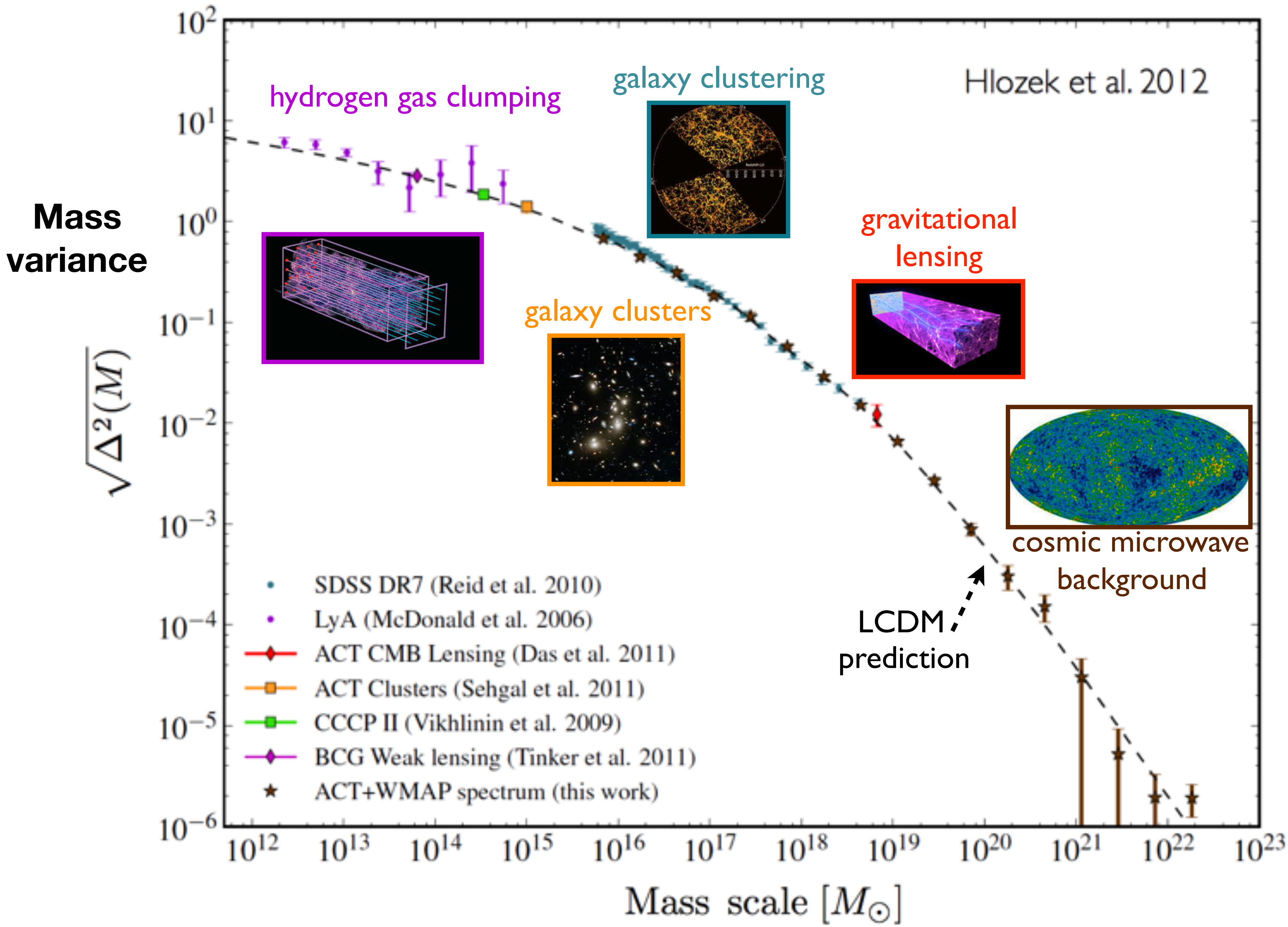
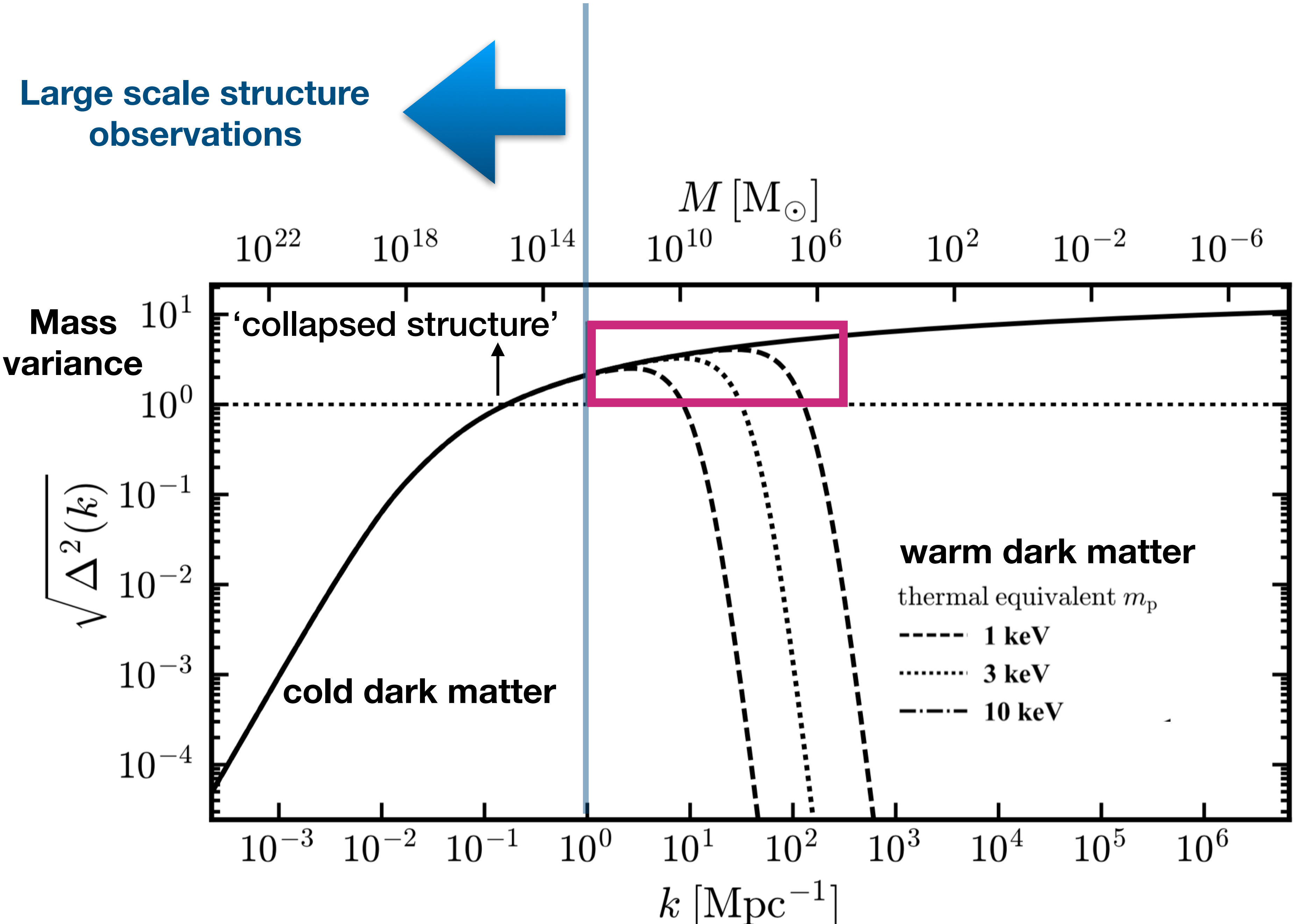
Structure formation simulations

