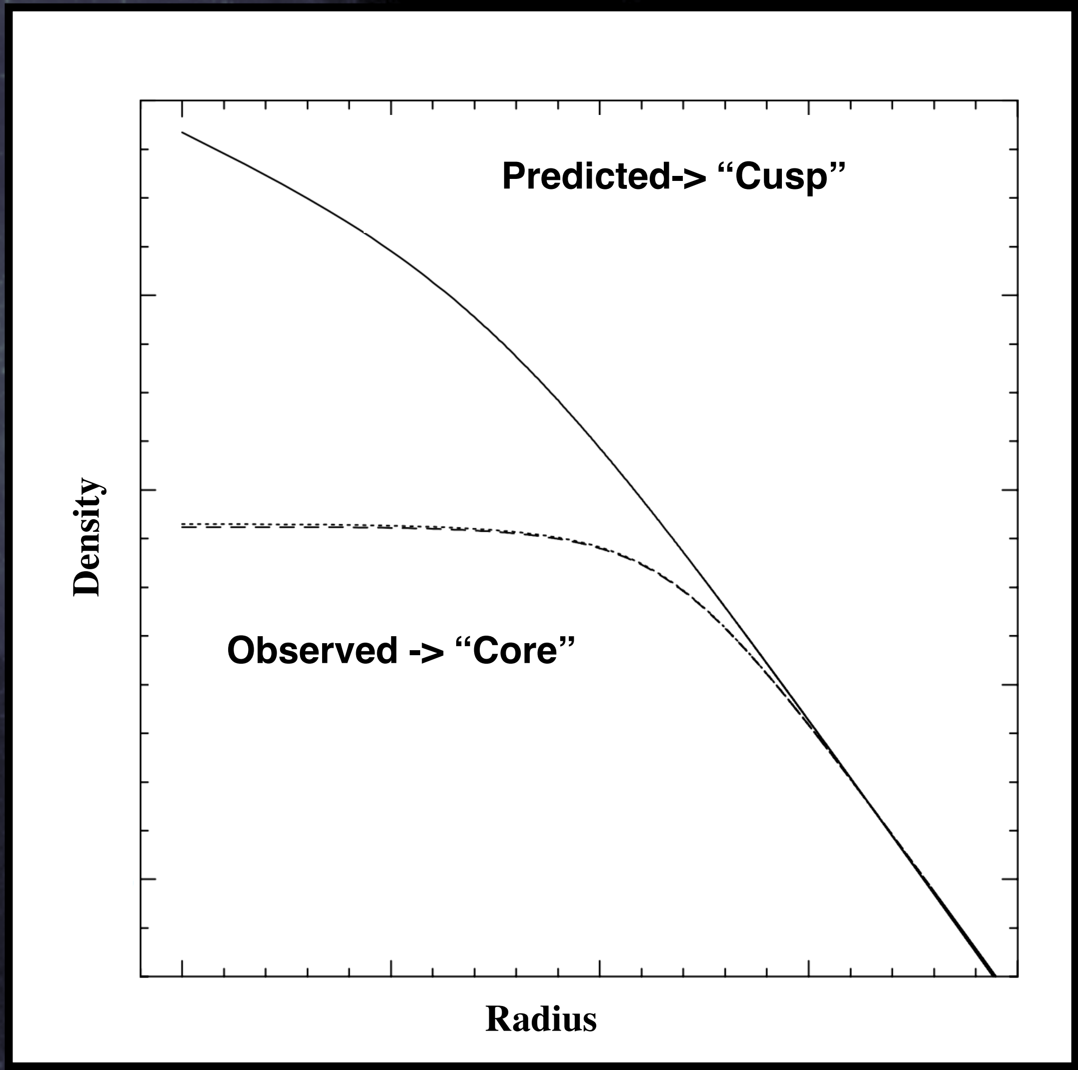
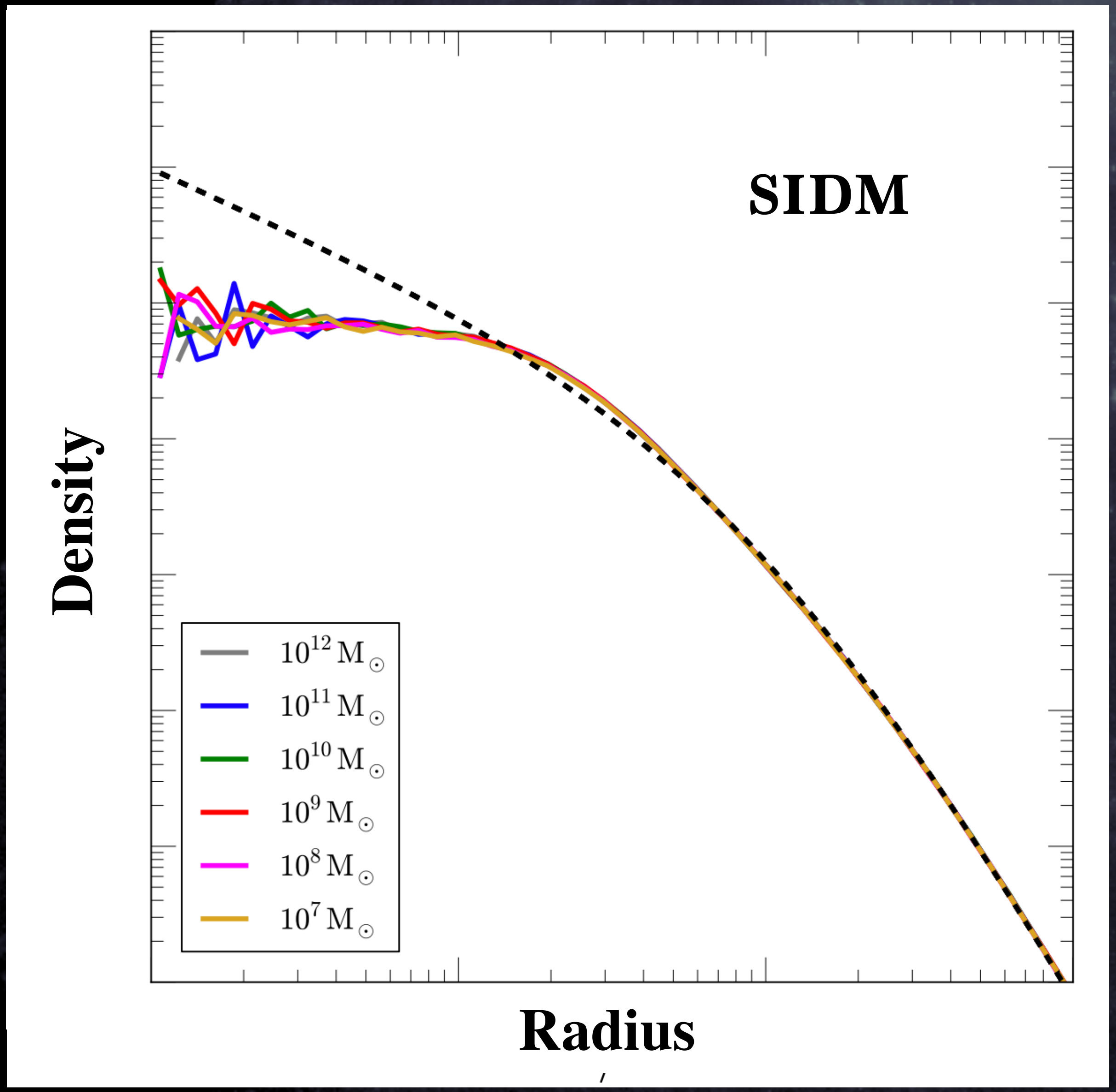
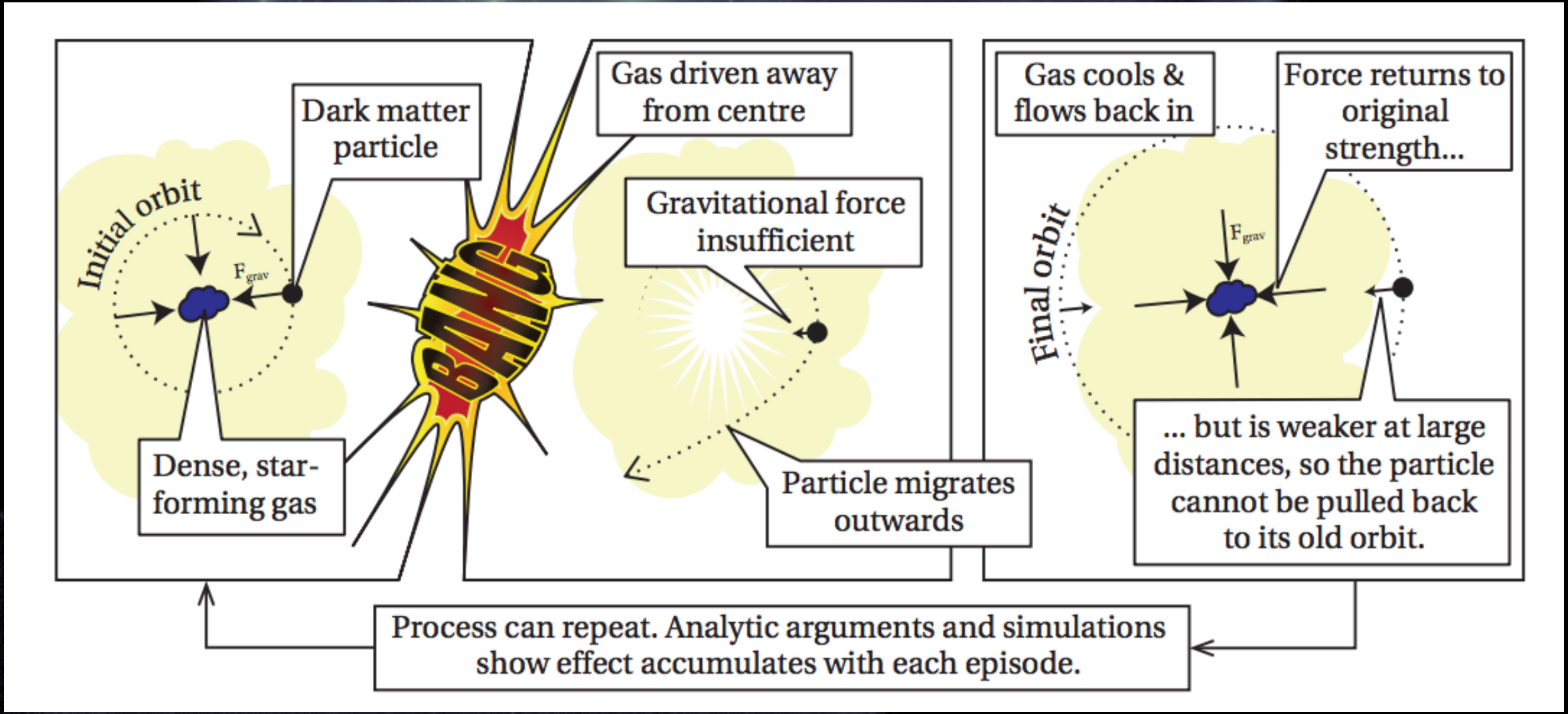




Vogelsberger et al. 2012

Alternative solution: Dark matter particle has some self-interaction cross section

How the galaxy effects dark matter through feedback



Dark matter particle

Initial orbit

Dense, star-forming gas

Gas driven away from centre

Gravitational force insufficient

Particle migrates outwards

Gas cools & flows back in

Final orbit

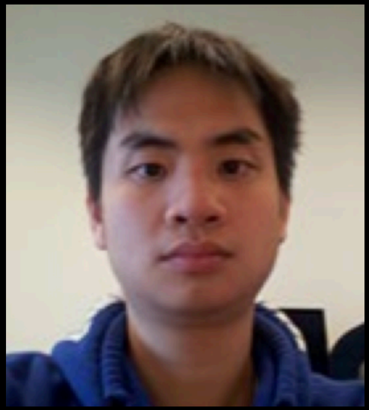
Force returns to original strength...

... but is weaker at large distances, so the particle cannot be pulled back to its old orbit.

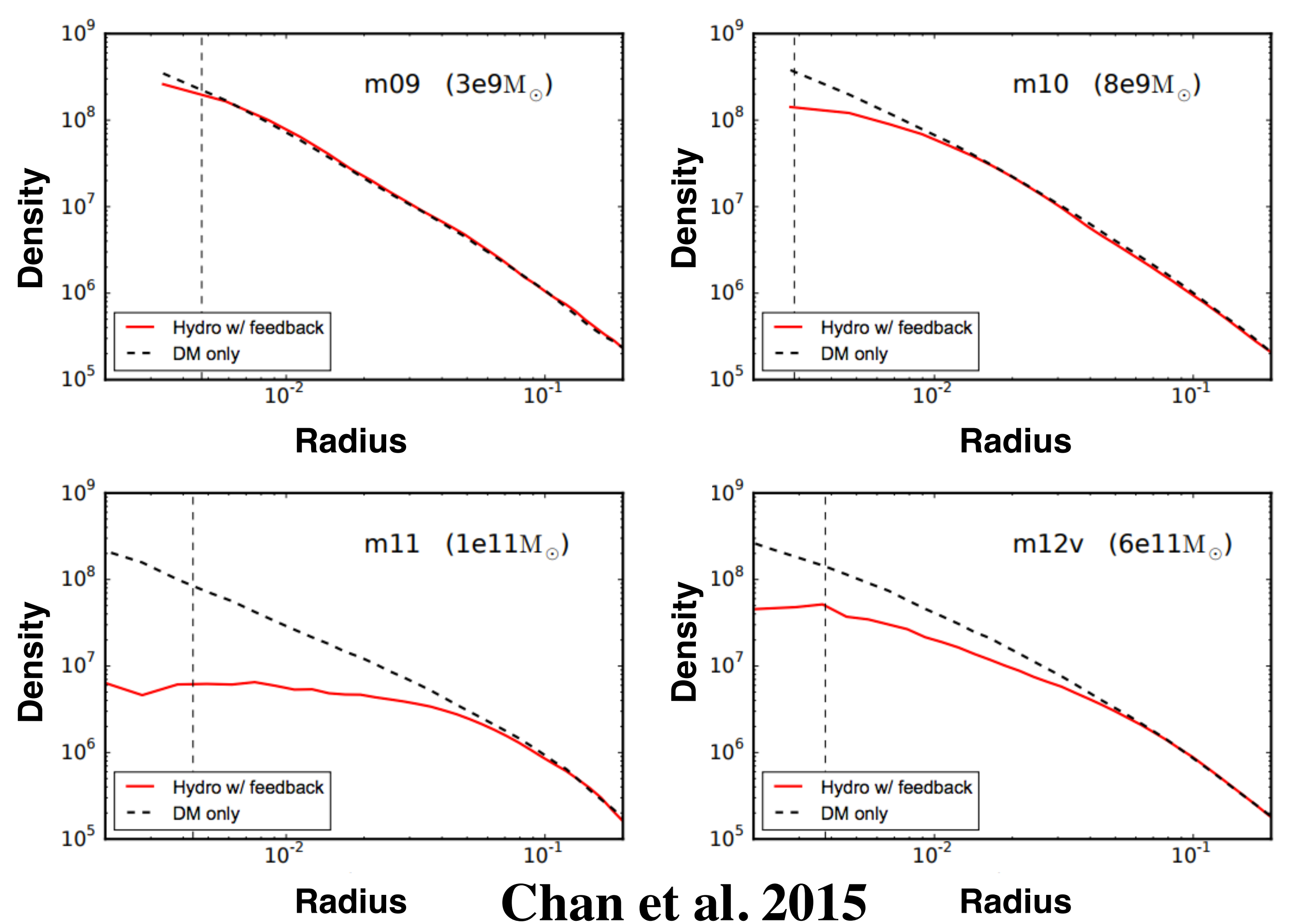
Process can repeat. Analytic arguments and simulations show effect accumulates with each episode.

Pontzen & Governato 2014

$M_{DM} \sim 10^{10}\ M_\odot$ at transition from inefficient to efficient core formation



TK Chan (UCSD)



Chan et al. 2015

No cores predicted in ultra-faint dwarfs

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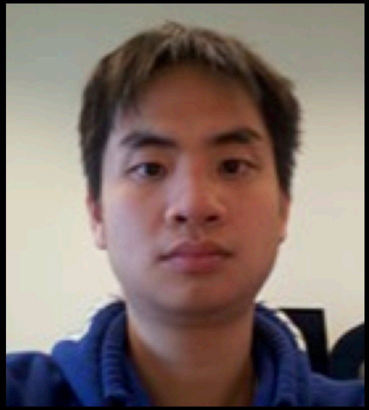

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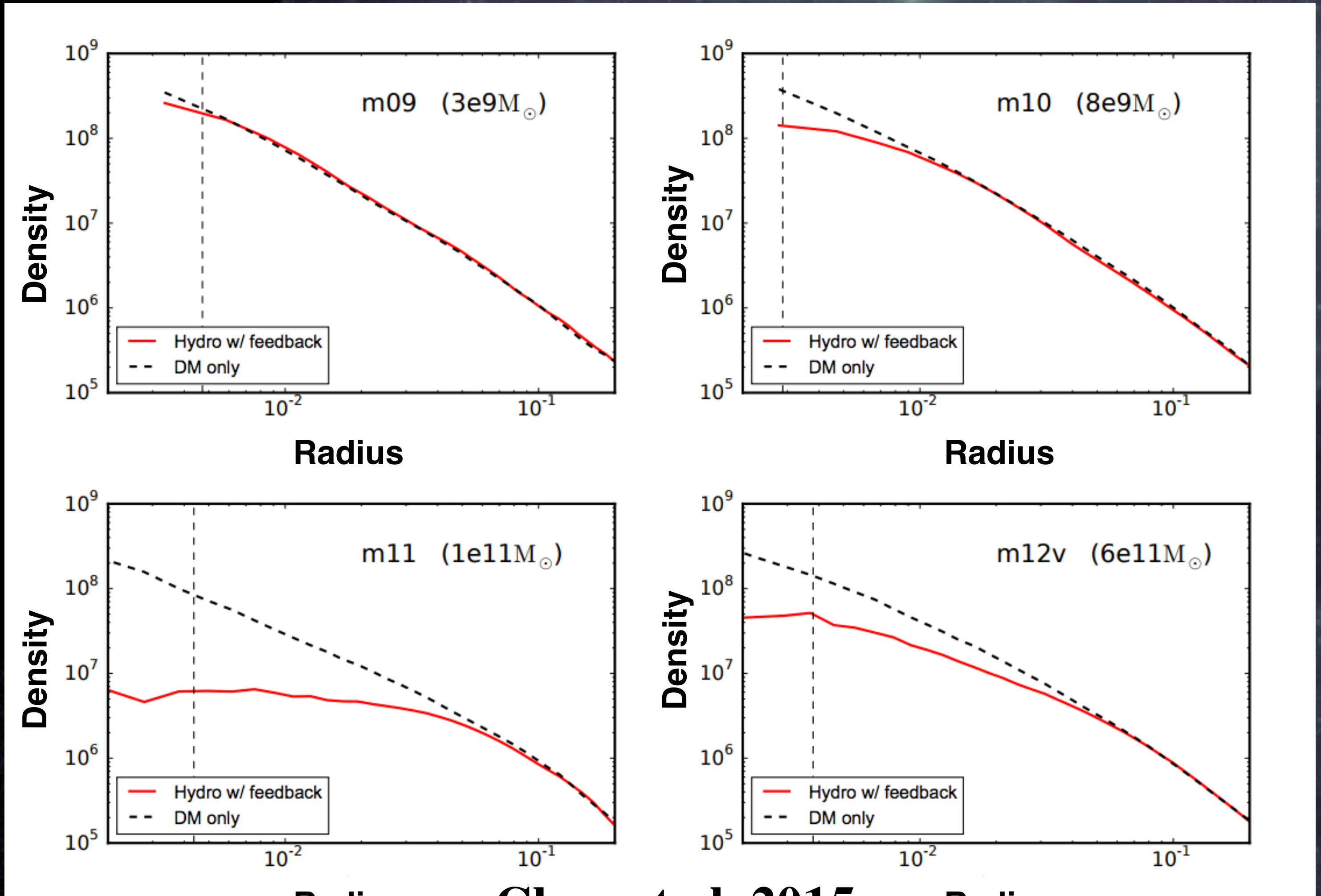