James Bullock
UC Irvine

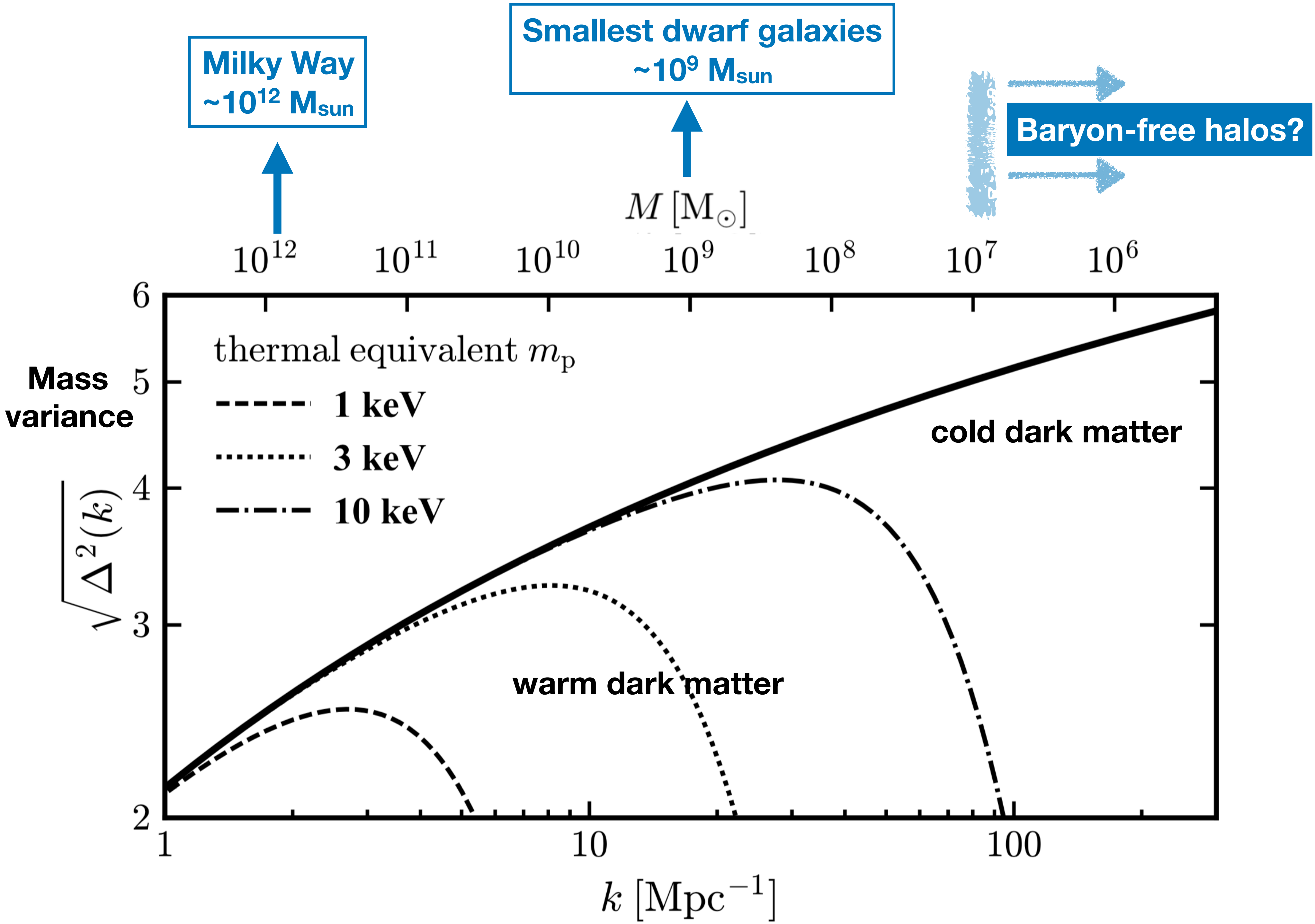
LCDM: CLUSTERING ON (QUASI) LINEAR SCALES



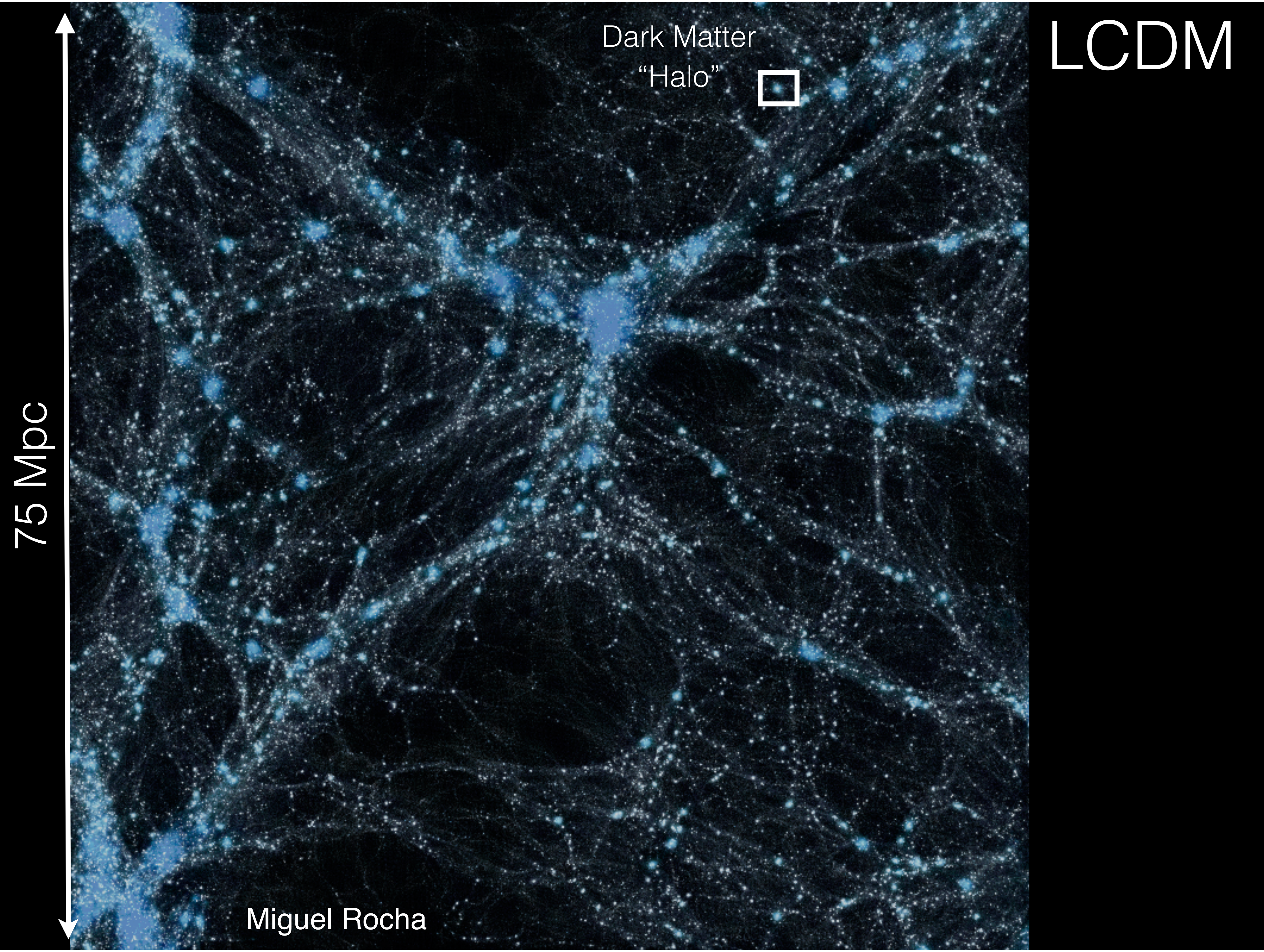
Dimensionless processed linear power spectrum (z=0):



JSB & Boylan-Kolchin, ARAA, 2017

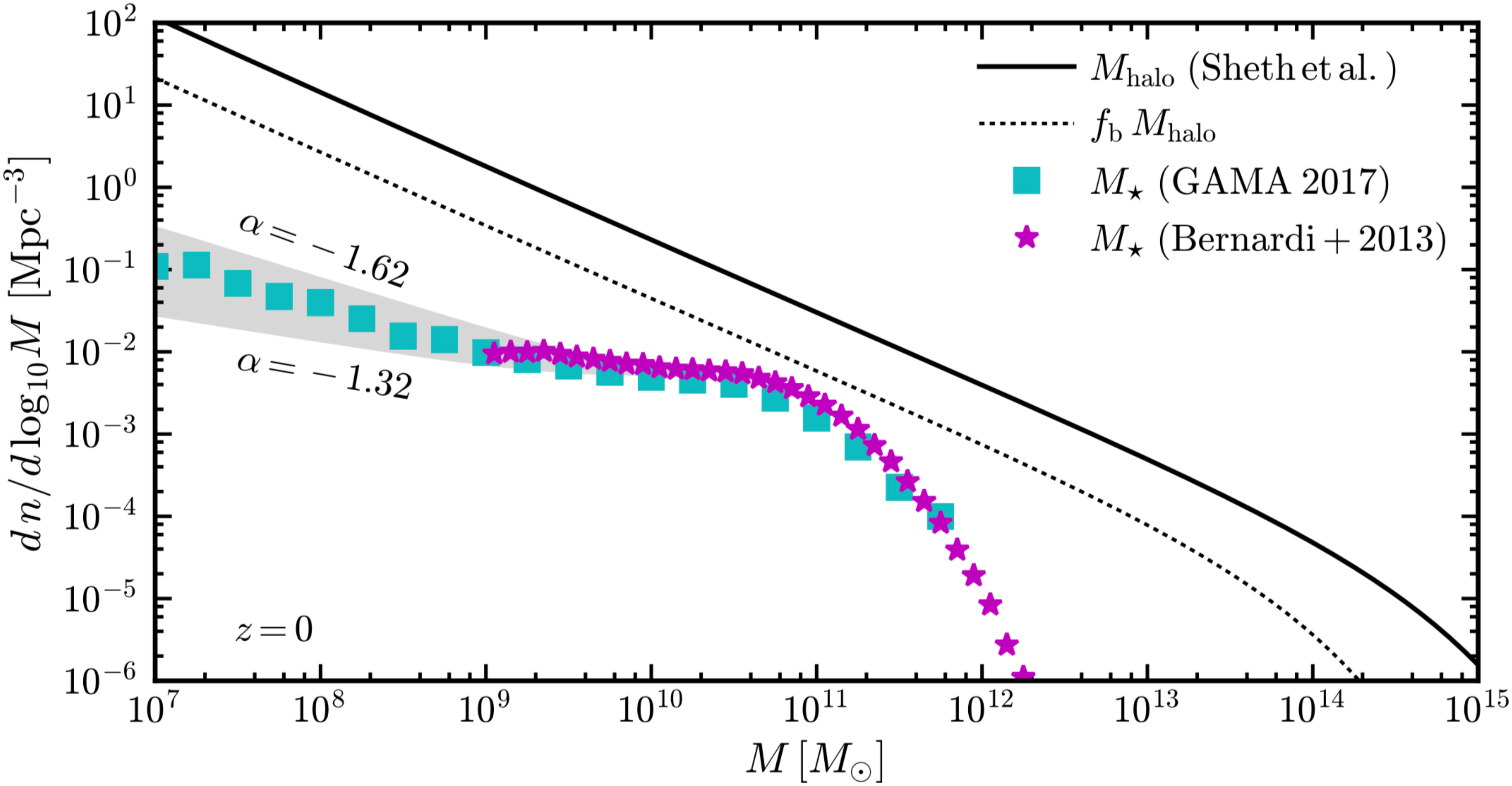


JSB & Boylan-Kolchin, ARAA, 2017



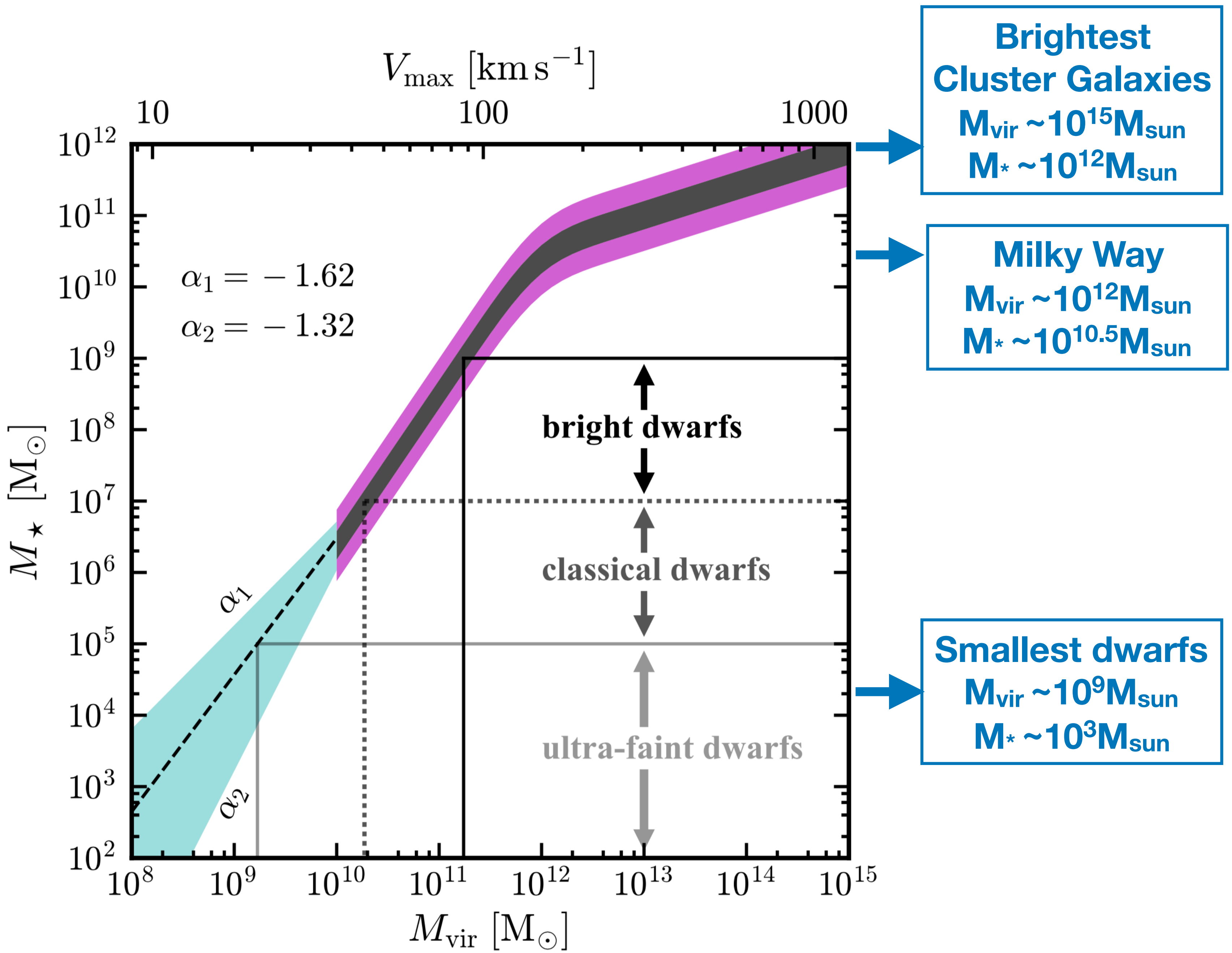
LCDM
Dark Matter
"Halo"
75 Mpc
Miguel Rocha