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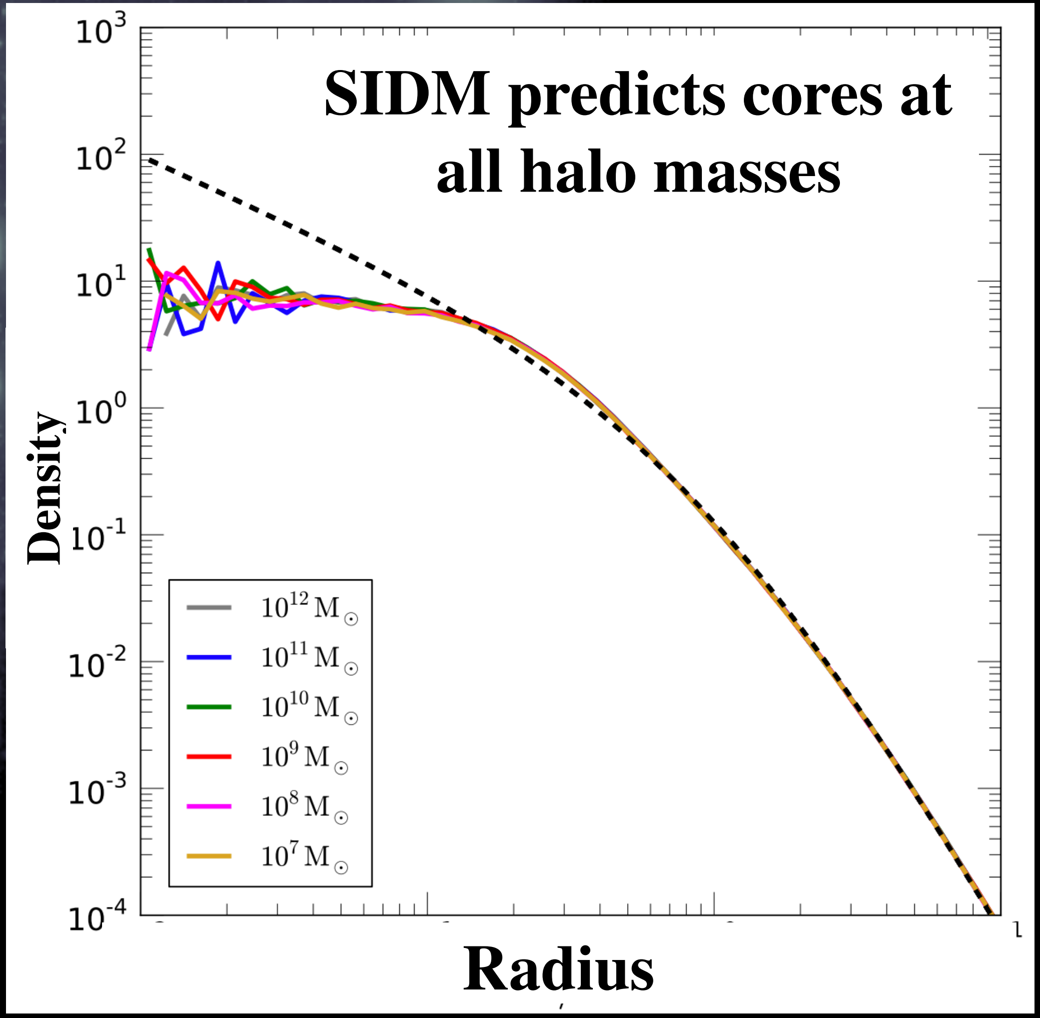


SIDM predicts cores at all halo masses

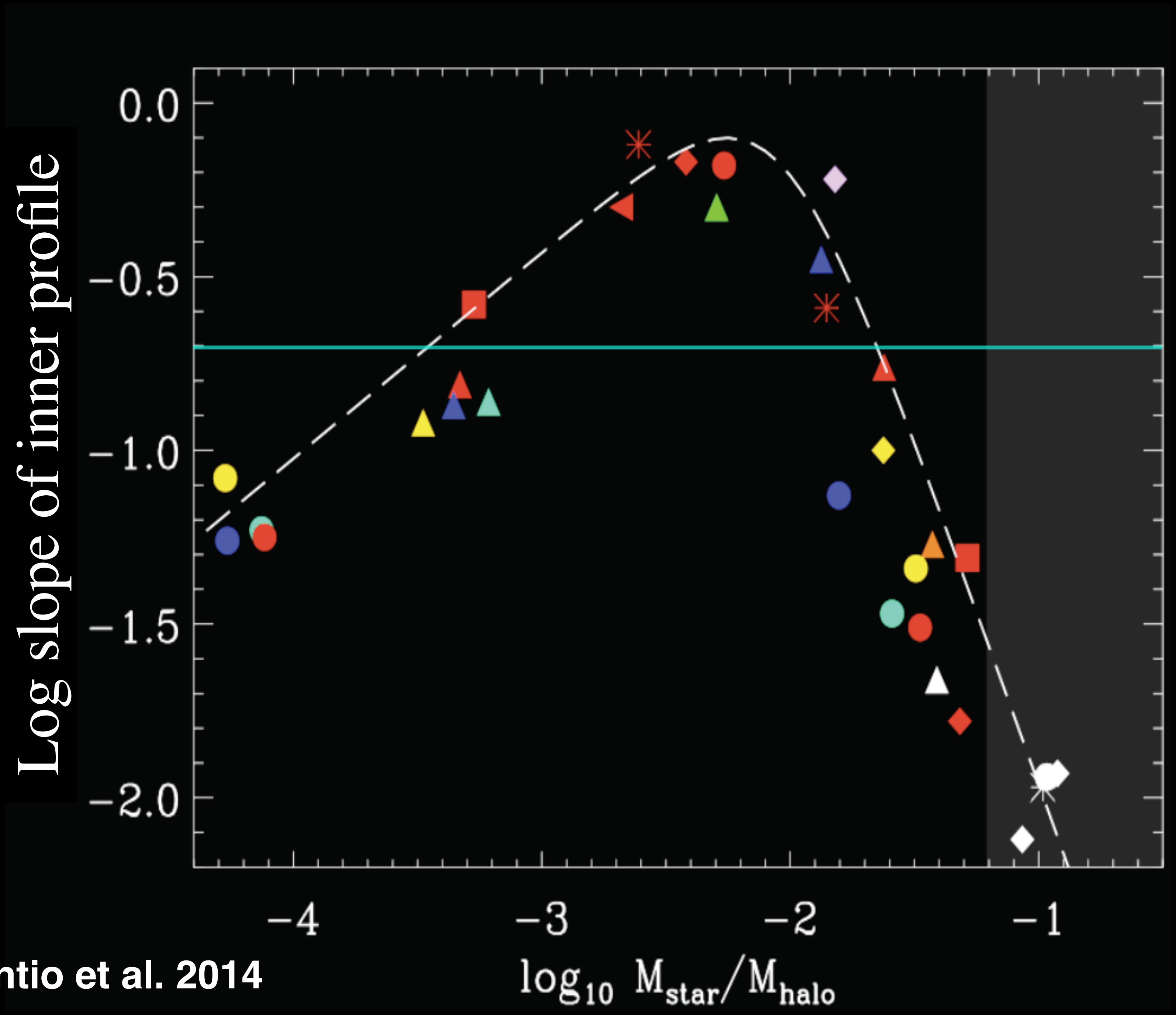
Vogelsberger et al. 2012

No cores predicted in ultra-faint dwarfs

Feedback can create "cores" for range of M^*/M_{halo}

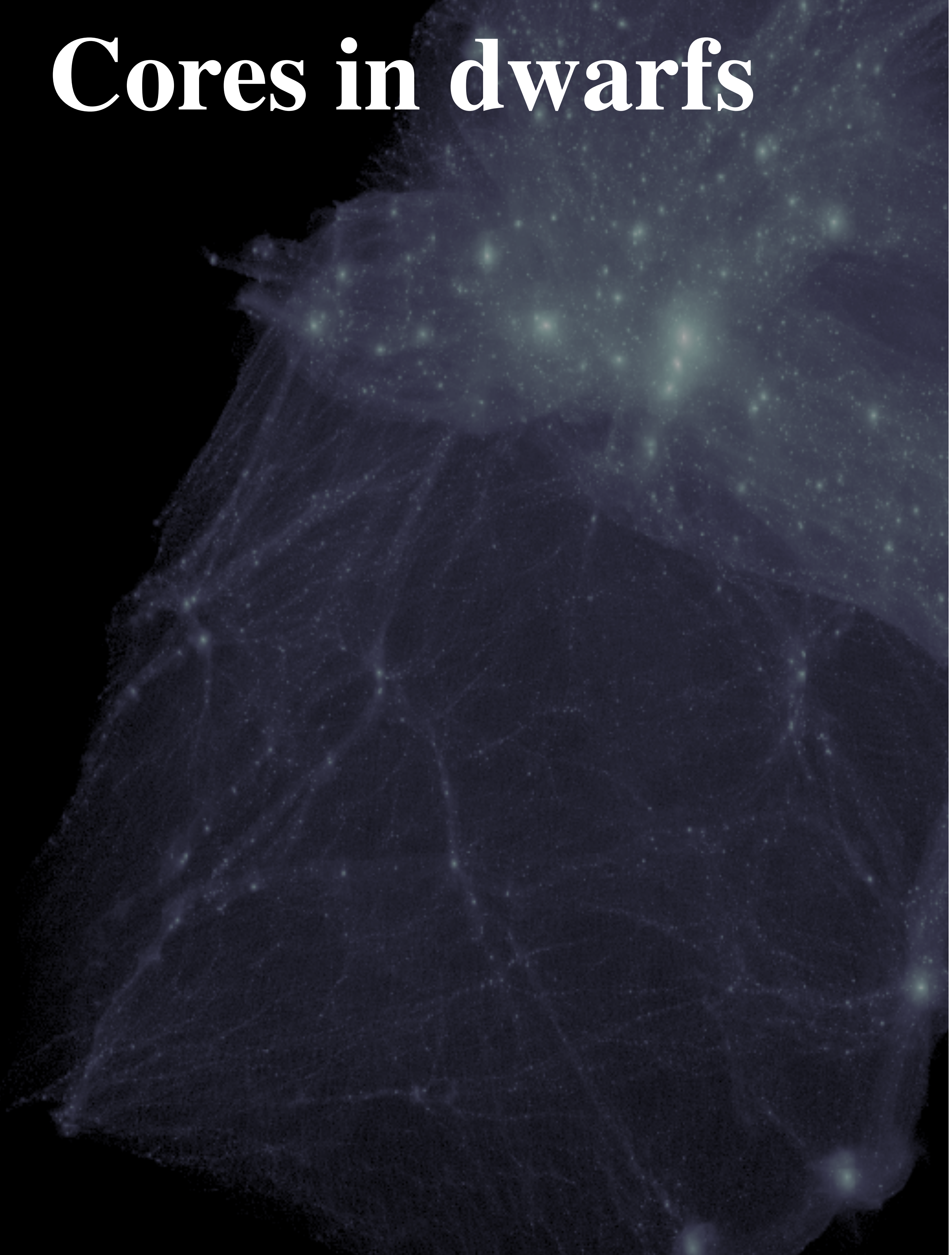
Core

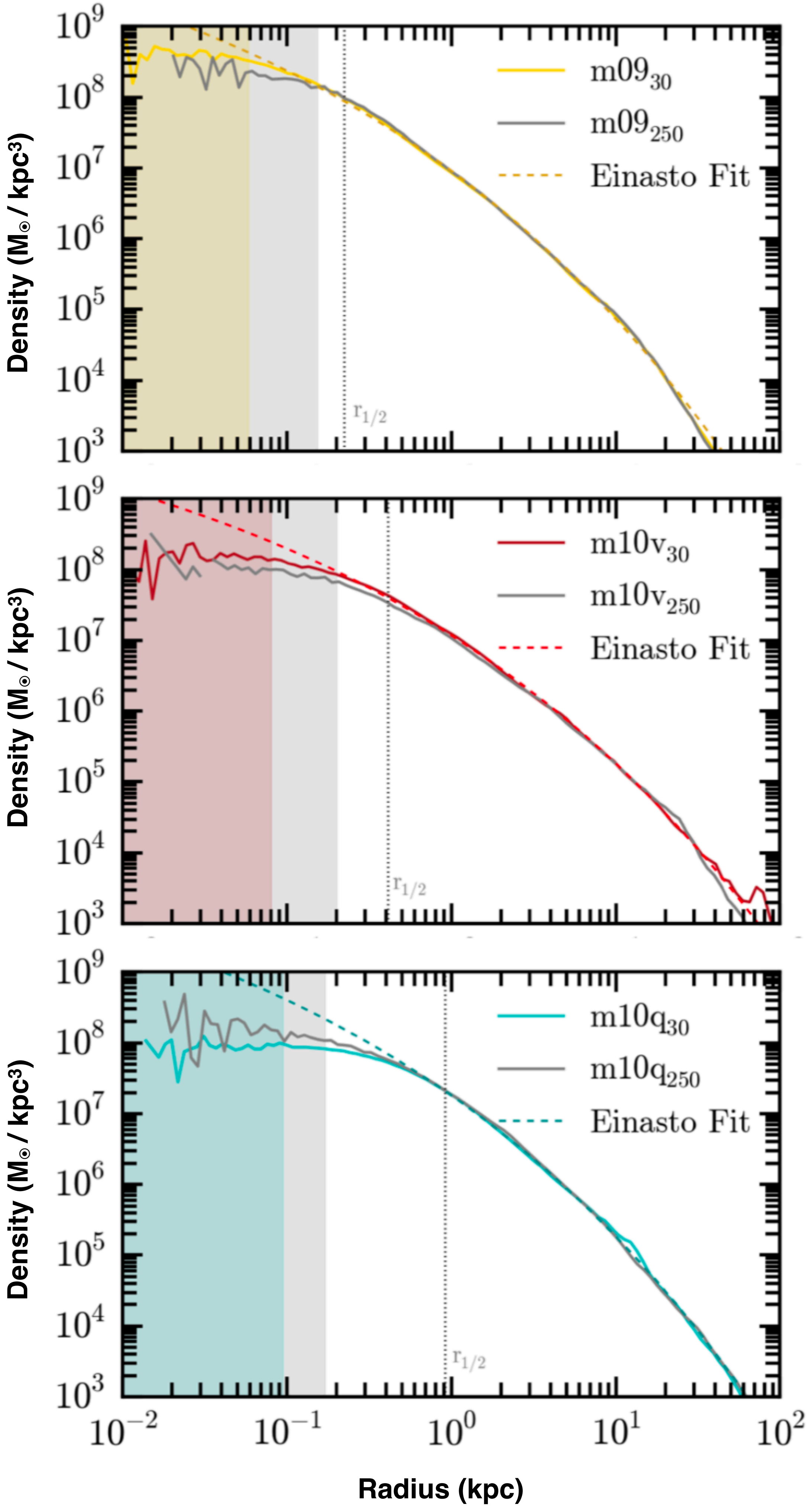
Cusp



DiCintio et al. 2014

Cores in dwarfs





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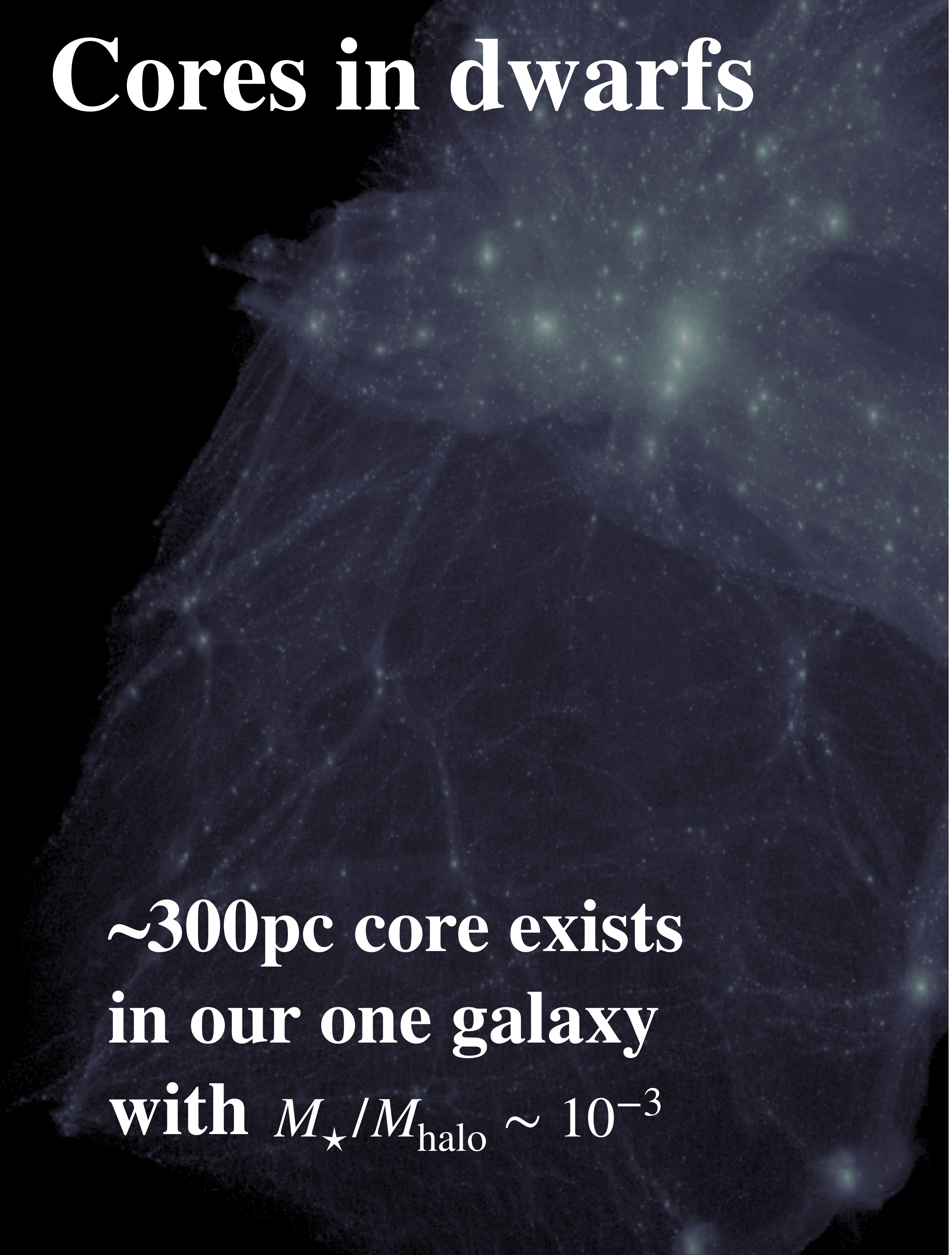
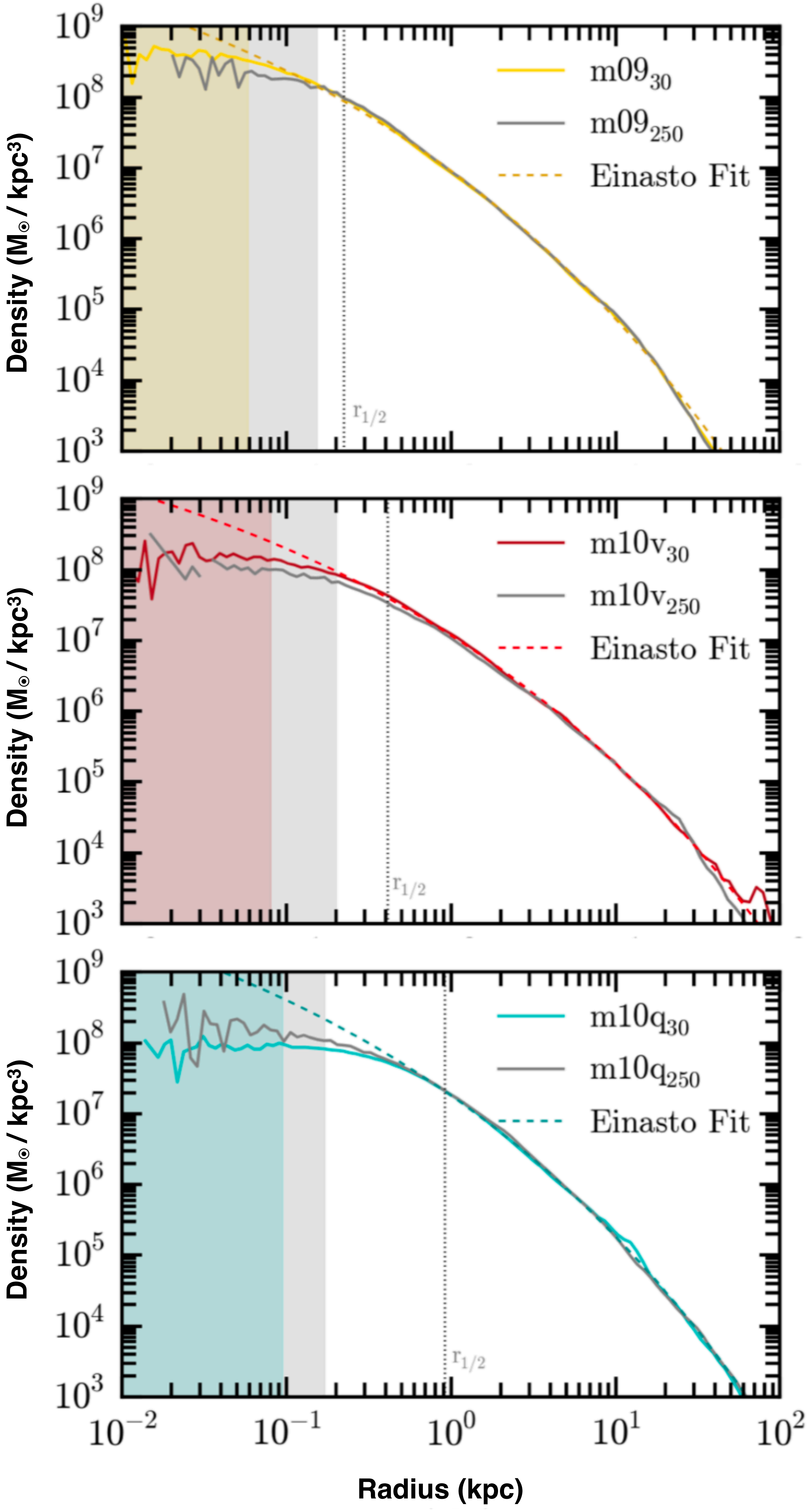
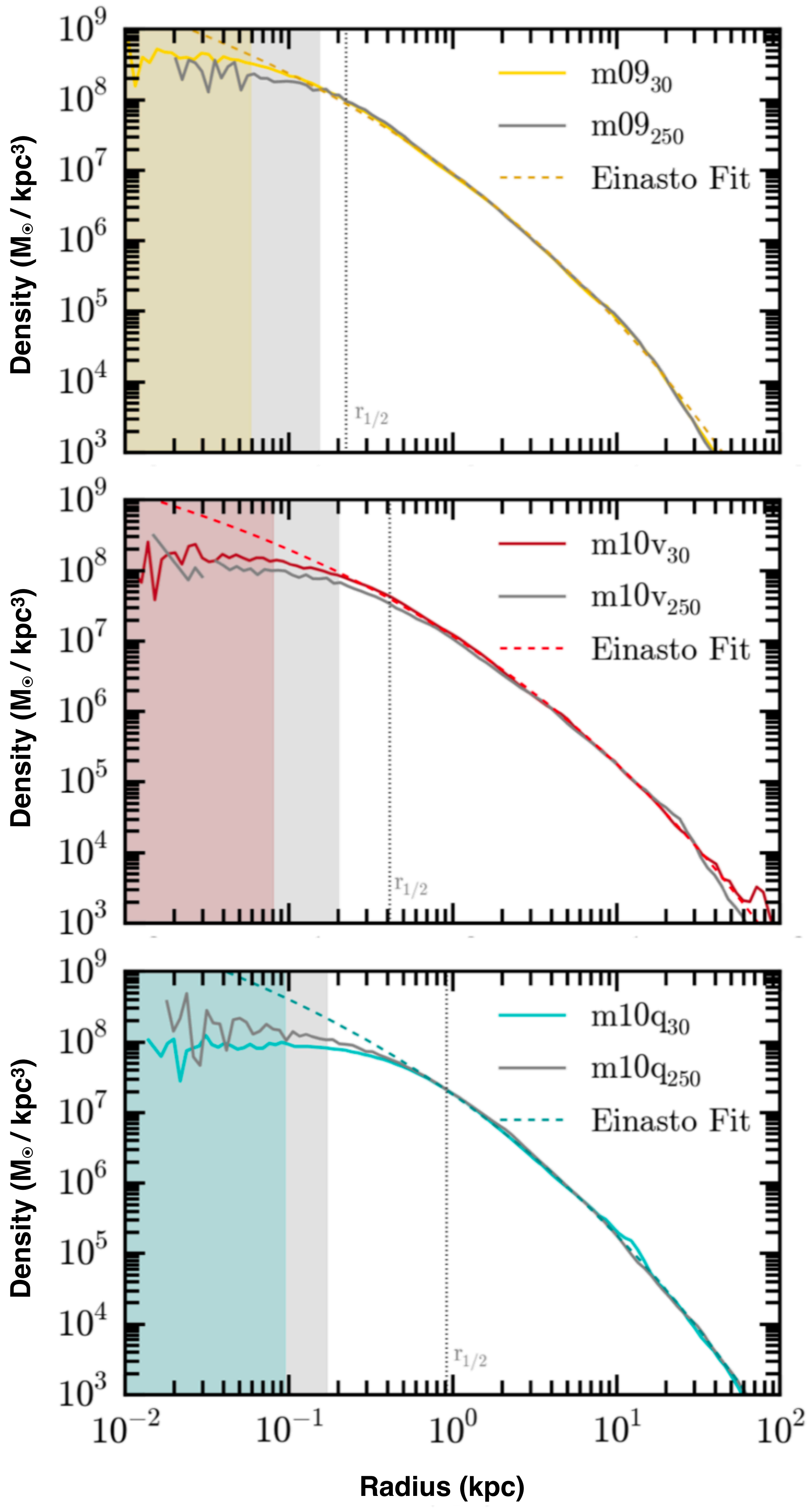


~300pc core exists in our one galaxy with $M_\star/M_{\rm halo} \sim 10^{-3}$



Cores in dwarfs

Cusps down to at least 100pc in all galaxies with $M_\star/M_{\rm halo} < 10^{-4}$



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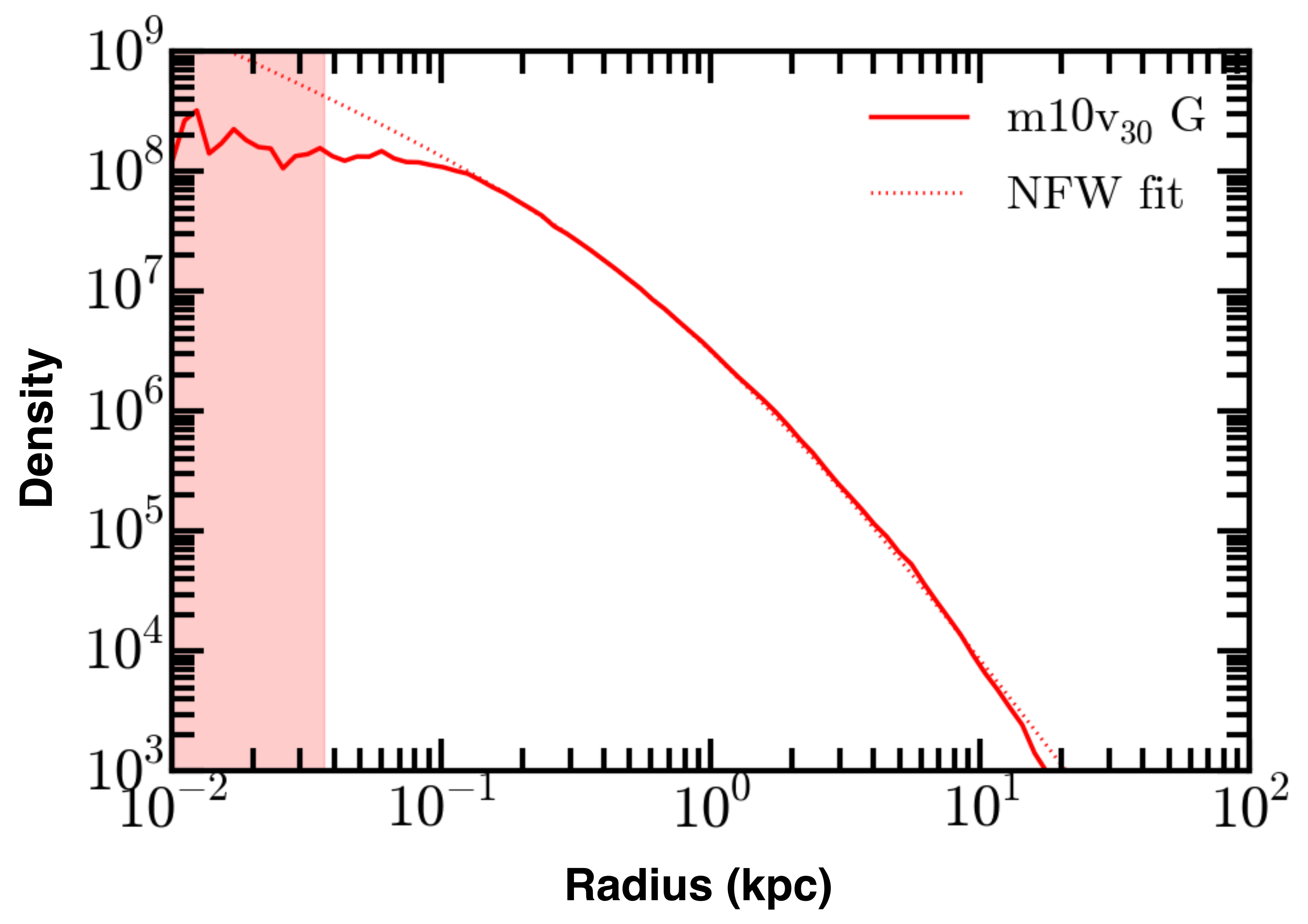
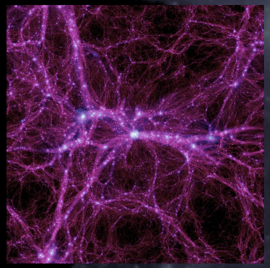
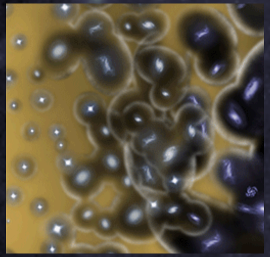
At high resolution, small core visible in some UFDs -> 100 pc-scale cores won’t break LCDM



Why sweat the small stuff?



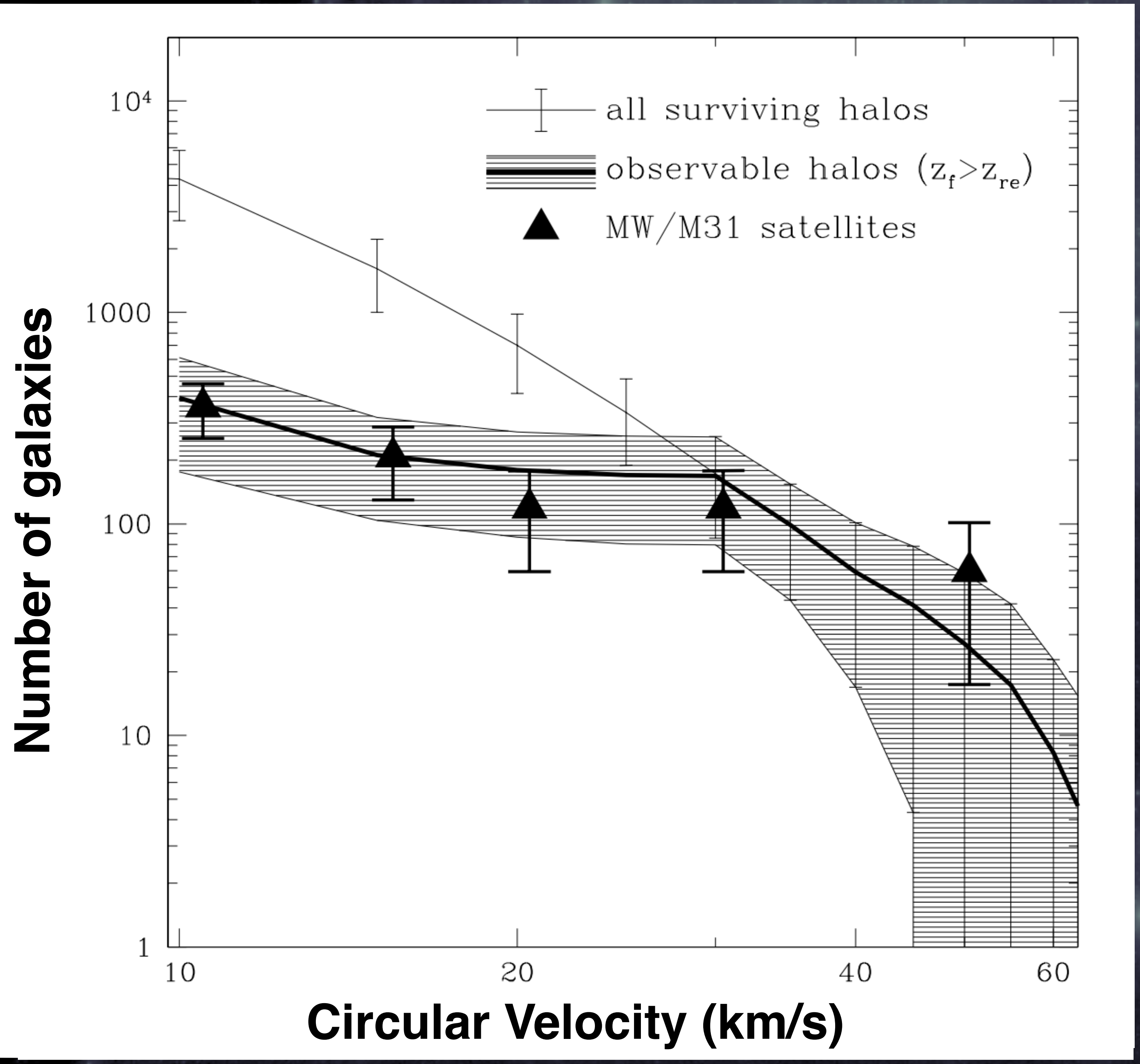
Dwarf galaxies can teach us about dark matter



Dwarf galaxies can teach us about reionization

Dwarf galaxies can teach us about star formation and feedback

Dwarf galaxies can teach us about reionization



Bullock + 2000

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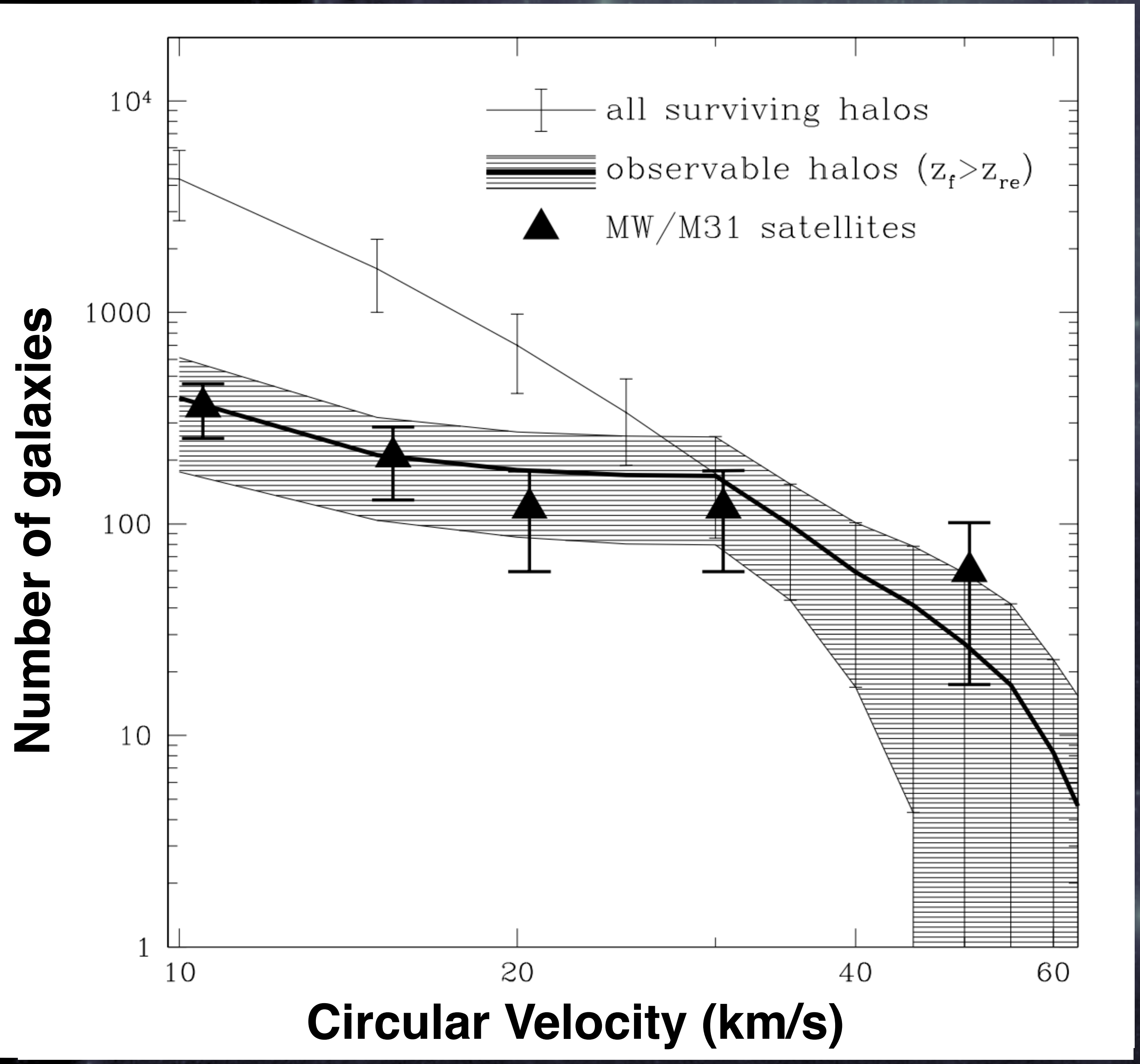