Dark Halo Mass Function vs. Stellar Mass Function



JSB & Boylan-Kolchin, ARAA, 2017

Abundance Matching

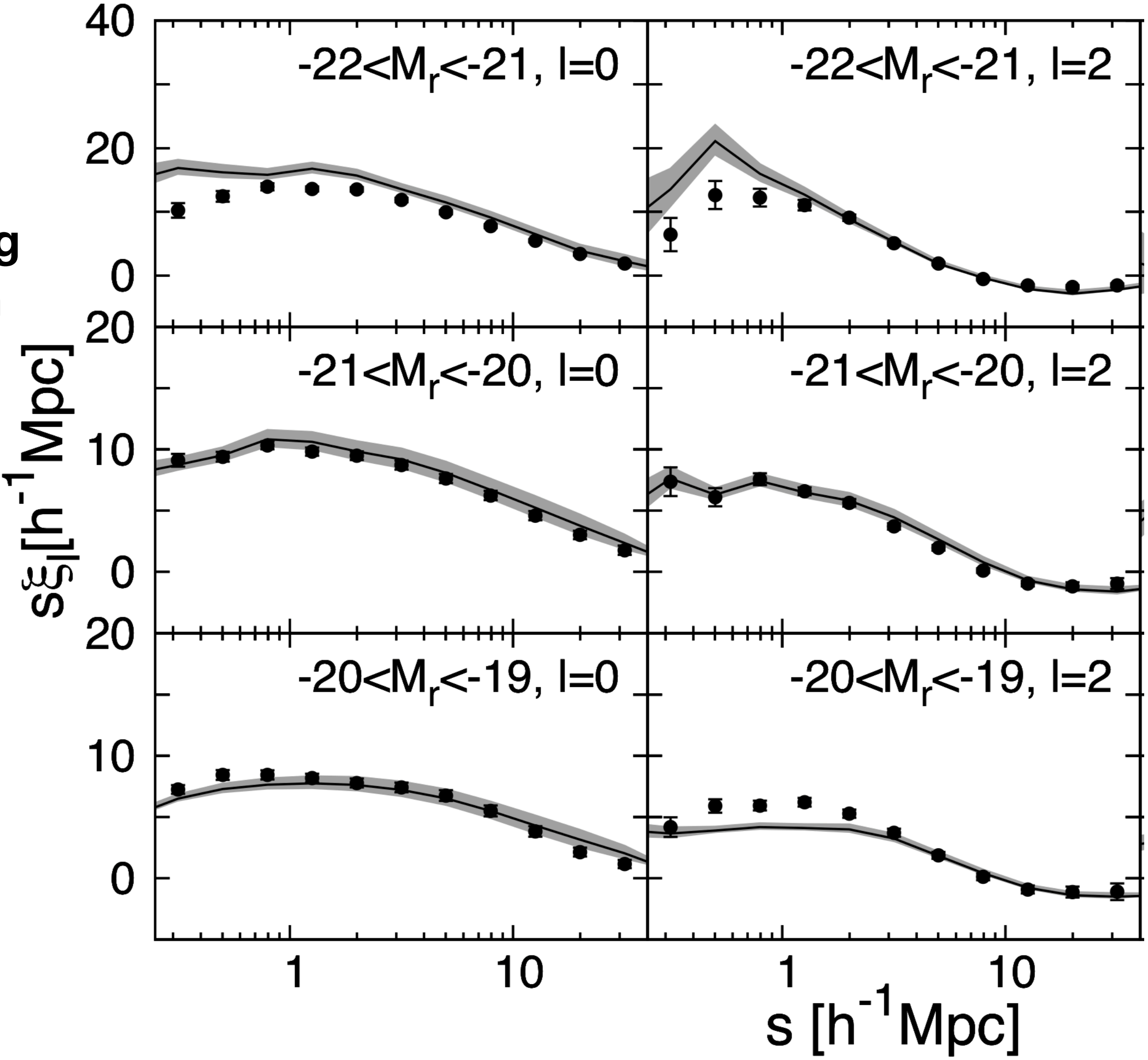


JSB & Boylan-Kolchin, ARAA, 2017

Abundance Matching <=> Clustering

multipole correlation functions sξl(s) (l = 0, 2): SDSS observations (symbols) vs. halo catalogs (lines)