Cosmic reionization prevents smallest halos from forming stars

Bullock + 2000

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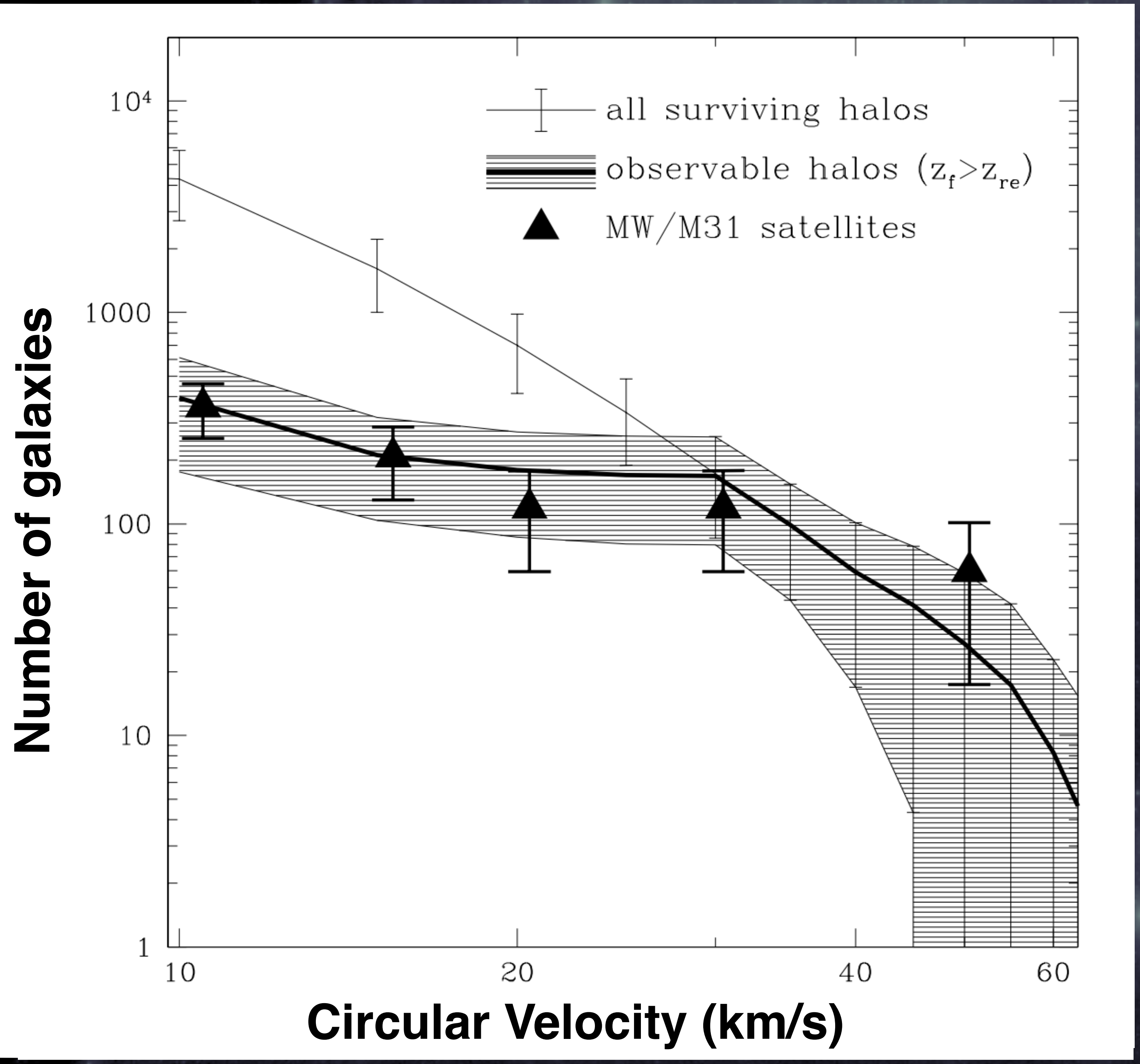

Cosmic reionization prevents smallest halos from forming stars

This may help “solve” the missing satellites problem

Bullock + 2000

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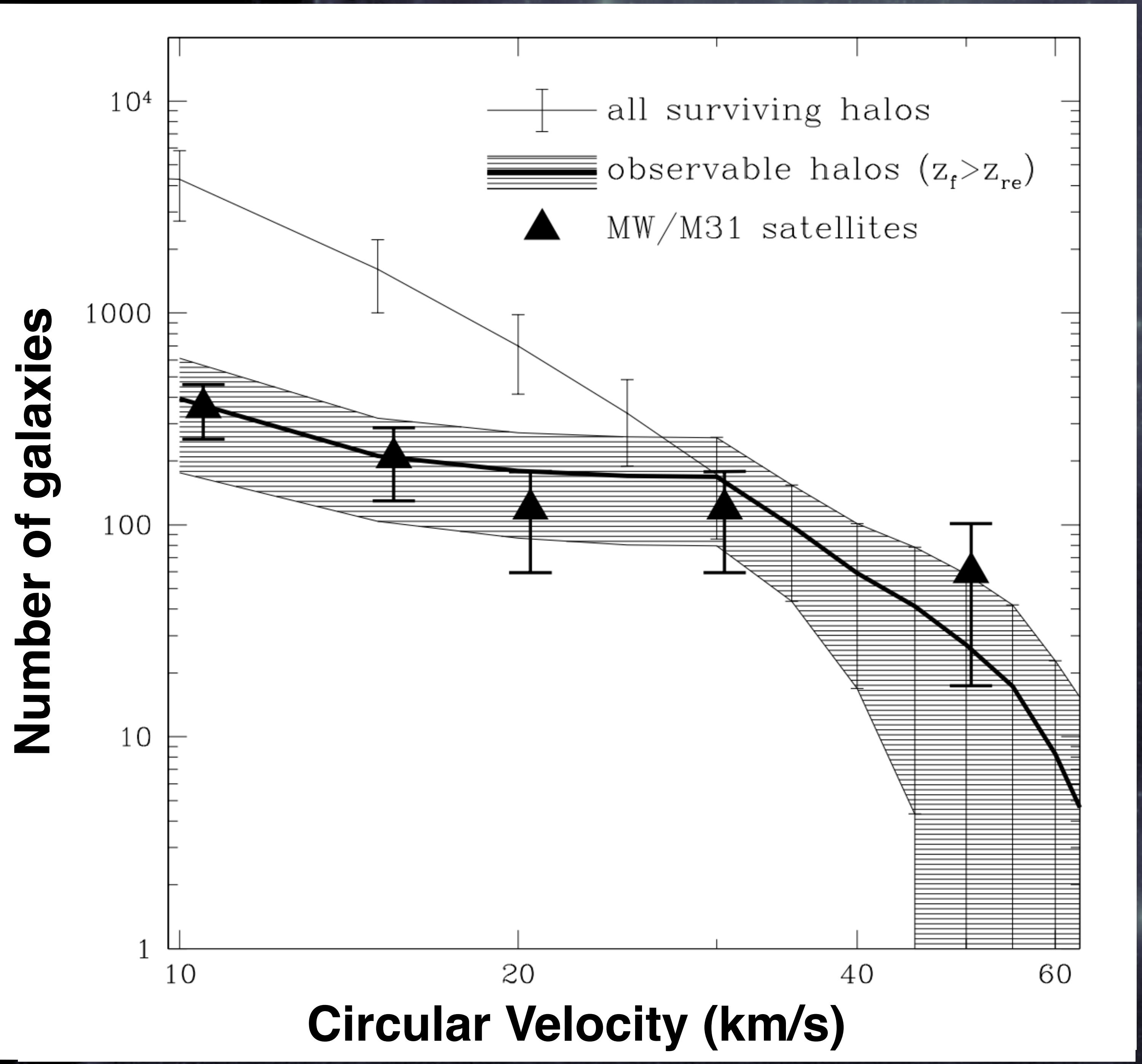


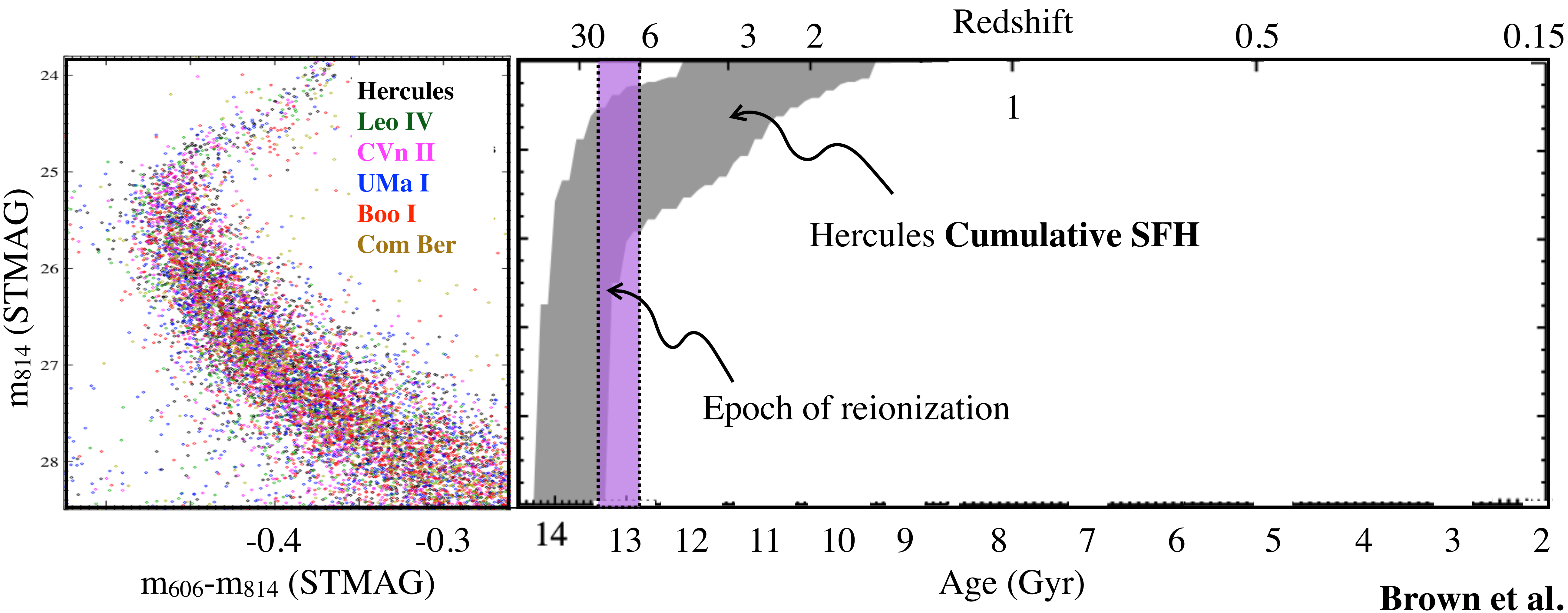
Cosmic reionization prevents smallest halos from forming stars

This may help “solve” the missing satellites problem

What effect does it have on existing galaxies?

Bullock + 2000

Ultra-faint MW sats have ancient stellar populations



Hercules **Cumulative SFH**

Epoch of reionization

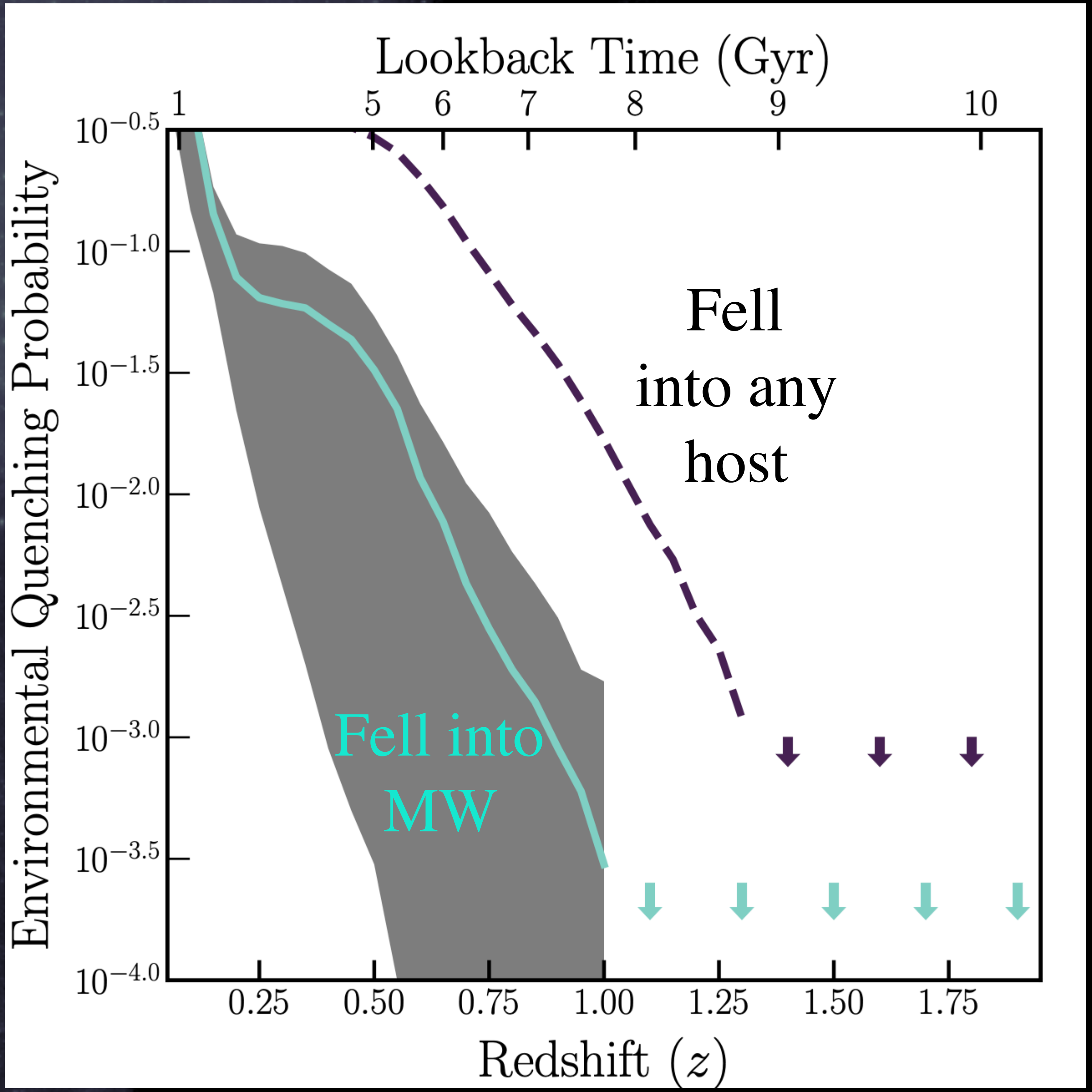
Brown et al. 2014

Reionization or infall?

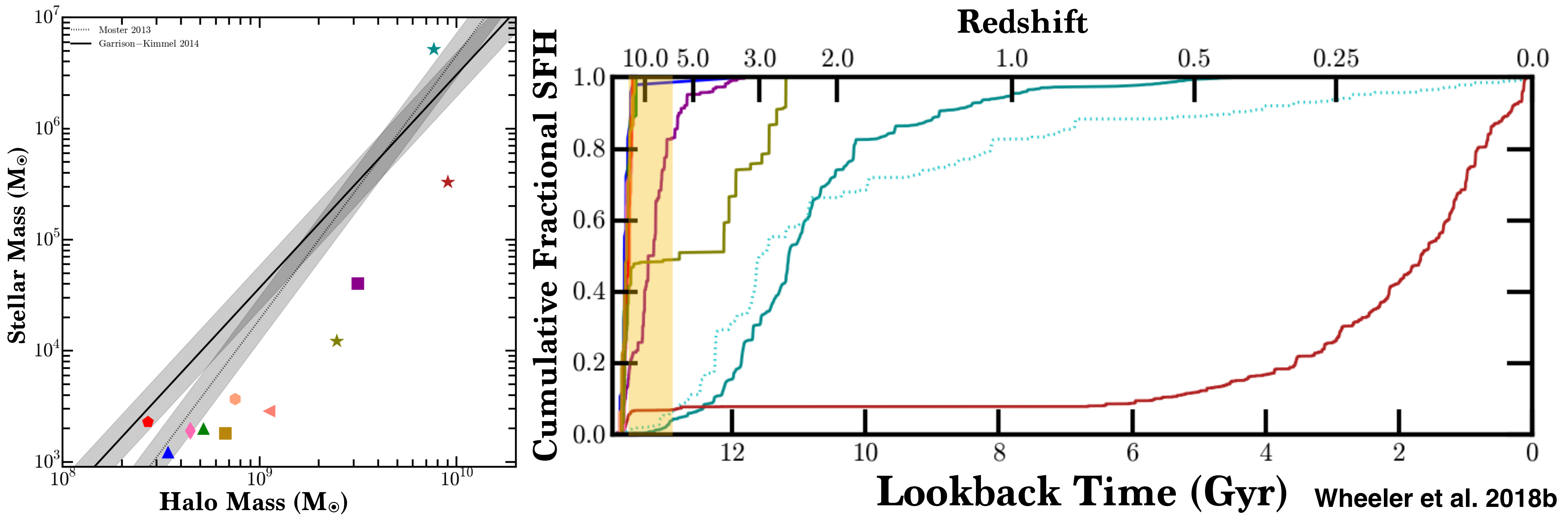
Unlikely all UFDs fell into Milky Way by z=1

Katy Rodriguez-Wimberly (UCI)

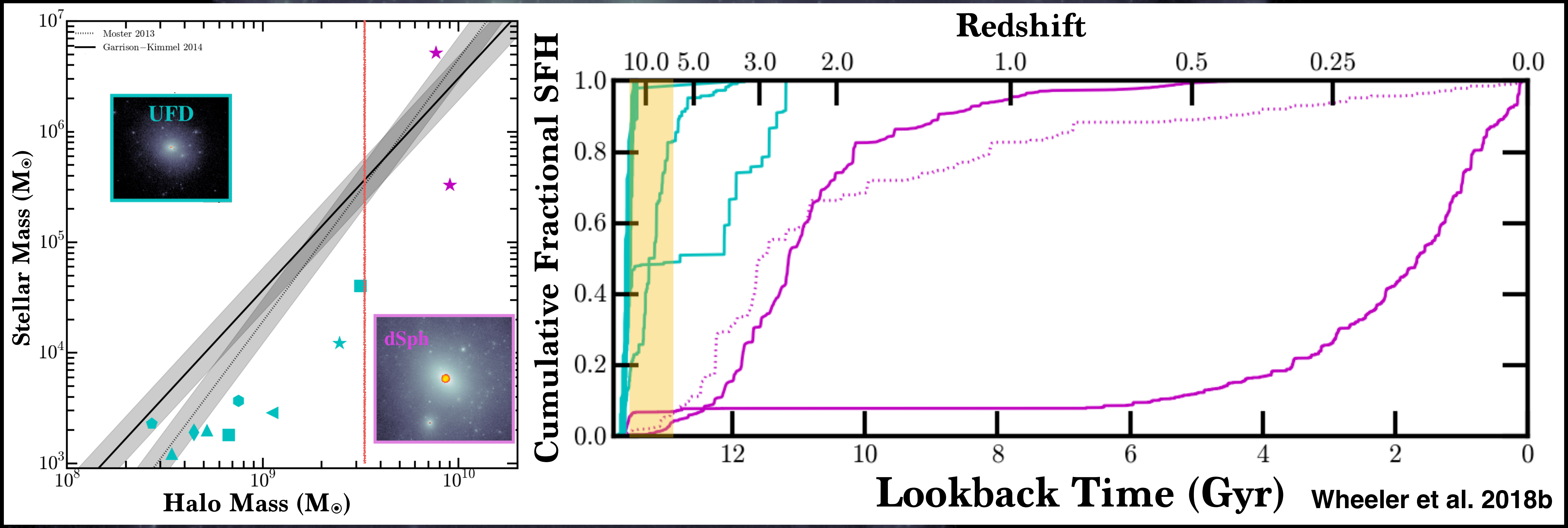
Less than 1% probability that all 6 Brown et al. UFDs quenched by infall