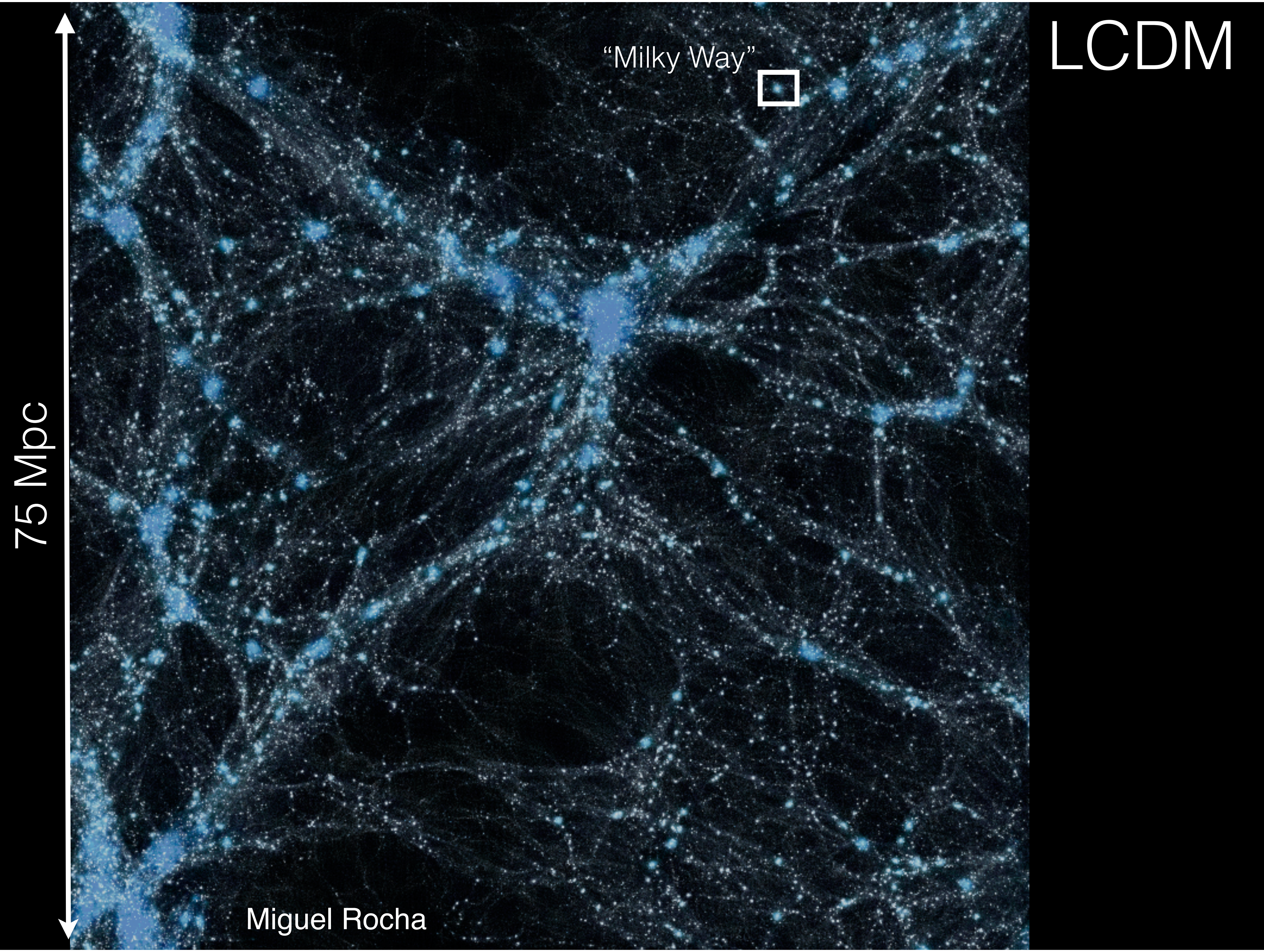
Clustering Strength

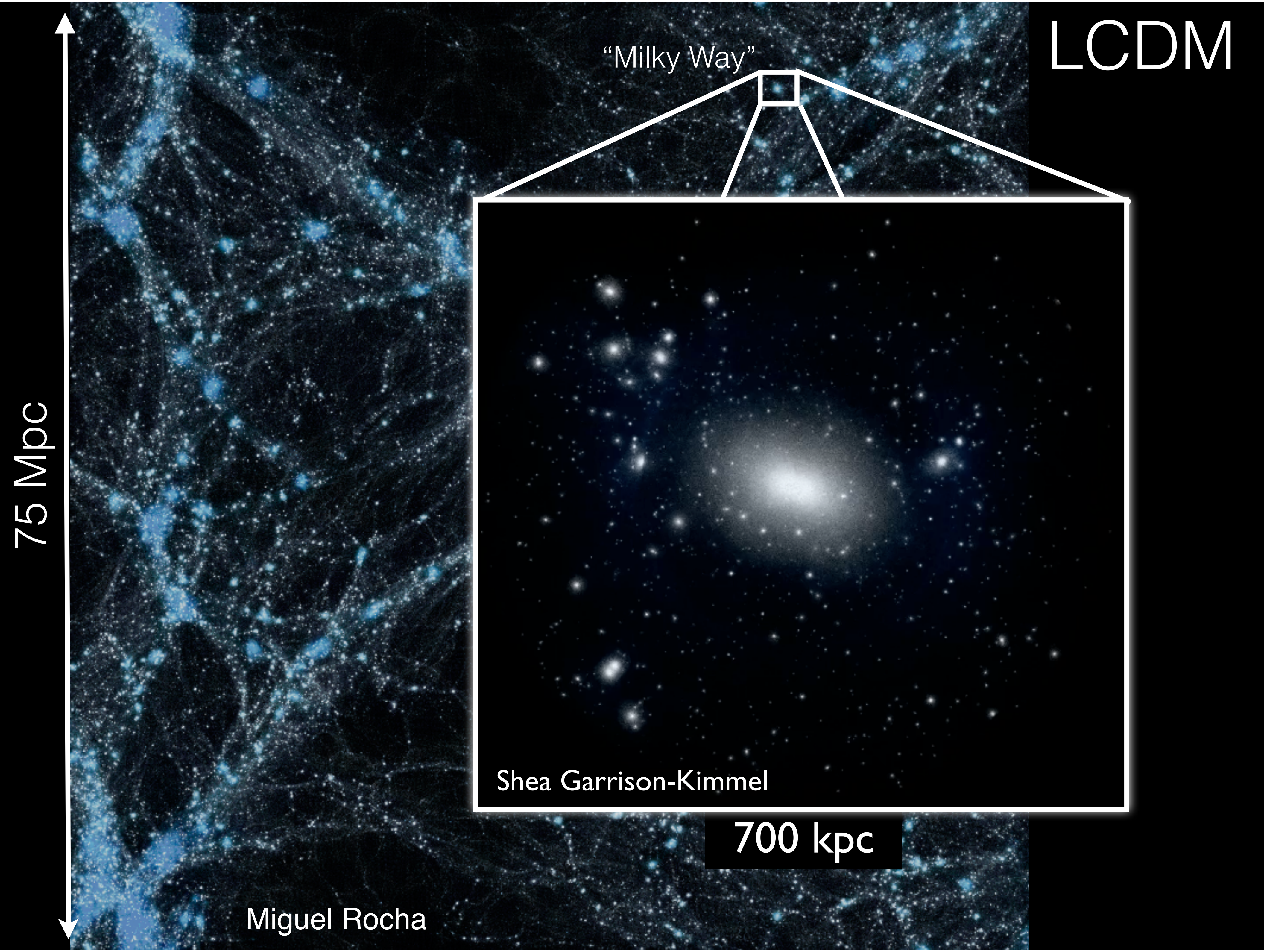


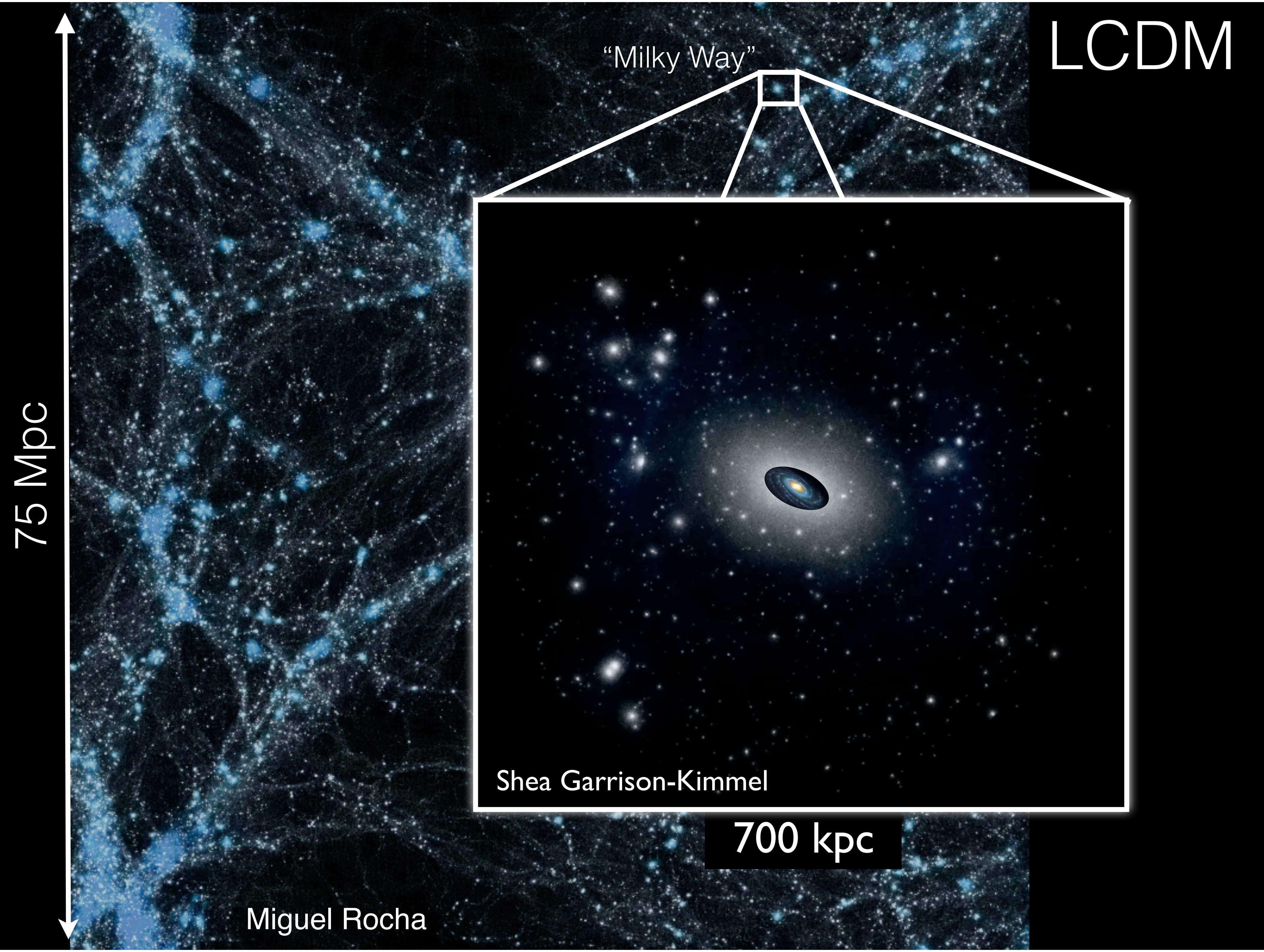
Bright galaxies (& big halos) -> more clustered