Rodriguez-Wimberly et al. 2018

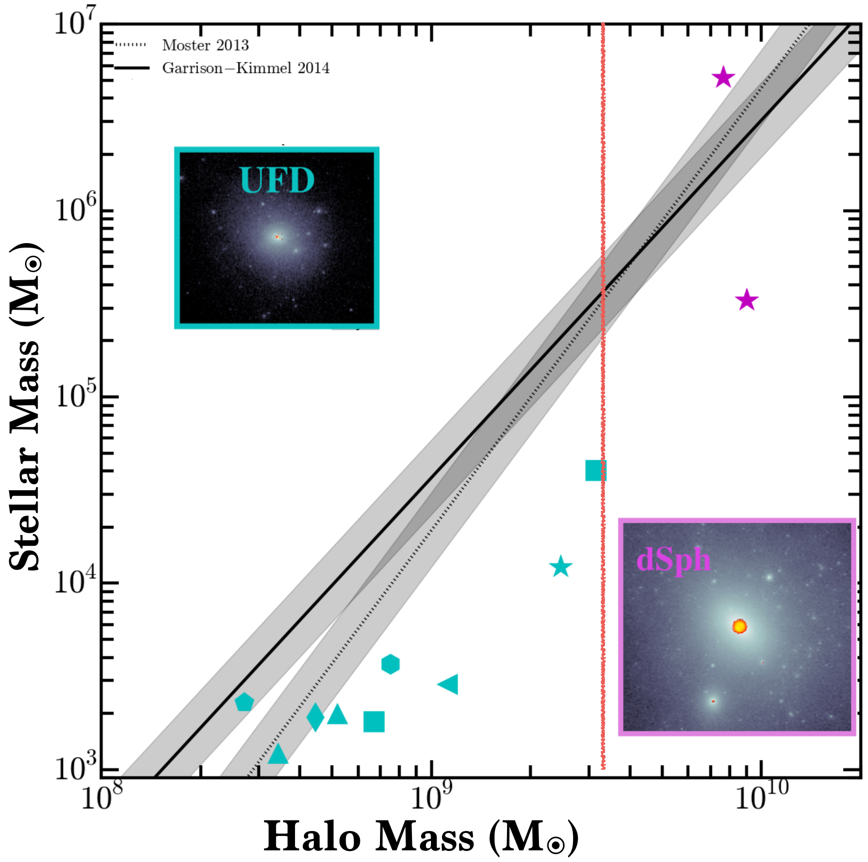


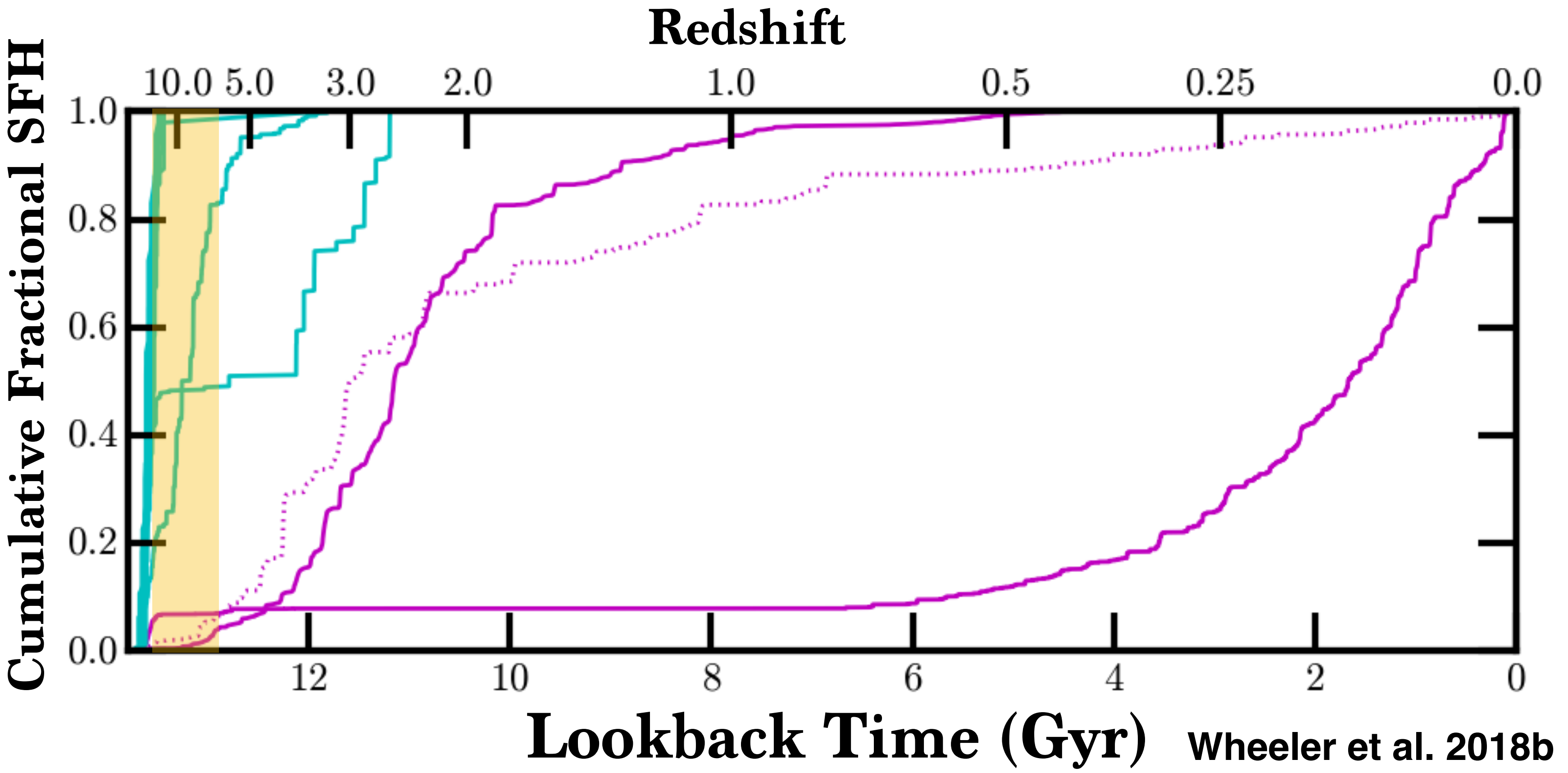
Wheeler et al. 2018b



Wheeler et al. 2018b

Simulated UFDs all have SF shut down by z=2





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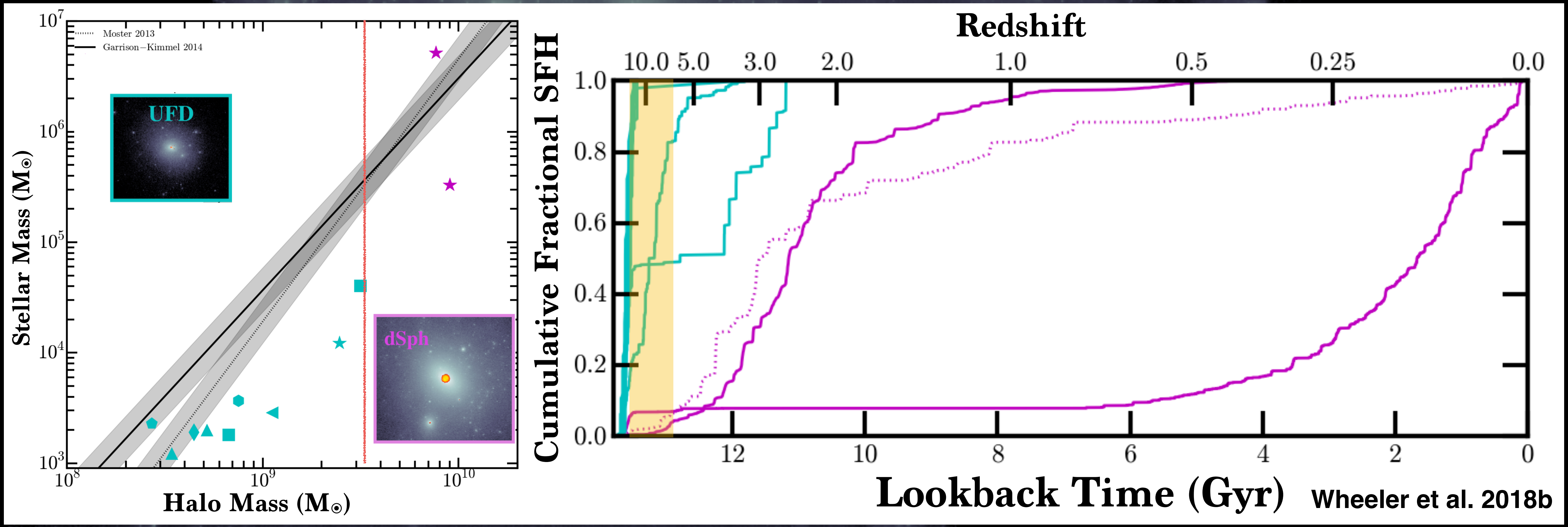
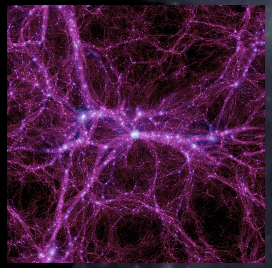


Wheeler et al. 2018b

Testable prediction: All UFDs, whether satellites or isolated, will have uniformly ancient stellar populations

Why sweat the small stuff?



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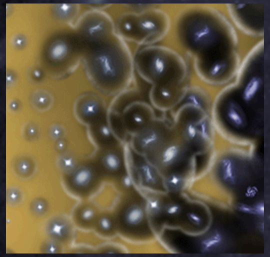

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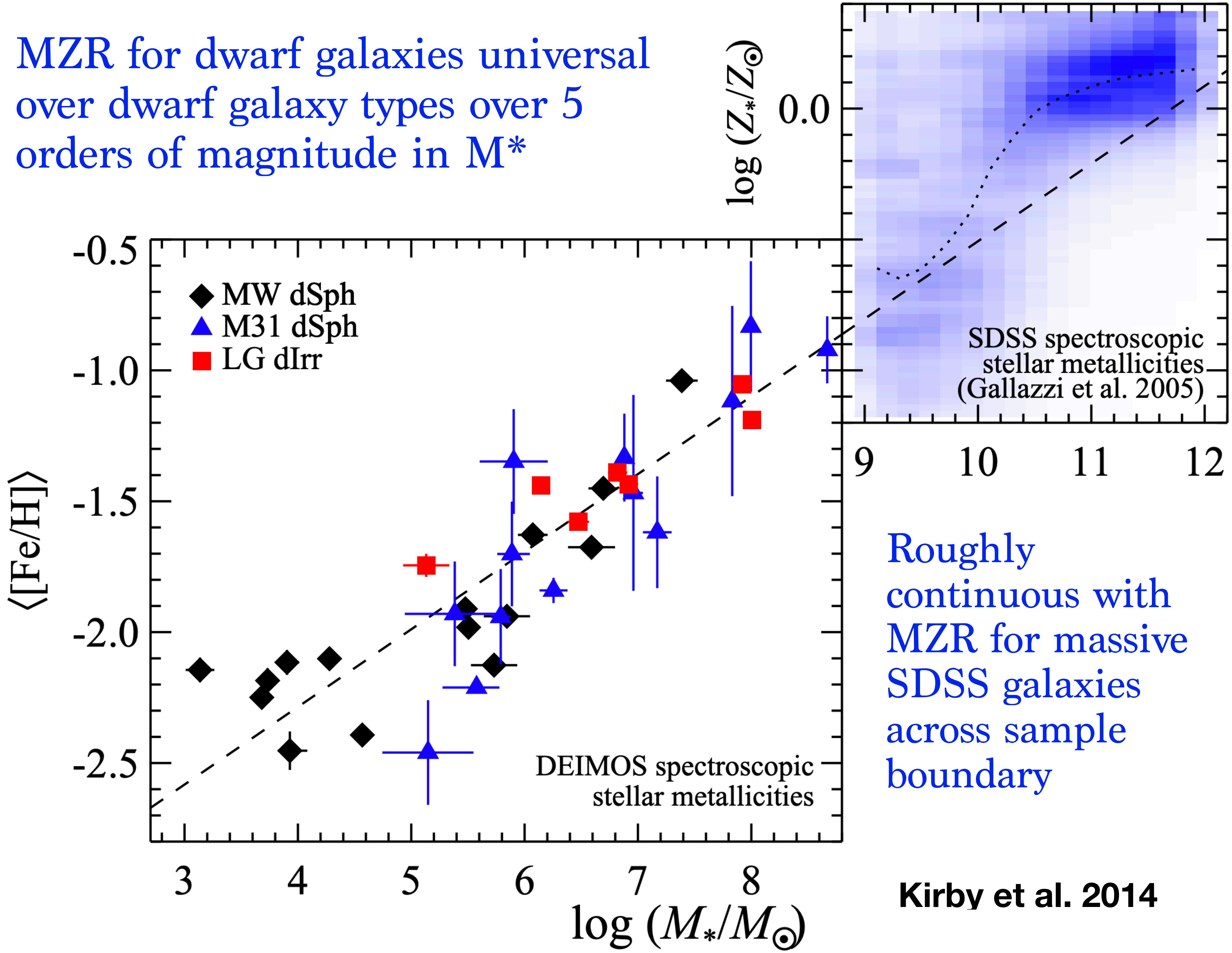
Universal Mass Metallicity Relation For Dwarfs?

MZR for dwarf galaxies universal over dwarf galaxy types over 5 orders of magnitude in M*



Roughly continuous with MZR for massive SDSS galaxies across sample boundary

Kirby et al. 2014

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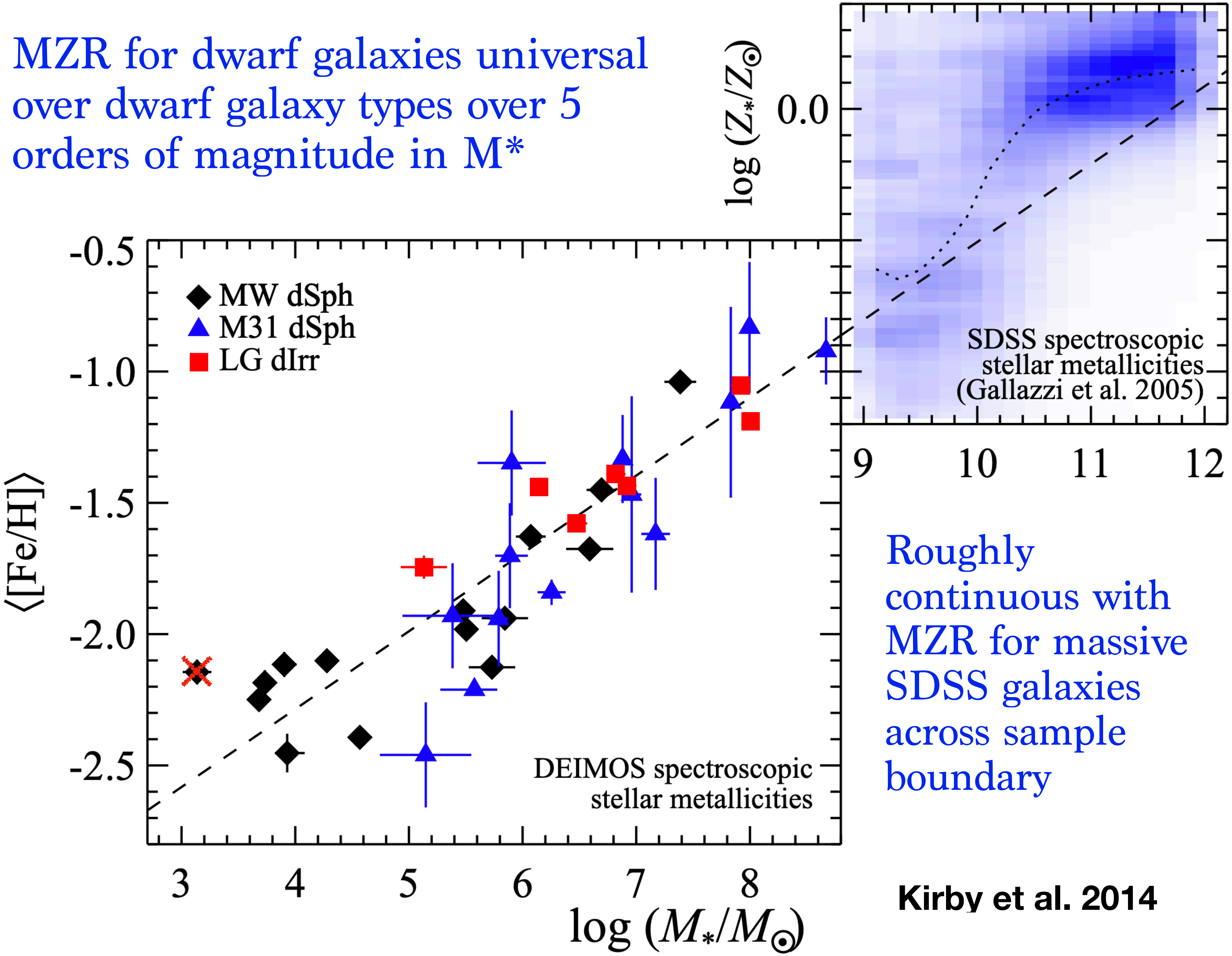

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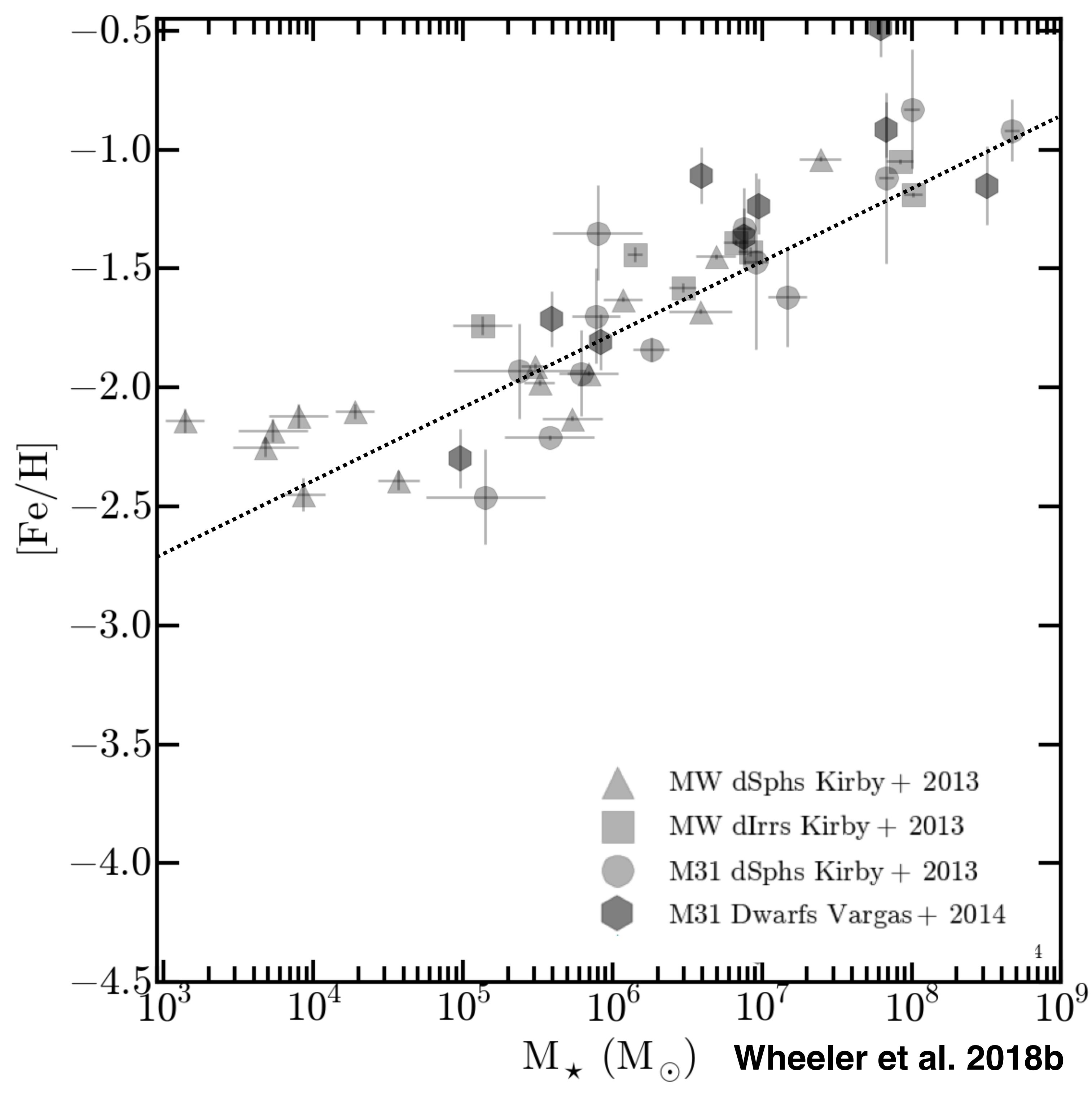
Mass Metallicity Relation