Faint galaxies (& small halos) -> less clustered

Yamamoto et al. 2015

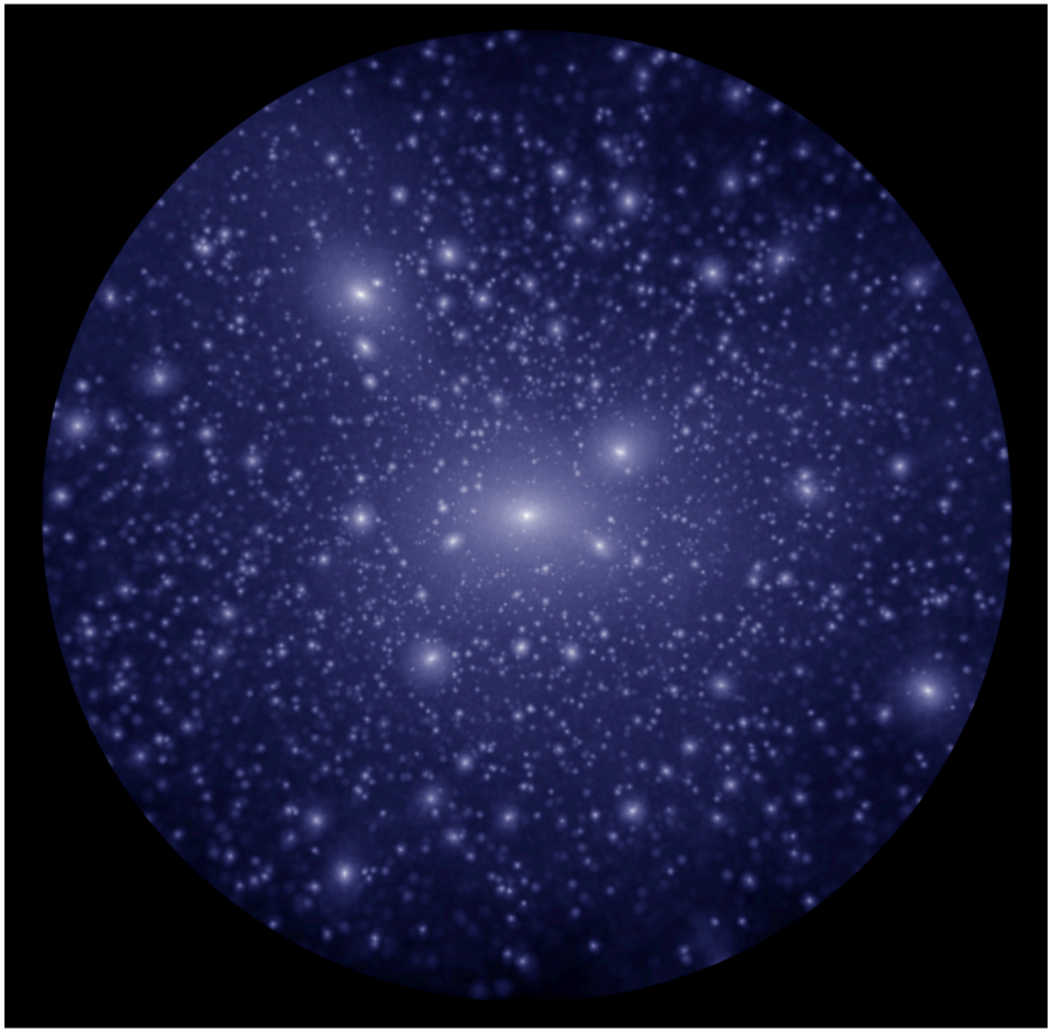

LCDM
"Milky Way"
75 Mpc
Miguel Rocha

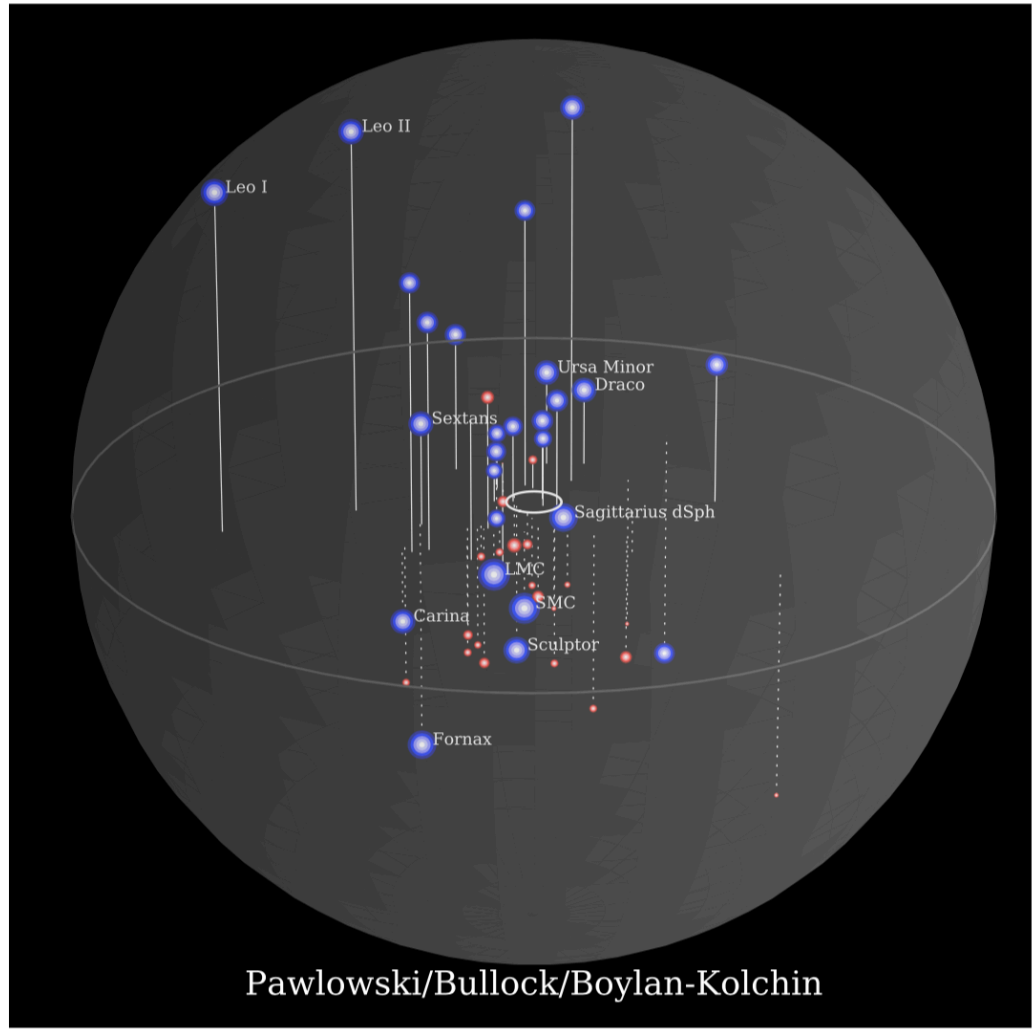

LCDM
"Milky Way"
75 Mpc
Shea Garrison-Kimmel
700 kpc
Miguel Rocha



LCDM
"Milky Way"
75 Mpc
Shea Garrison-Kimmel
700 kpc
Miguel Rocha

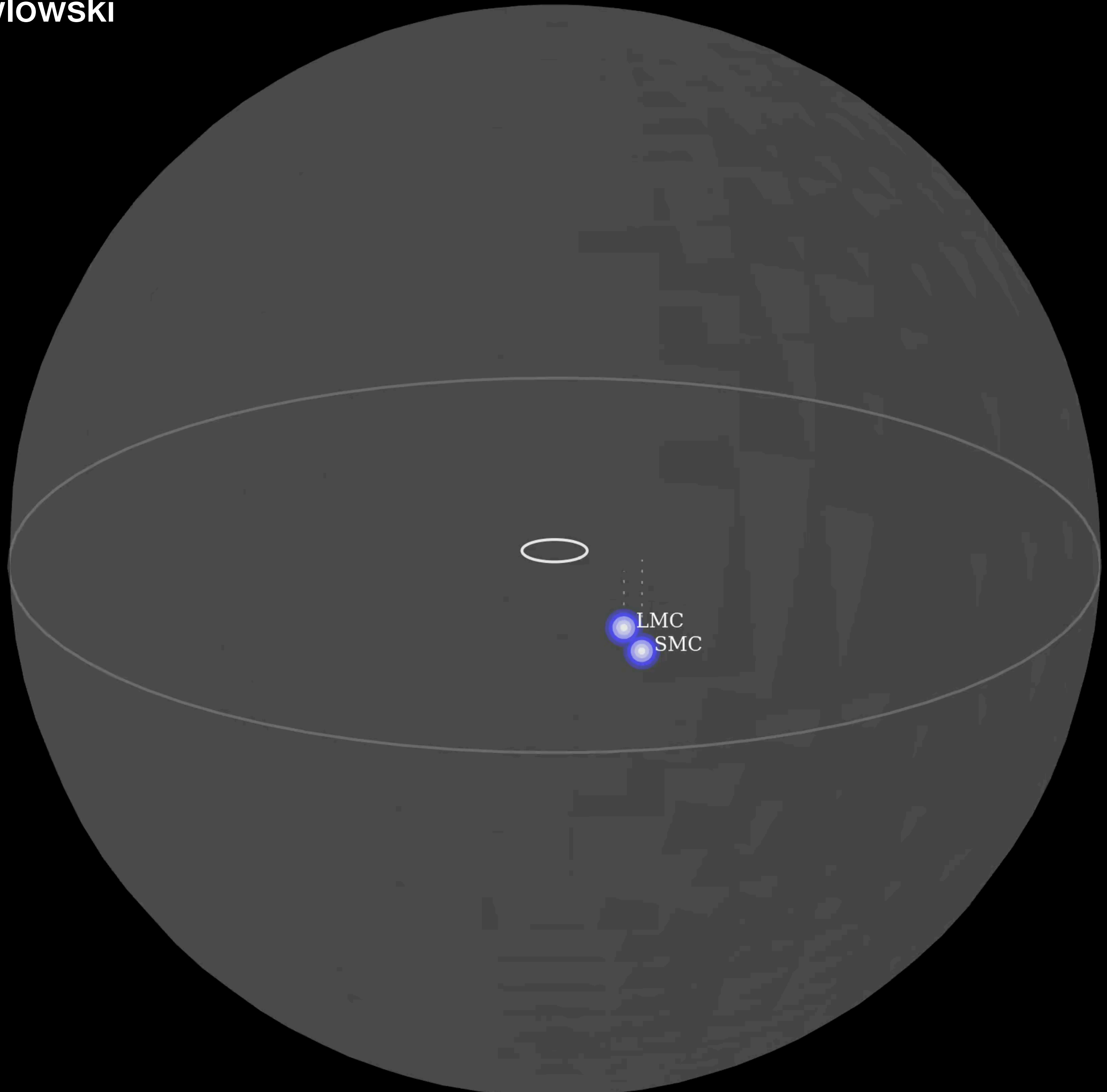
Missing Satellites Problem



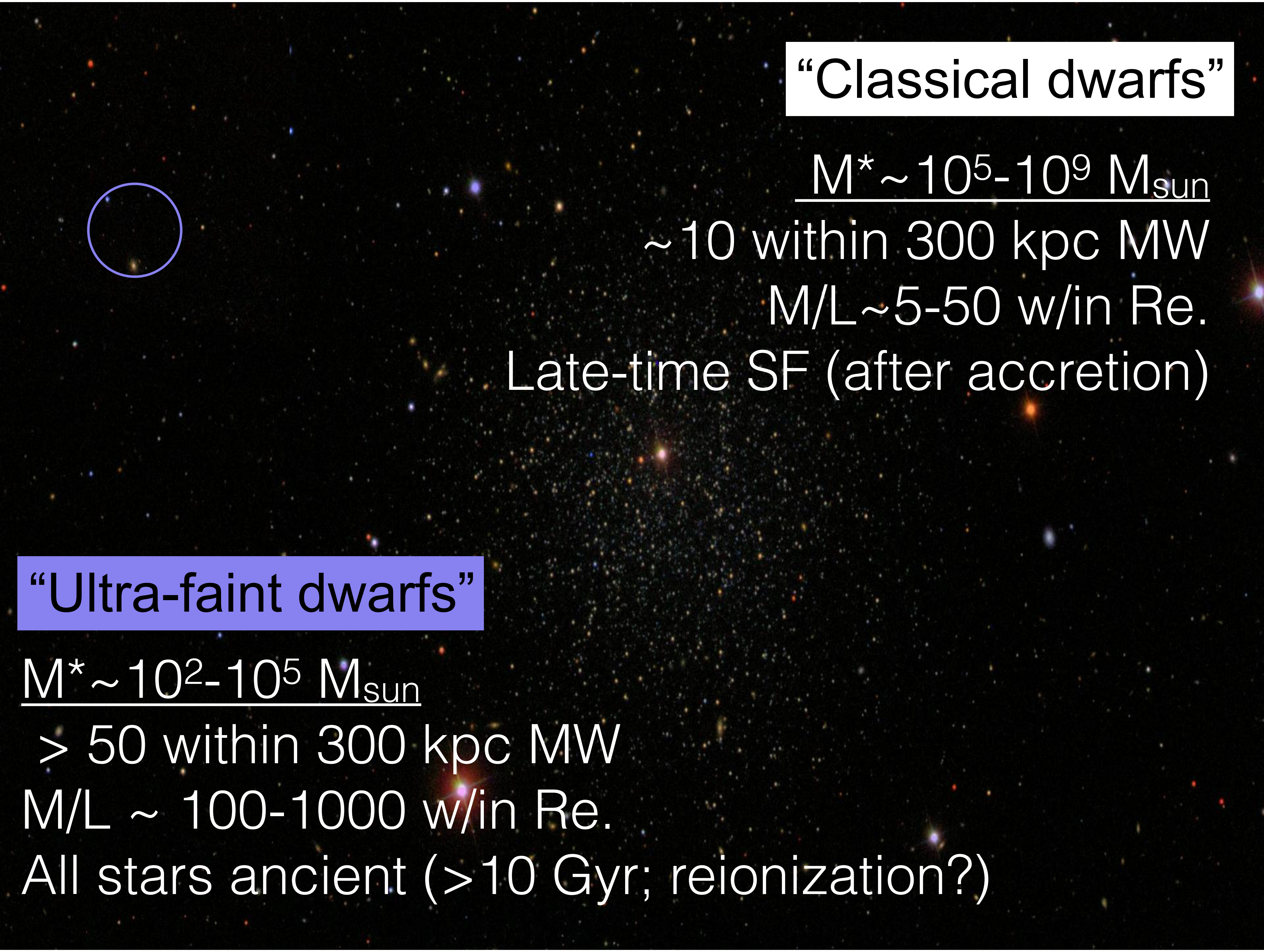


Klypin et al. 1999; Moore et al. 1999

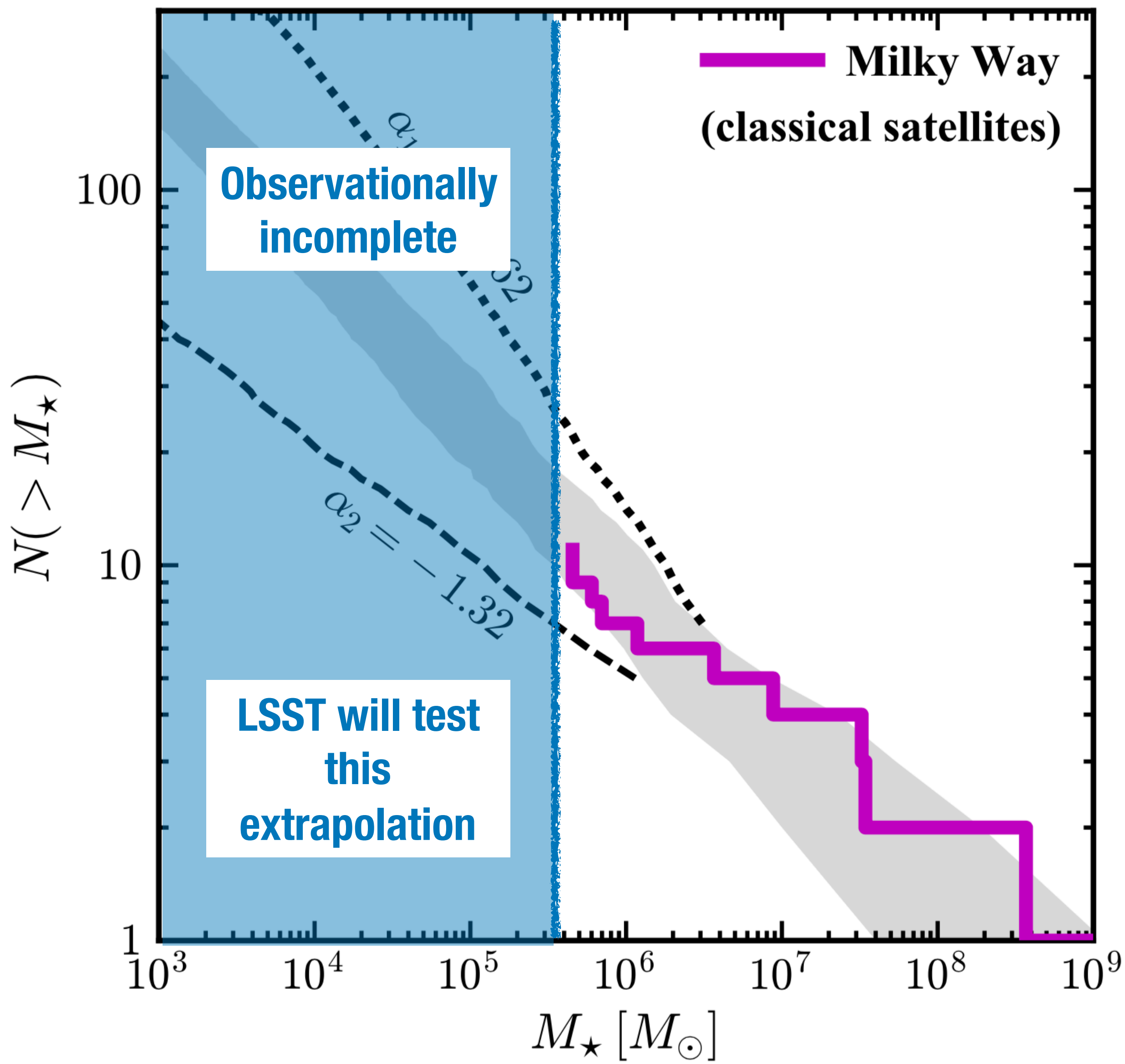
Movie: M. Pawlowski



Year 1916

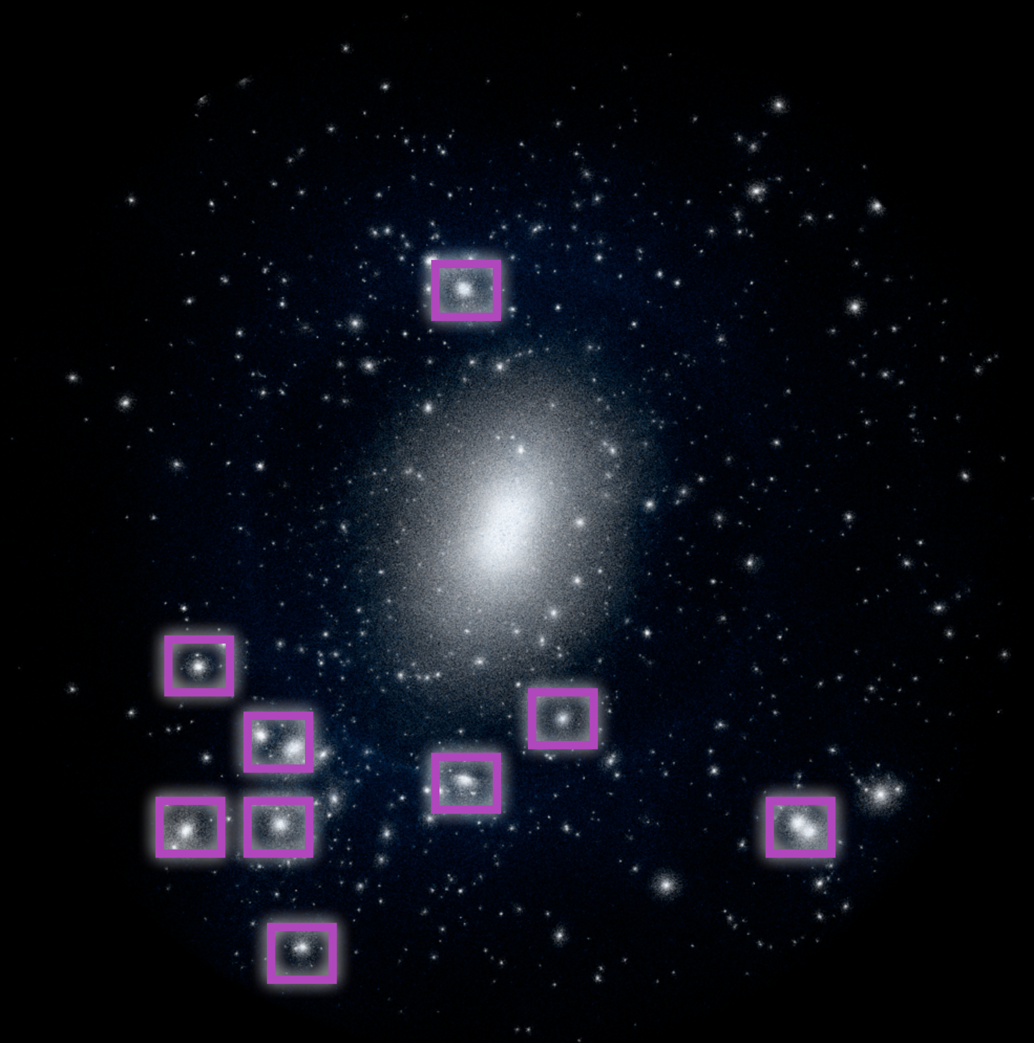

“Classical dwarfs”
$M^* \sim 10^5$-10^9 M_{sun}
~10 within 300 kpc MW
M/L~5-50 w/in Re.
Late-time SF (after accretion)
“Ultra-faint dwarfs”
$M^* \sim 10^2$-10^5 M_{sun}
> 50 within 300 kpc MW
M/L ~ 100-1000 w/in Re.
All stars ancient (>10 Gyr; reionization?)

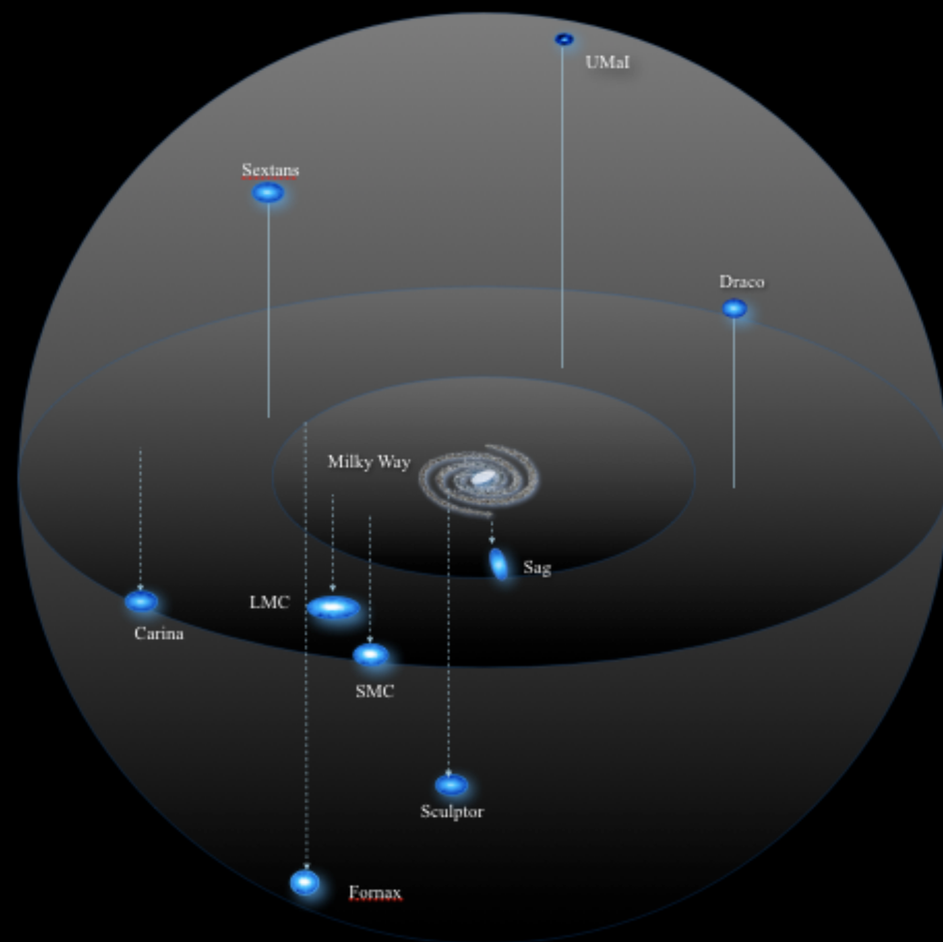
Assign halos stellar masses w abundance matching => 'solve' missing satellites



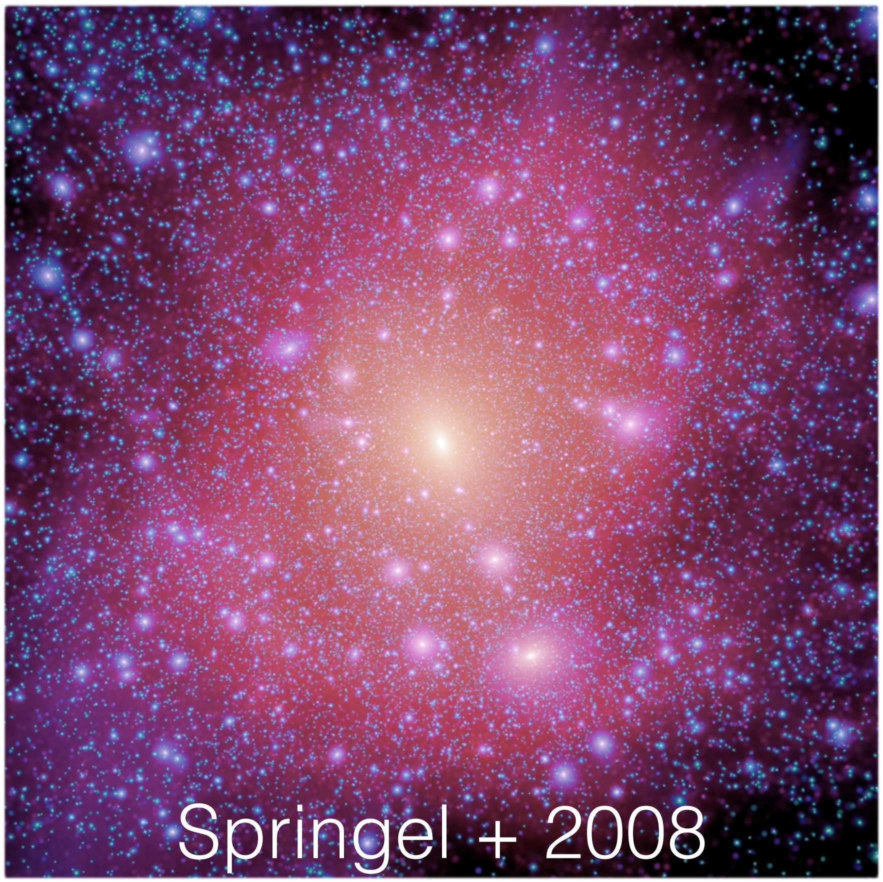
JSB & Boylan-Kolchin, ARAA, 2017

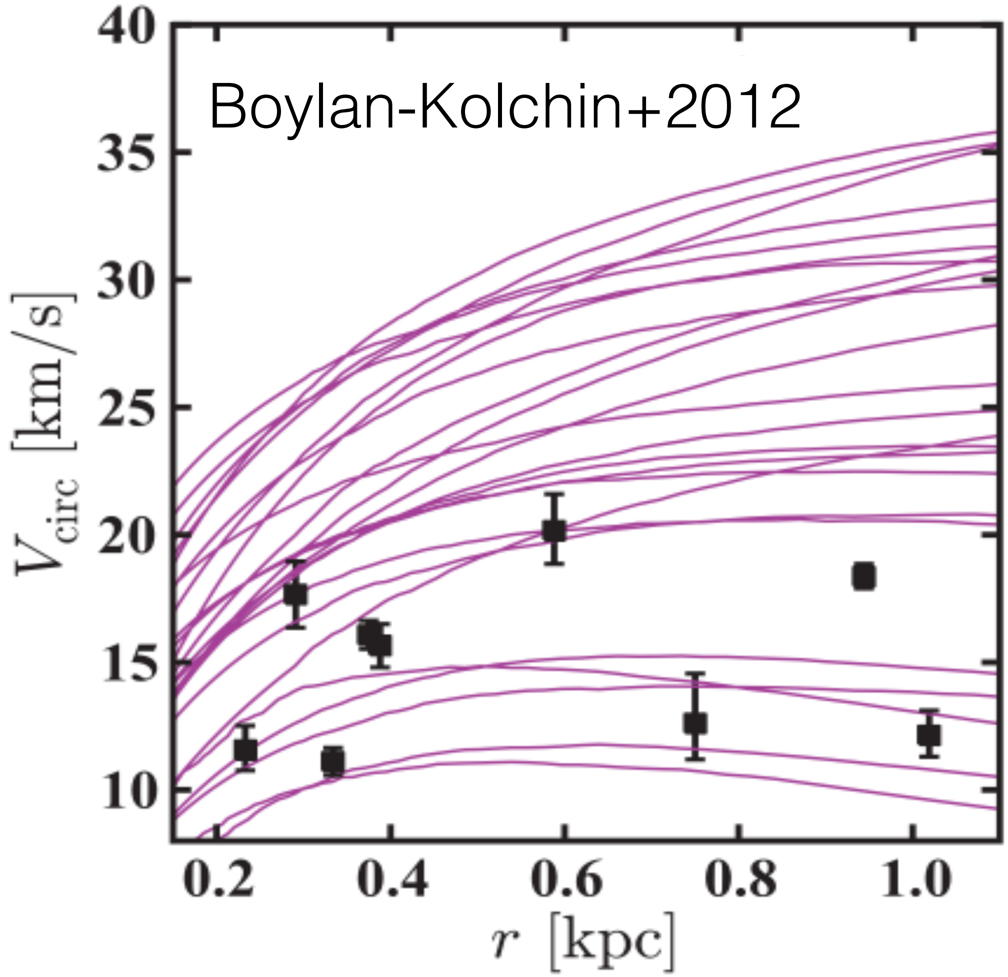
DOES THIS ACTUALLY WORK?