- Observations may suggest universal MZR at low masses, or possible flattening



Wheeler et al. 2018b

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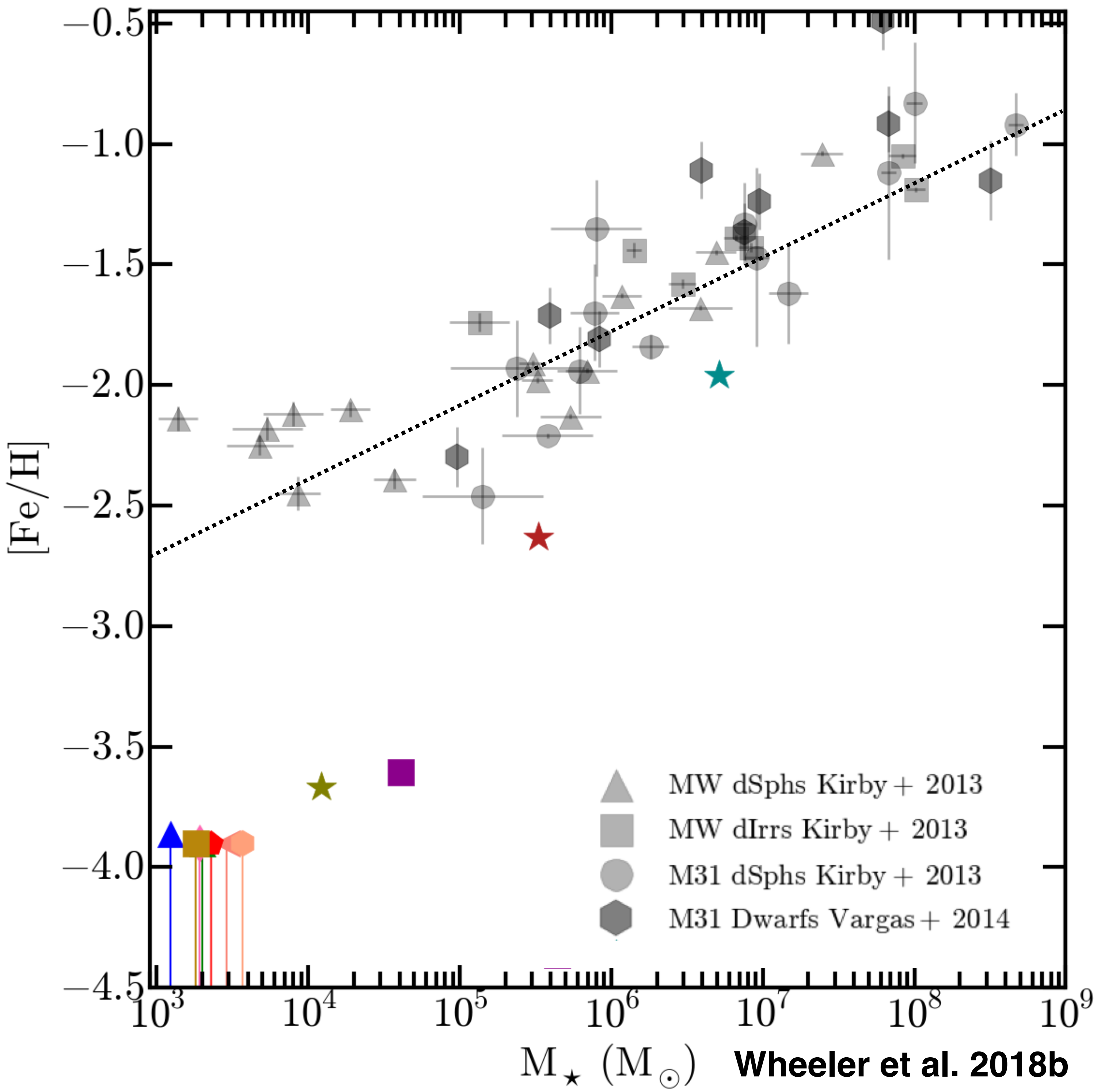
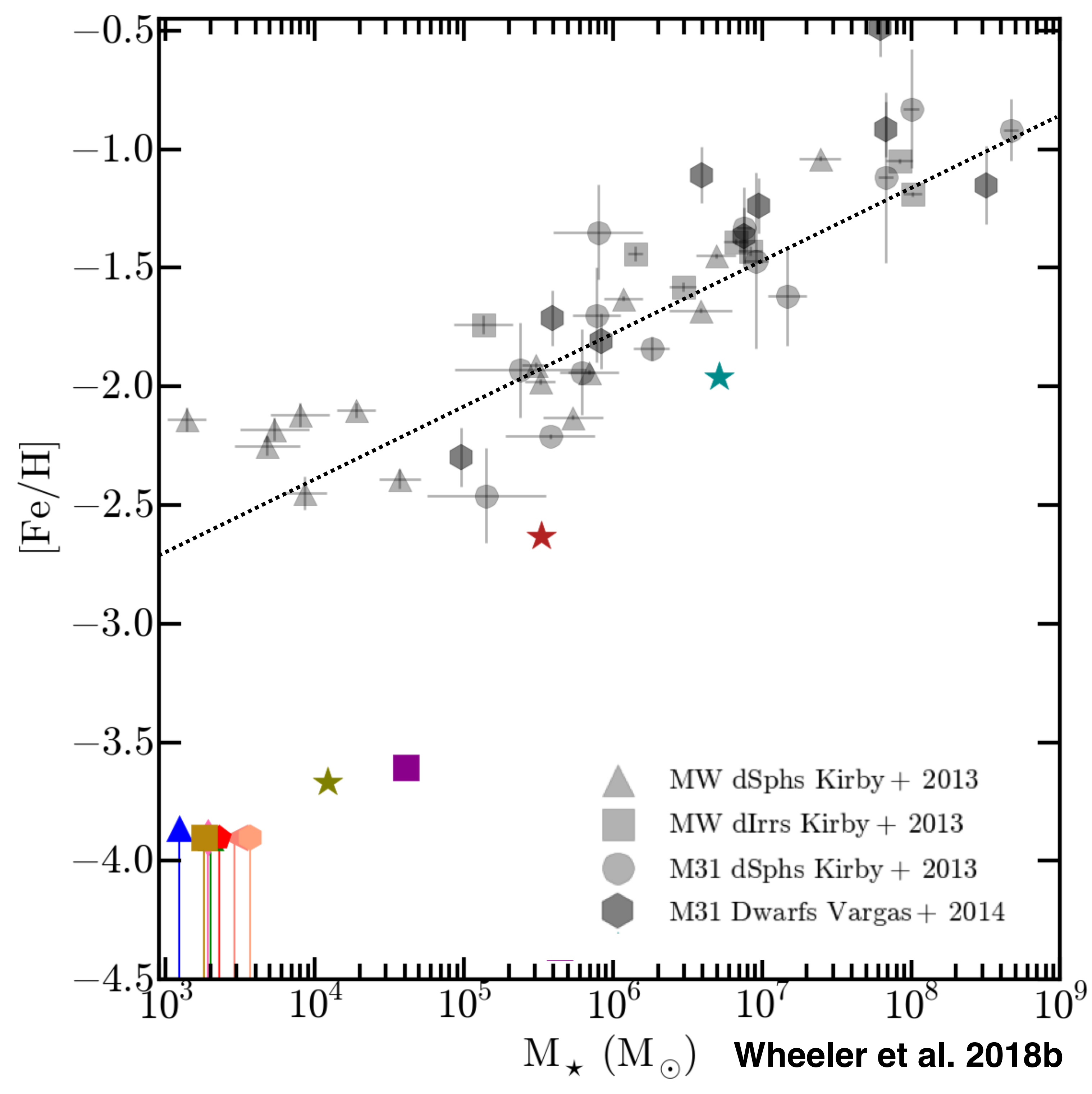
- First time highly resolved galaxies plotted at this low of mass - Yikes!



Wheeler et al. 2018b

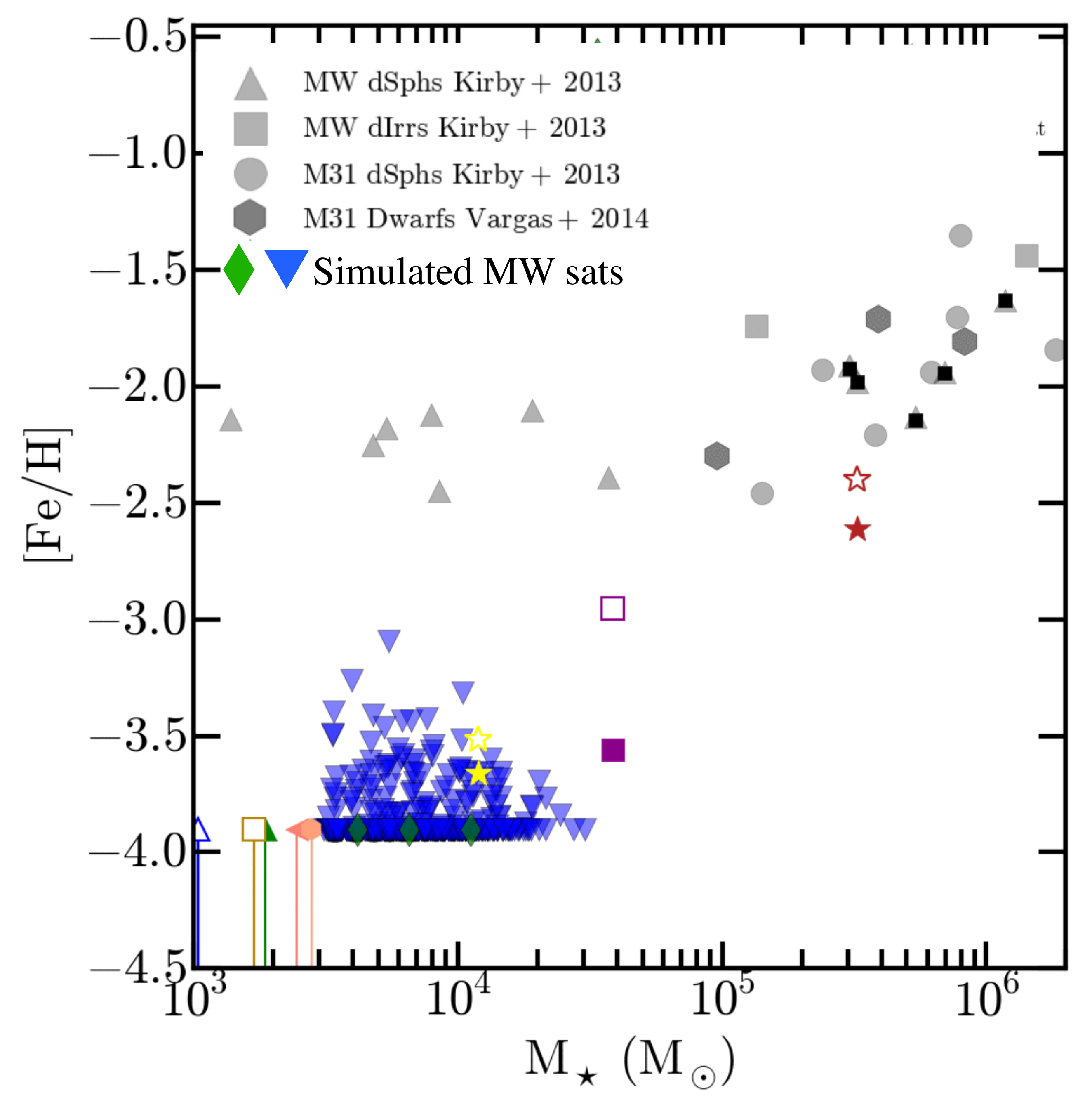
Mass Metallicity Relation

- Observations may suggest universal MZR at low masses, or possible flattening
- First time highly resolved galaxies plotted at this low of mass - Yikes!
- At lowest masses, offset only a few SNe
- Missing physics in sims? Pop III enrichment, yield tables? MW nearby?



Wheeler et al. 2018b

Can presence of a massive neighbor enrich UFDs?



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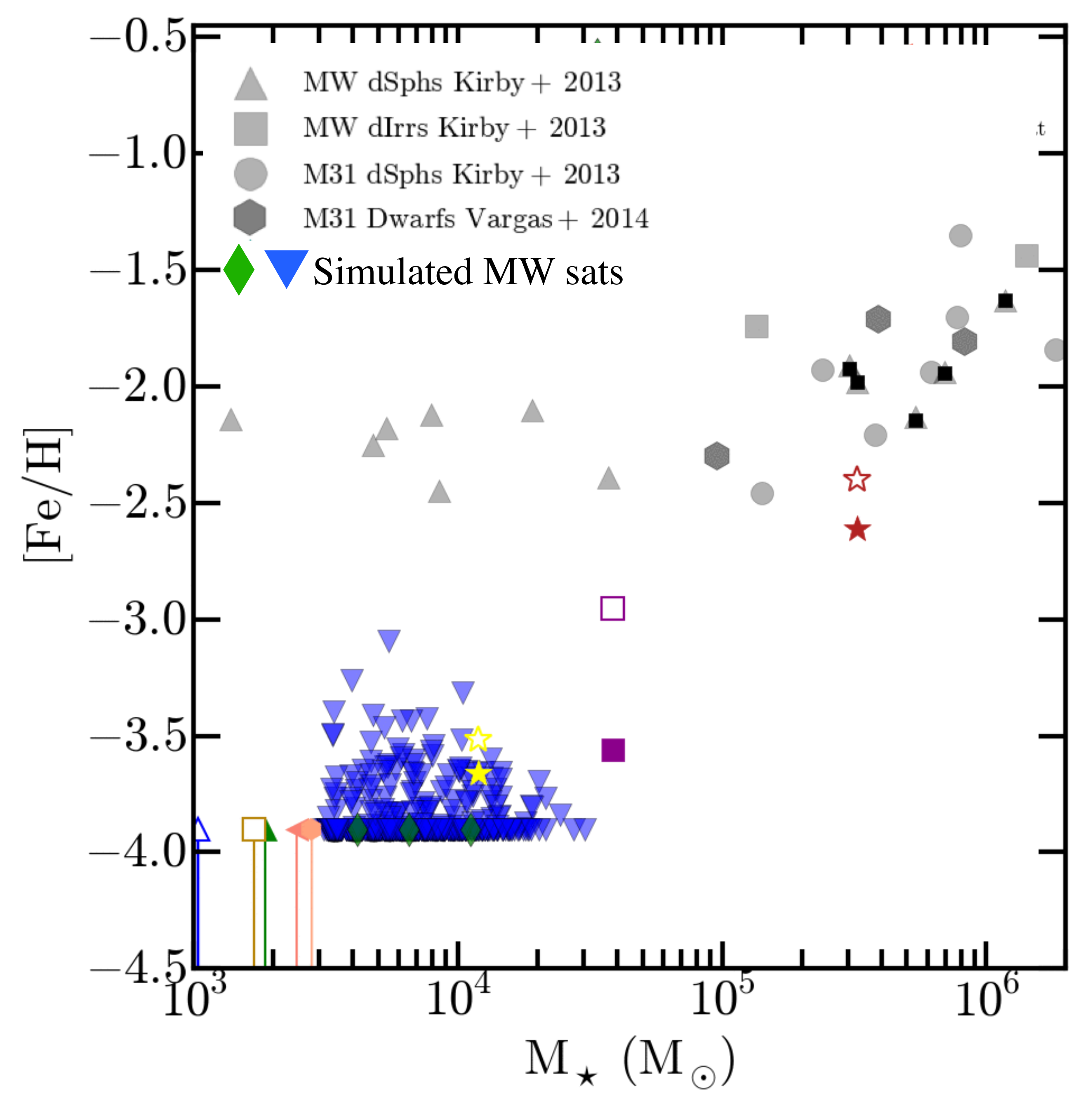
Ran two MW-sims with m_{bar} = 880 $M_\odot$ to z~4.5



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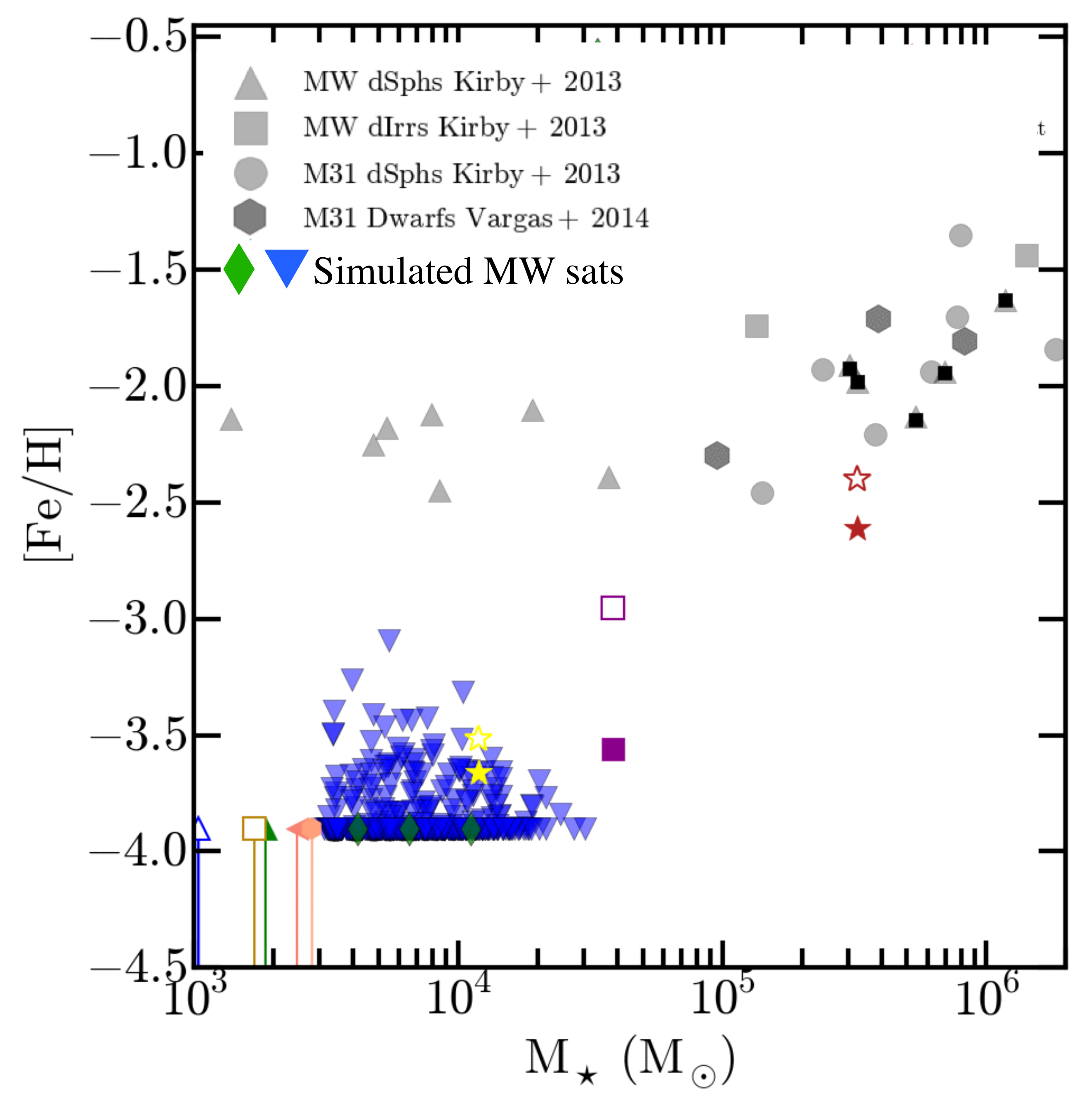
Look at galaxies that form 100% of their stars by z = 9,8,7,6,5



Can presence of a massive neighbor enrich UFDs?