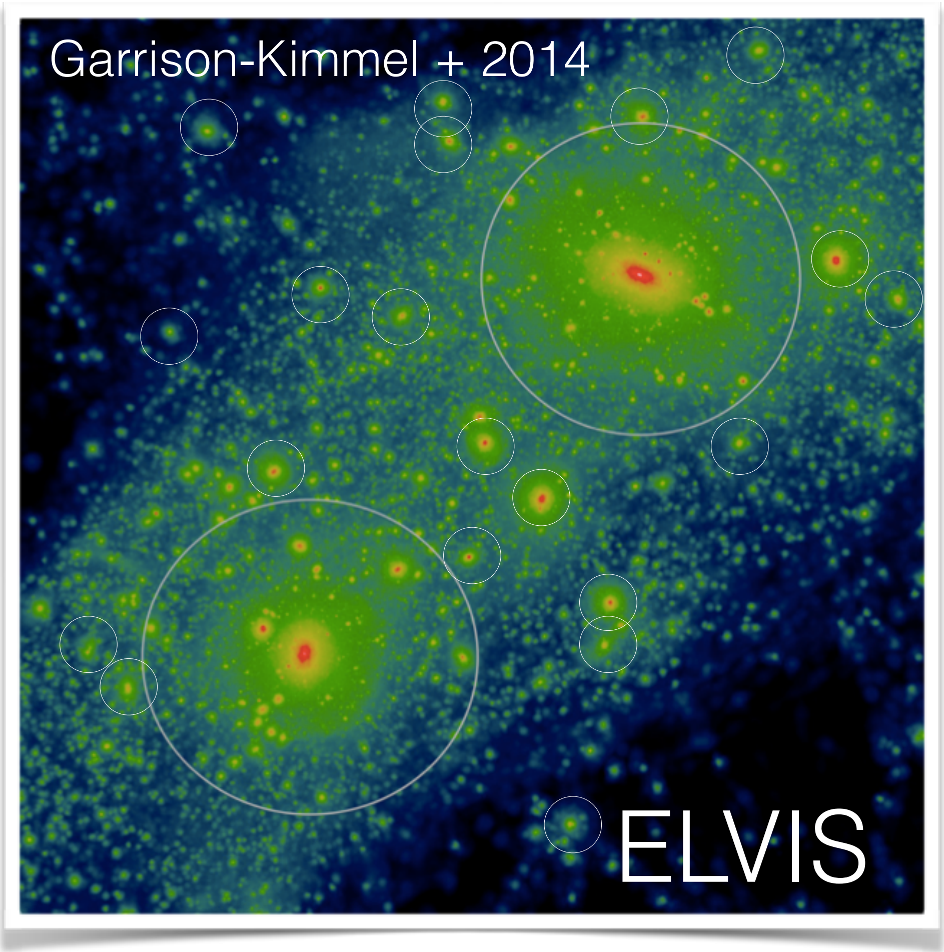


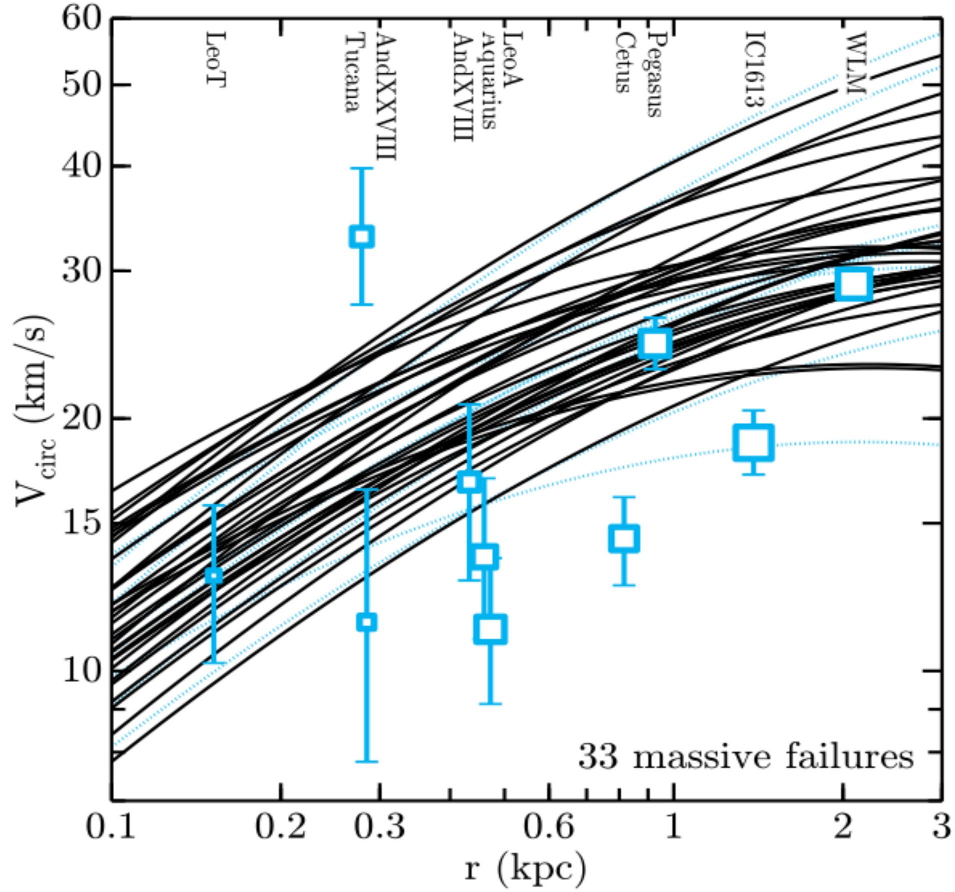
TOO BIG TO FAIL IN THE MILKY WAY



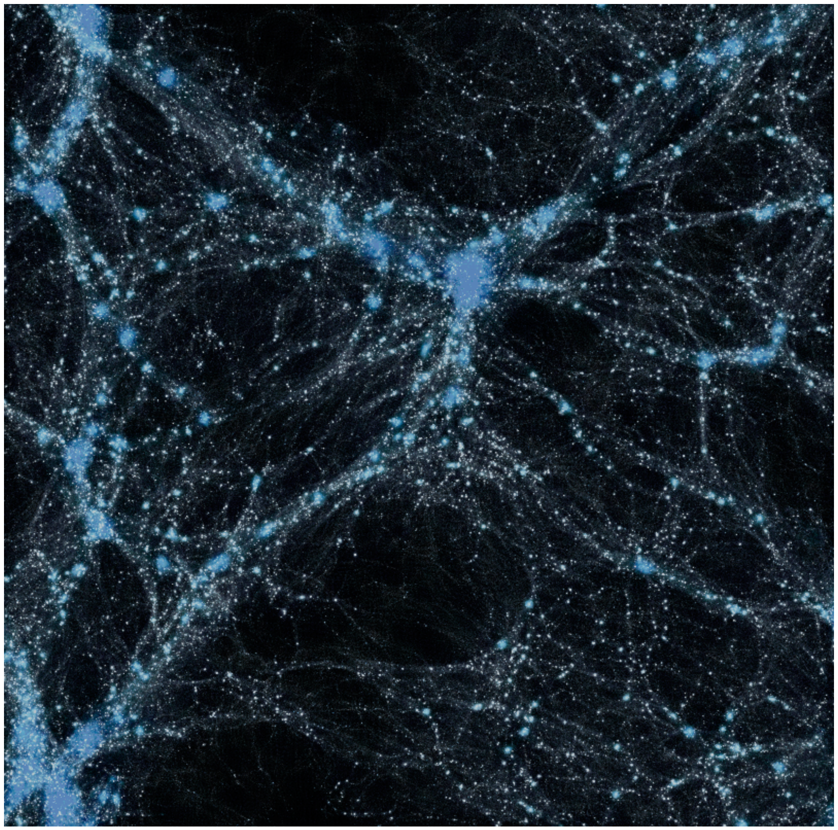


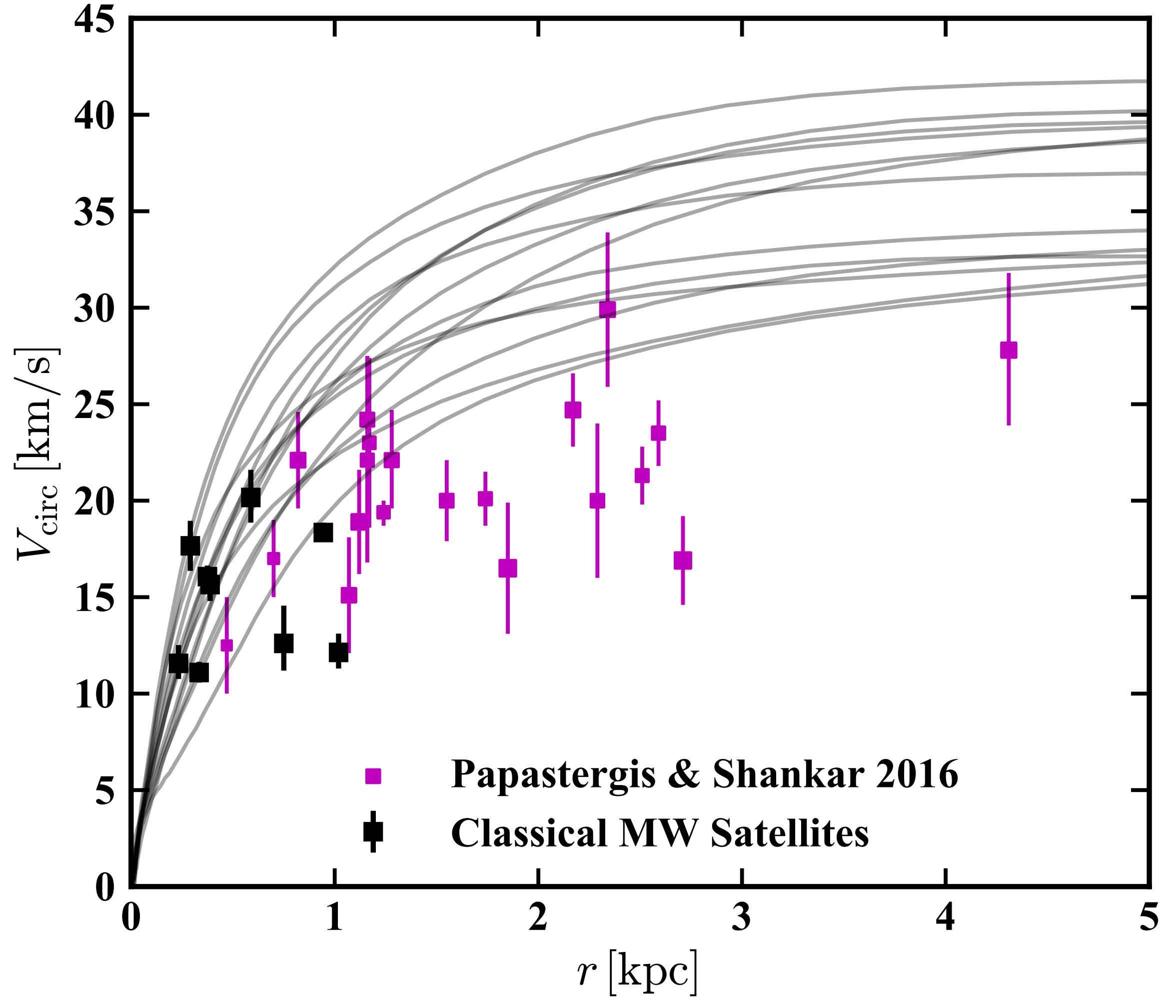
TOO BIG TO FAIL IN THE LOCAL GROUP





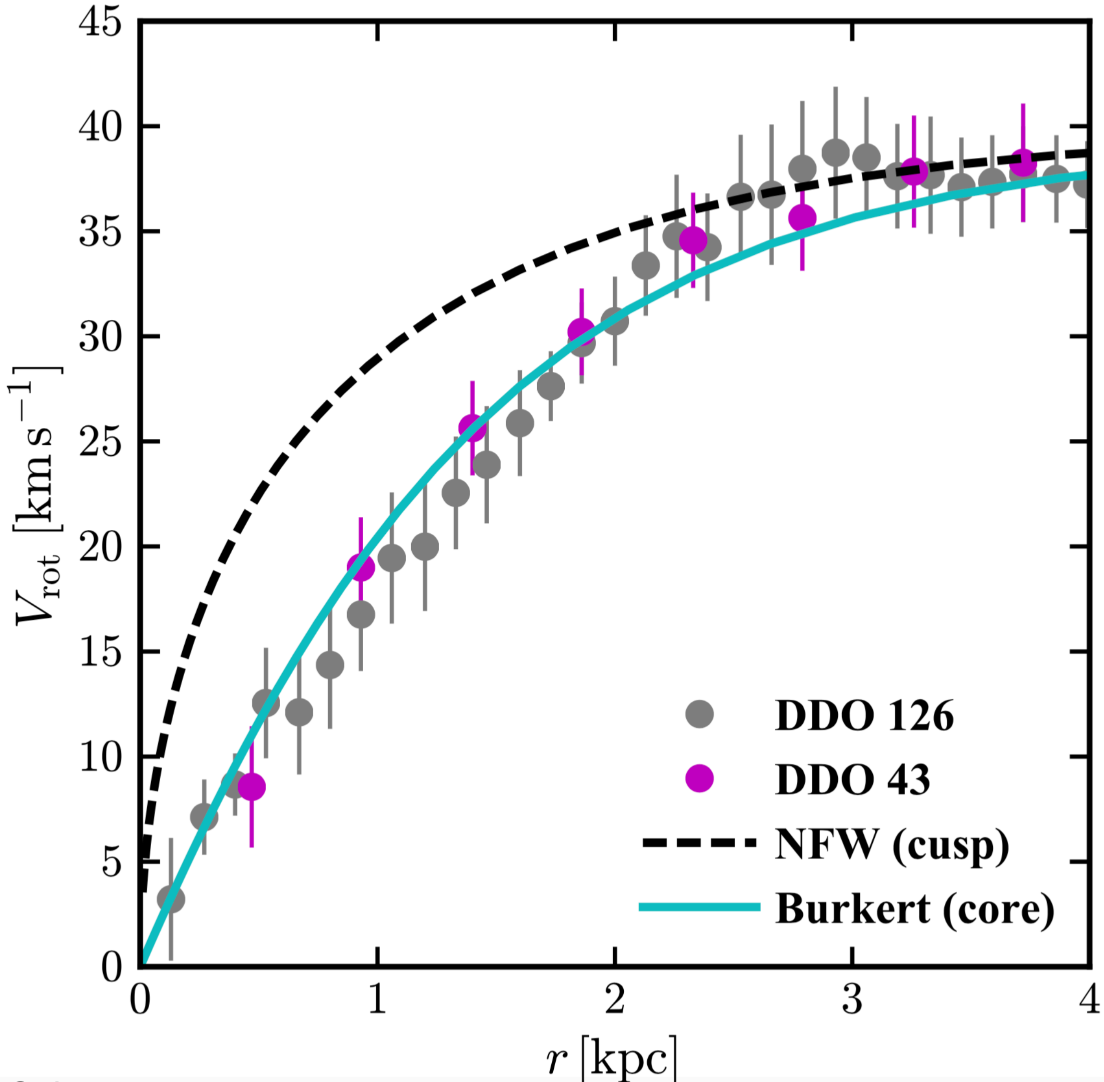
TOO BIG TO FAIL IN THE FIELD





JSB & Boylan-Kolchin, ARAA, 2017

Cusp/Core Problem



Flores & Primack 94;
Moore 94

QUESTION

Do we need to change dark matter physics?

Self-interacting Dark Matter?