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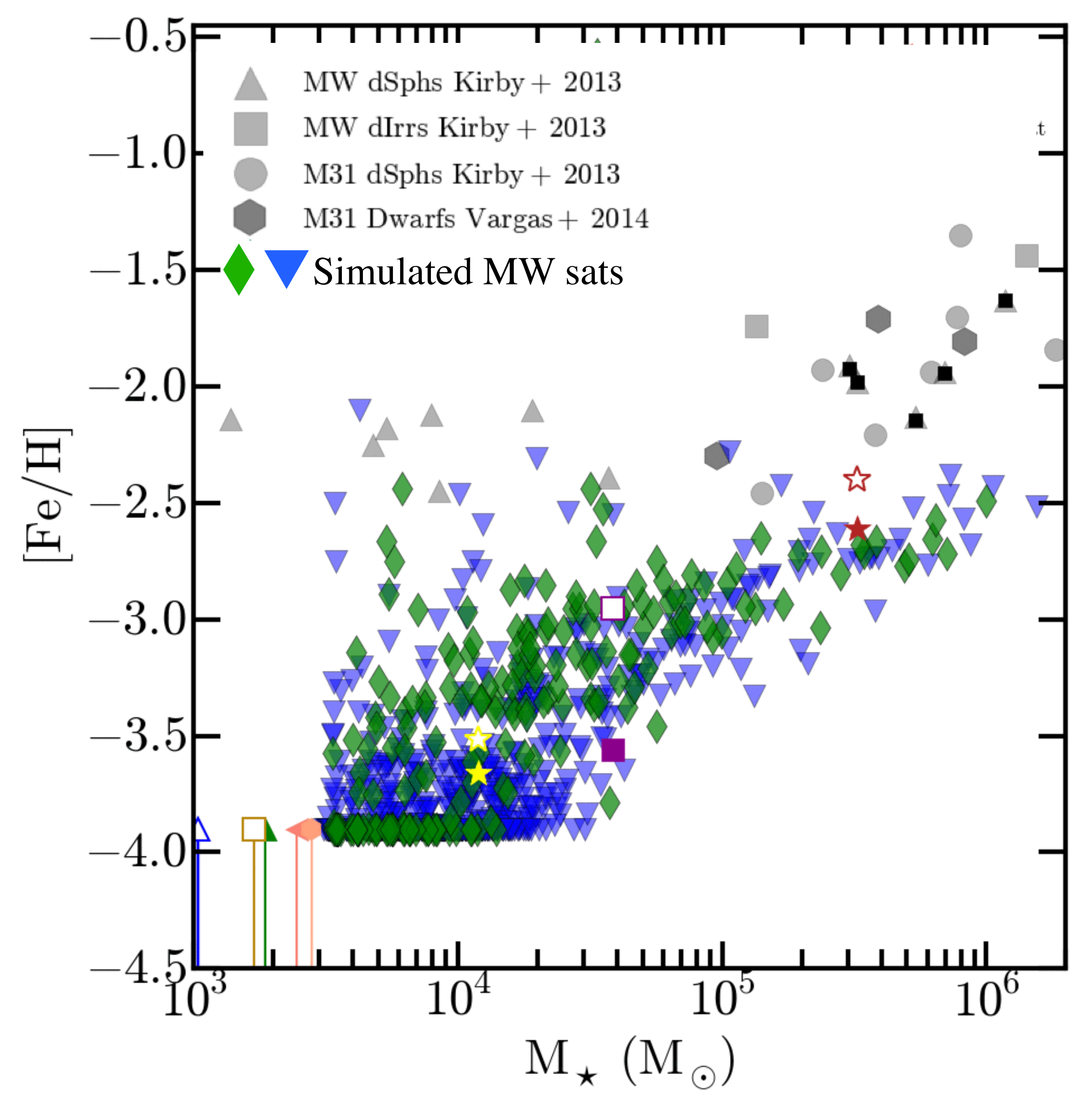
By z = 5, some UFDs enriched to observed levels



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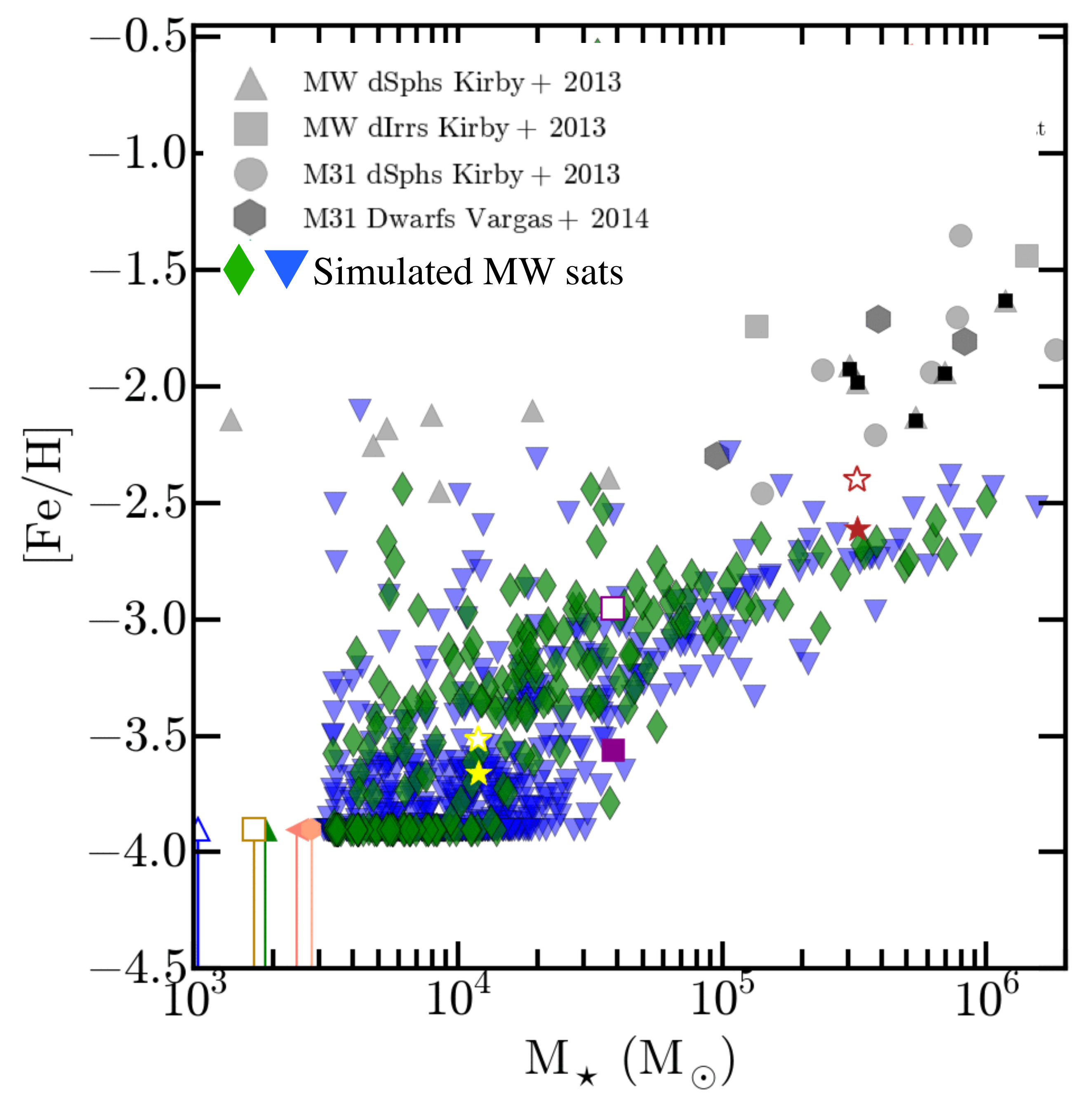

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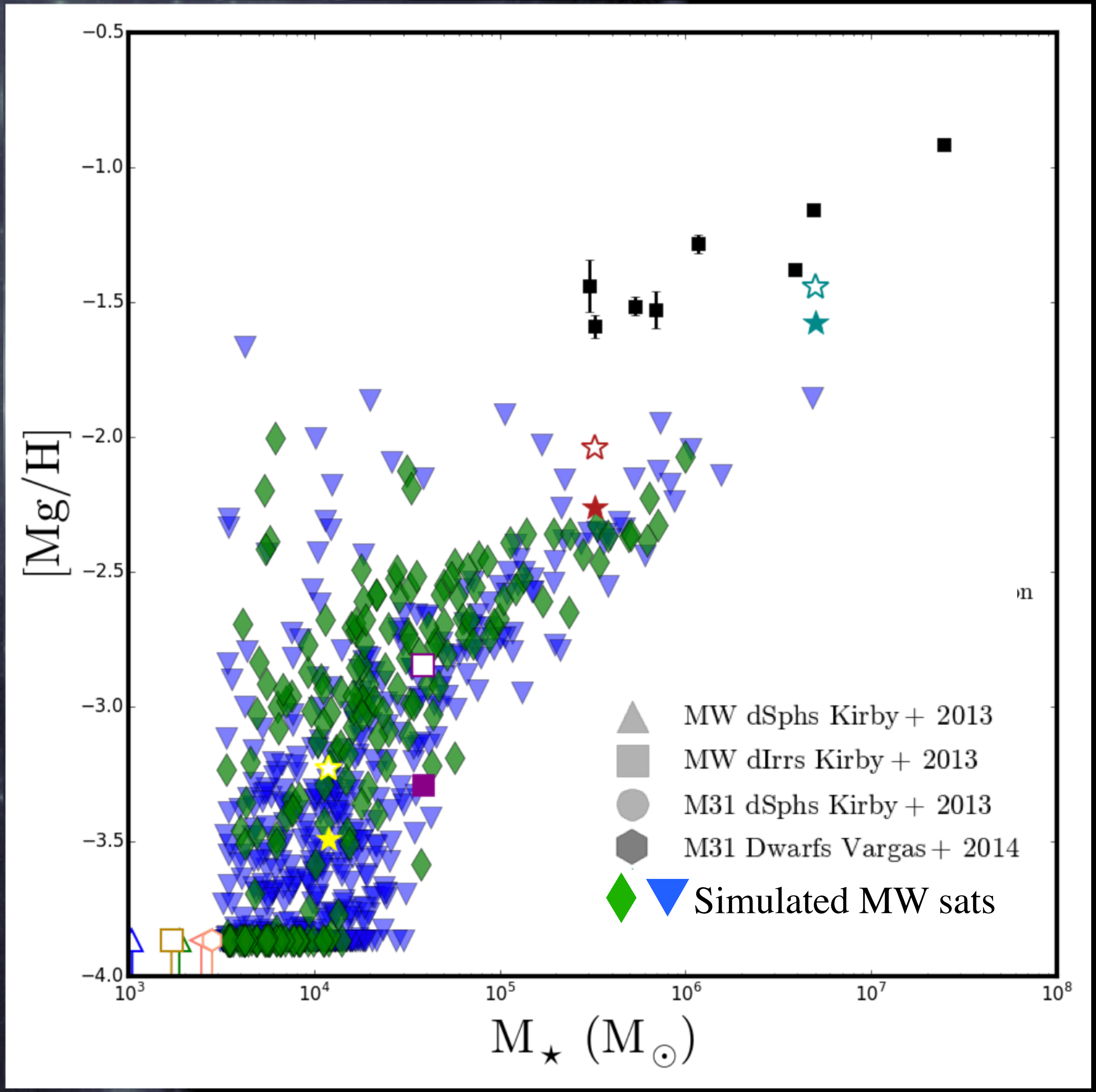

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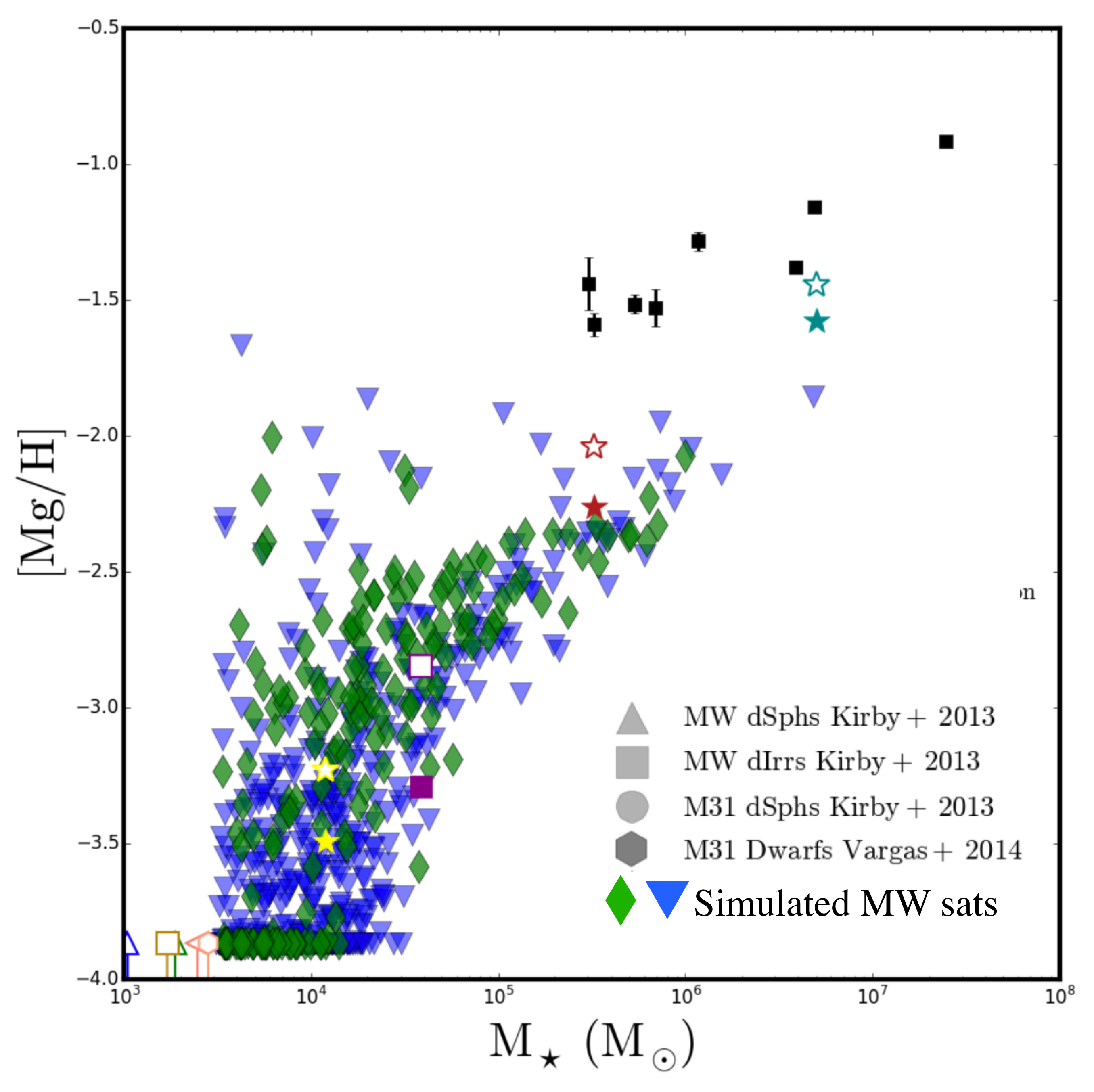
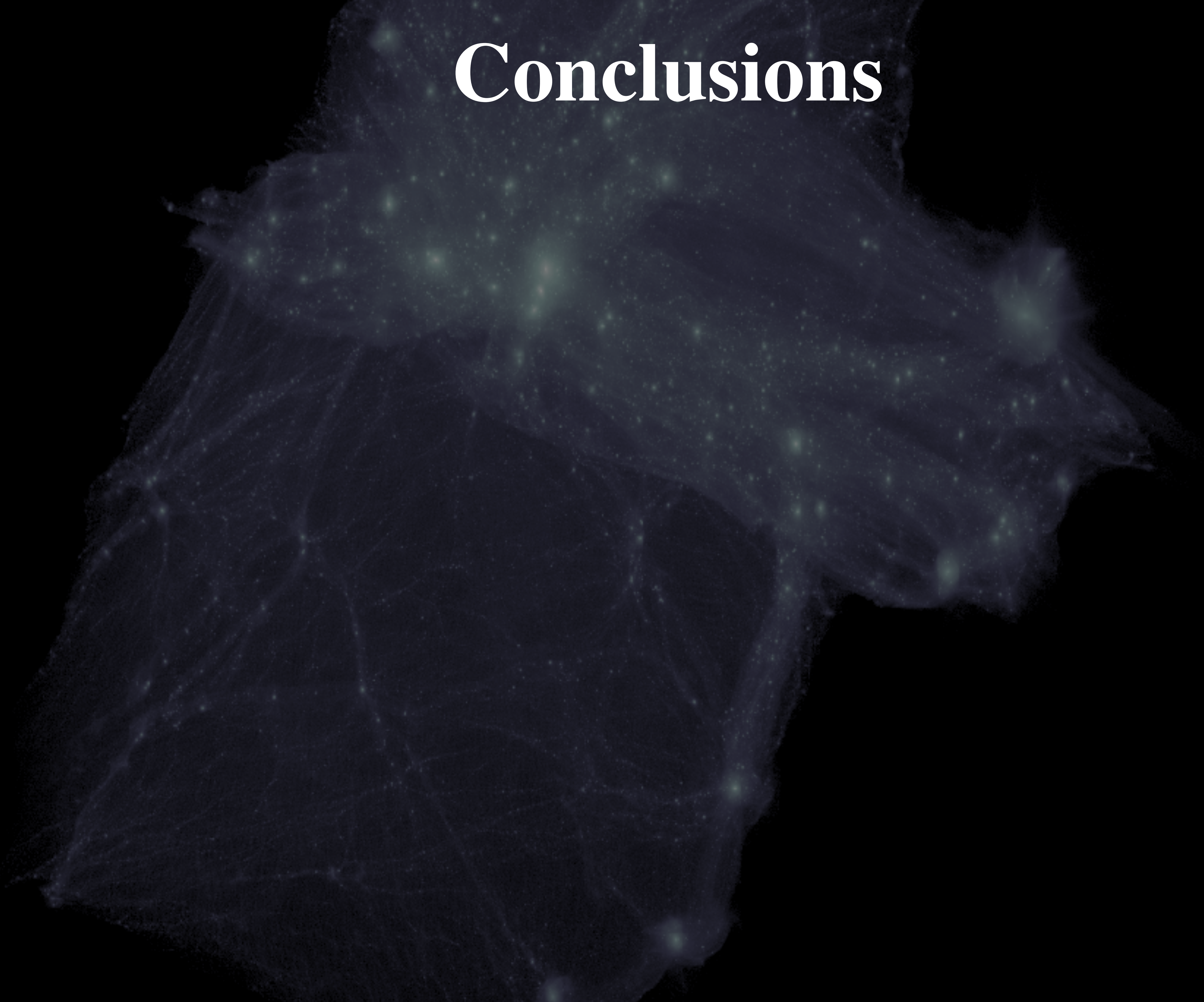


Testable prediction(?) Isolate UFDs will have higher [Fe/H] than sats

Conclusions



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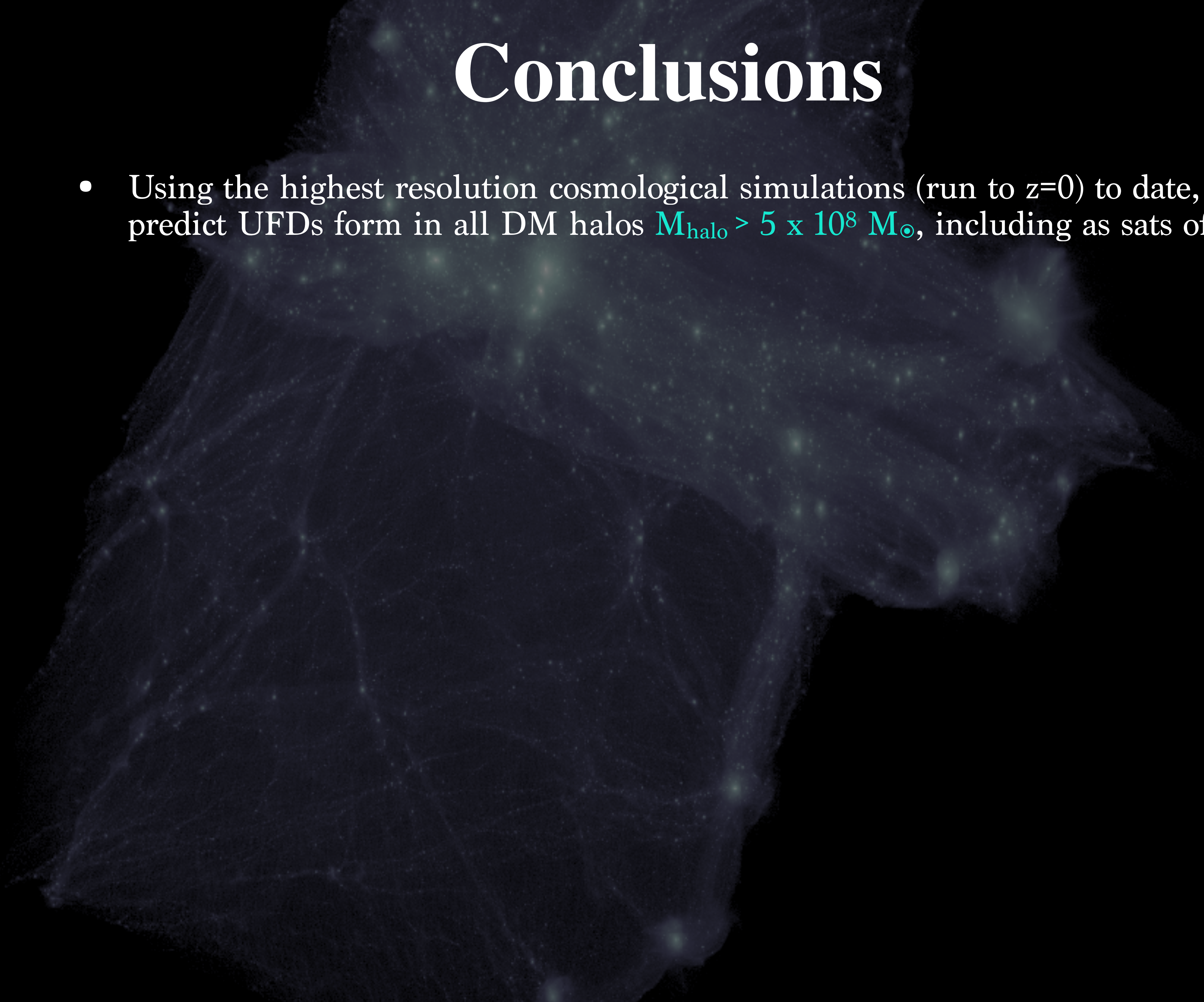

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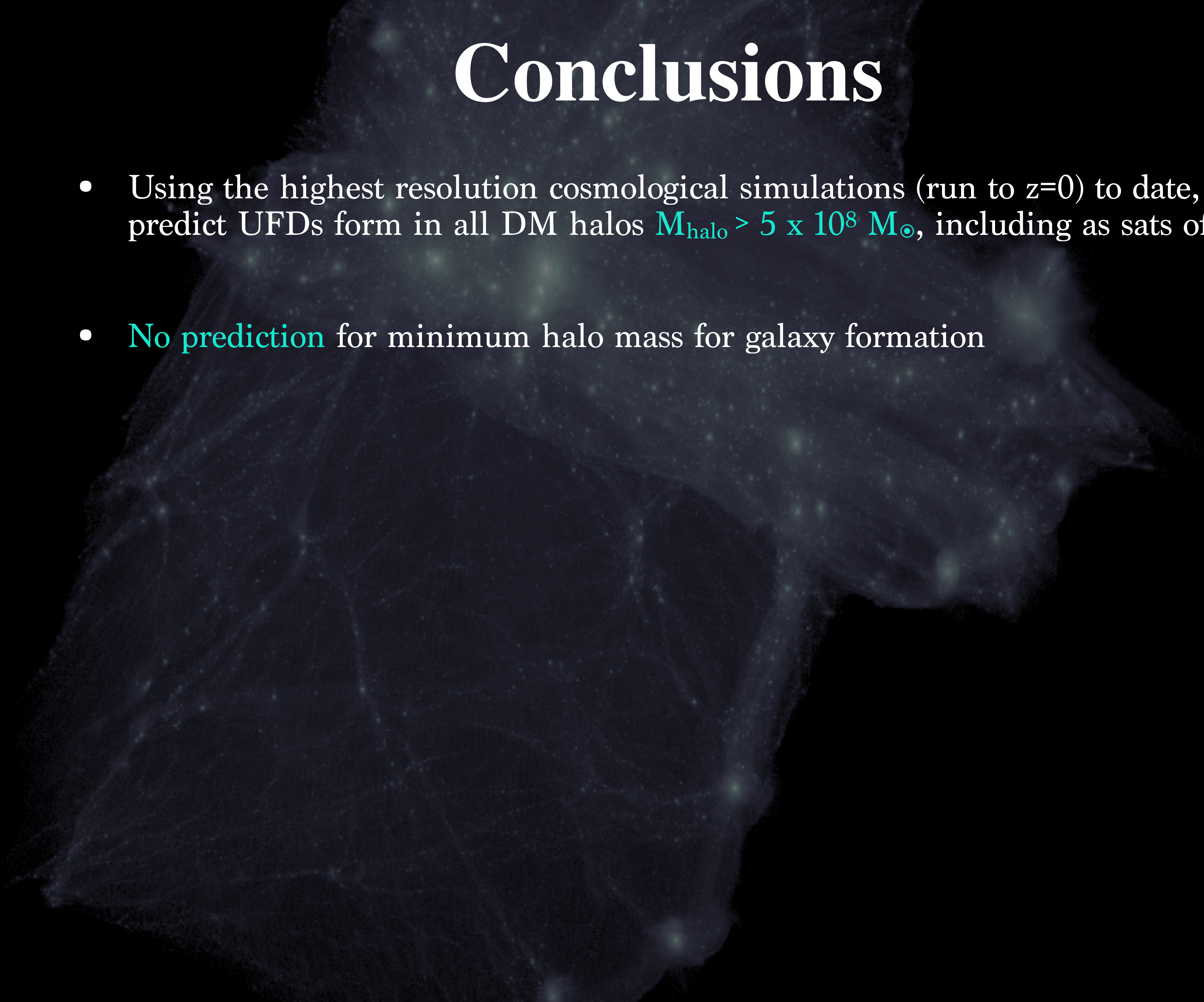

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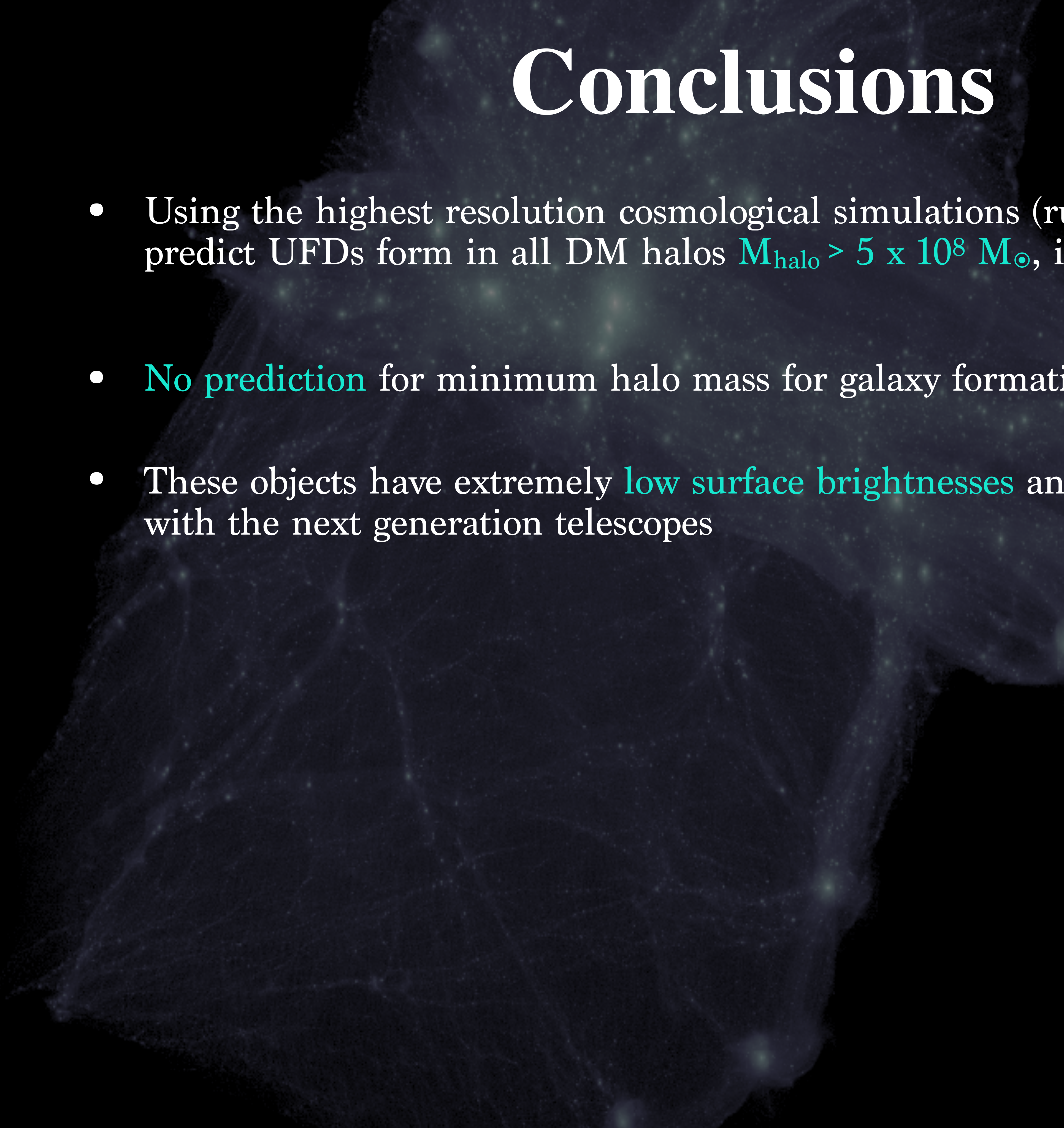

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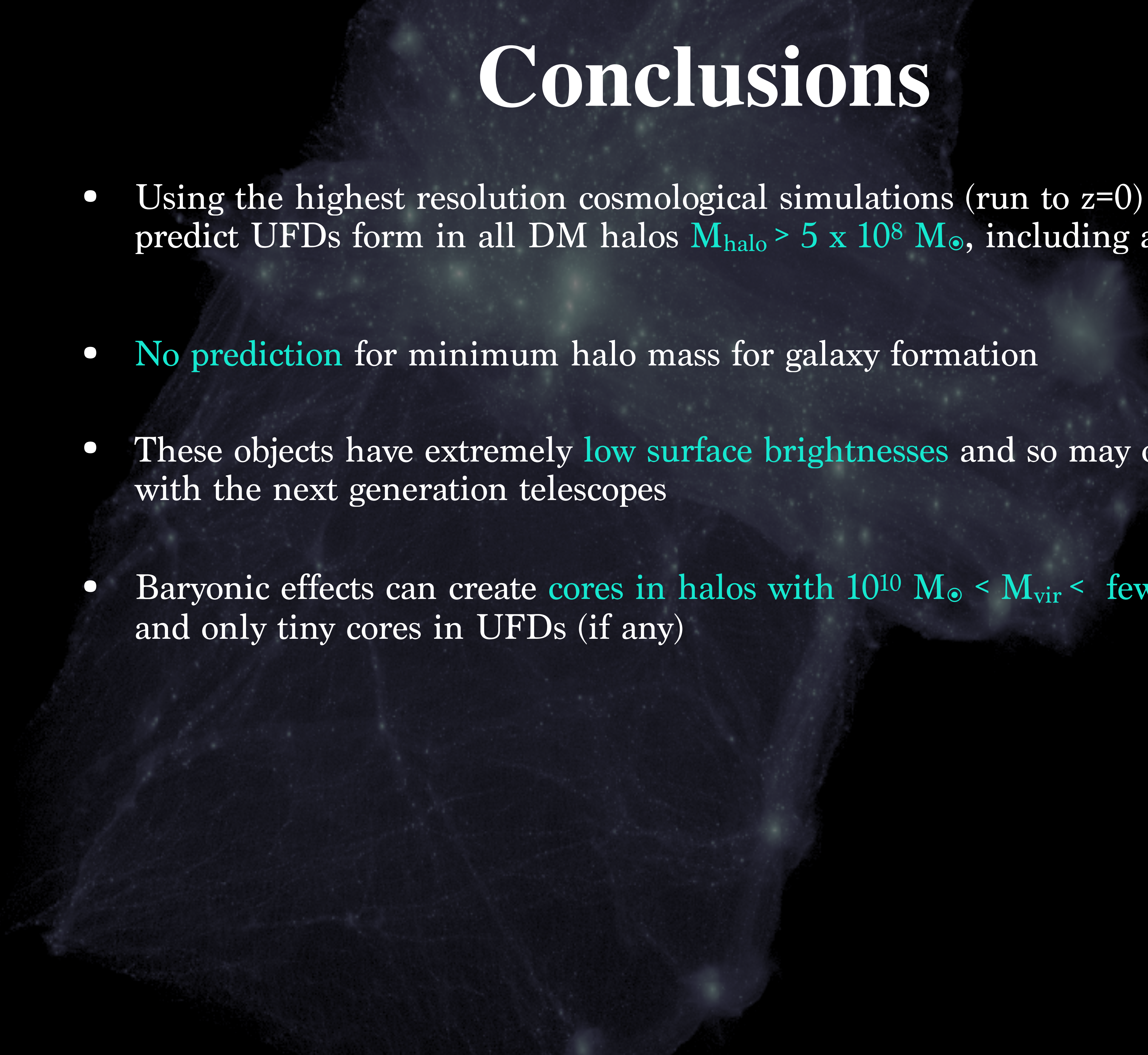

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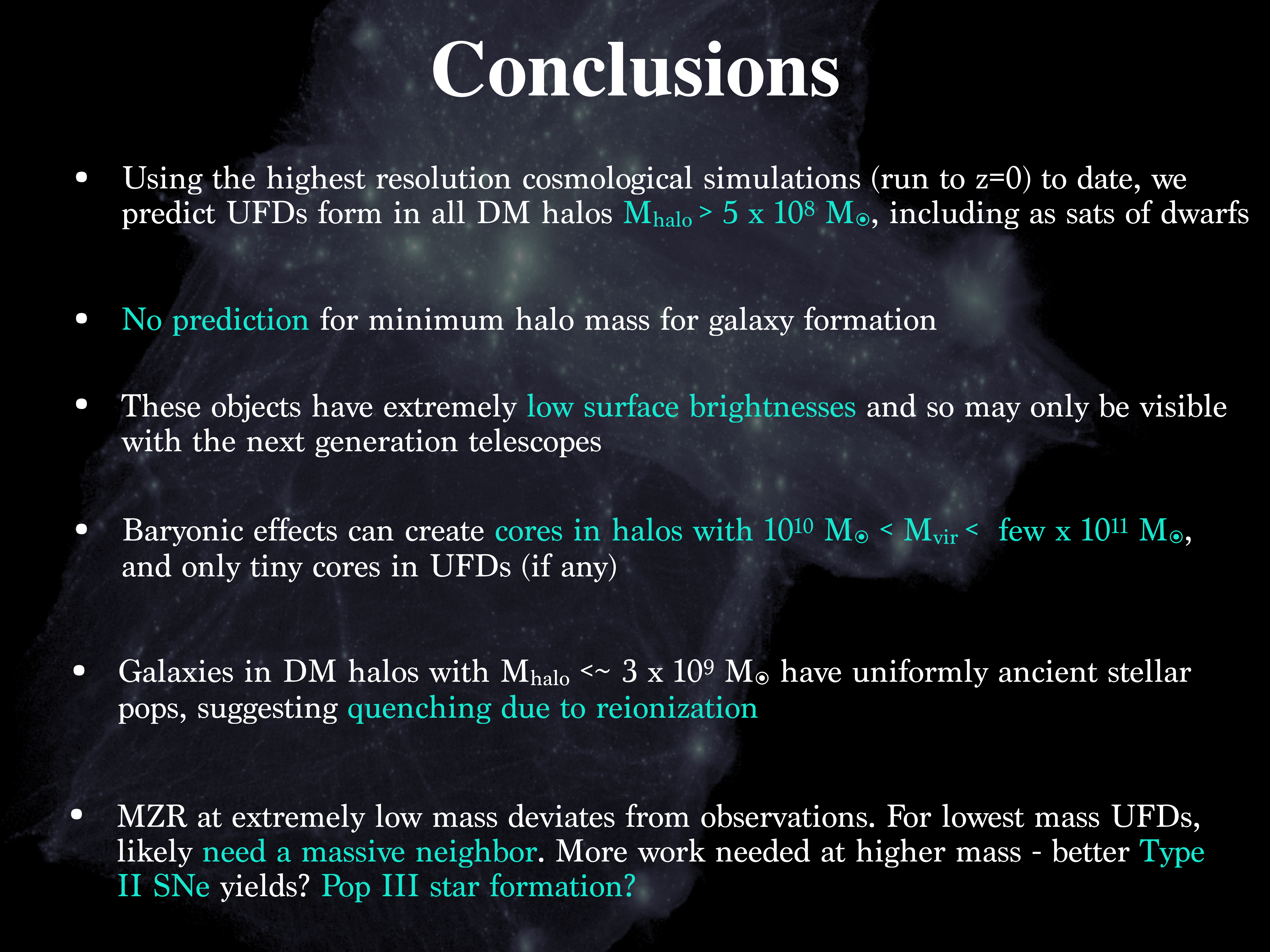

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- MZR at extremely low mass deviates from observations. For lowest mass UFDs, likely need a massive neighbor. More work needed at higher mass - better Type II SNe yields? Pop III star formation?

Thanks!