Warm Dark Matter?
Ultra-light Scalar Field Dark Matter?

Or does astrophysics / feedback solve problems?

STAR FORMATION & FEEDBACK

Star formation + Radiation pressure

Stellar winds

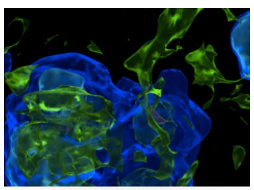
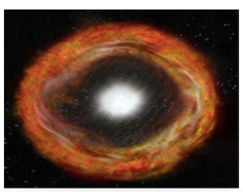


Photo-Ionization

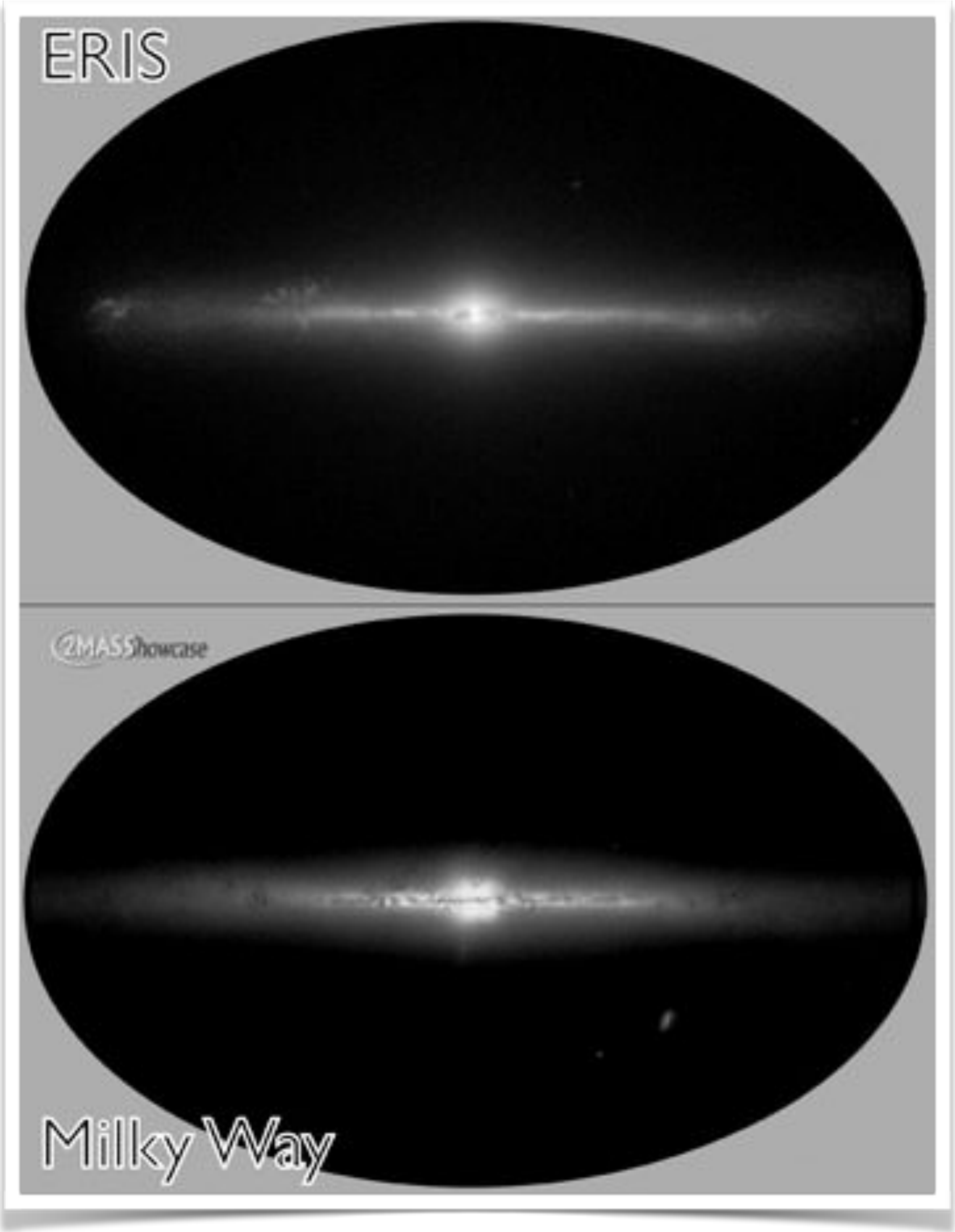


Supernovae: Impart energy & momentum

Active Galactic Nuclei

All require 'sub grid' recipes

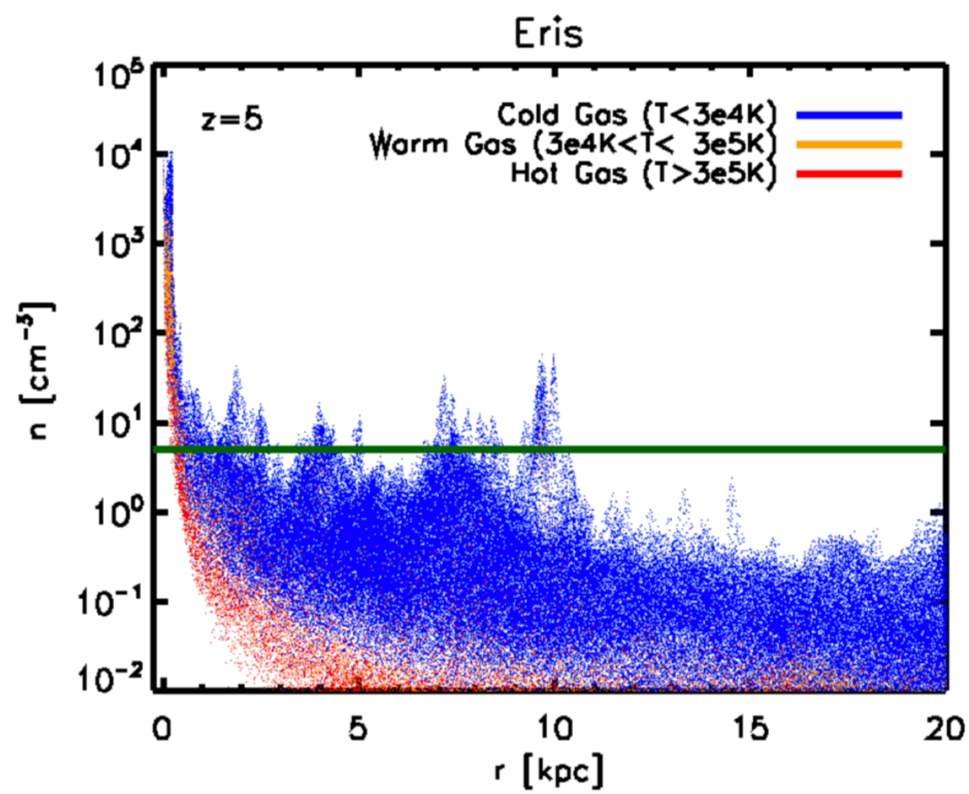
“Zoom Simulations”



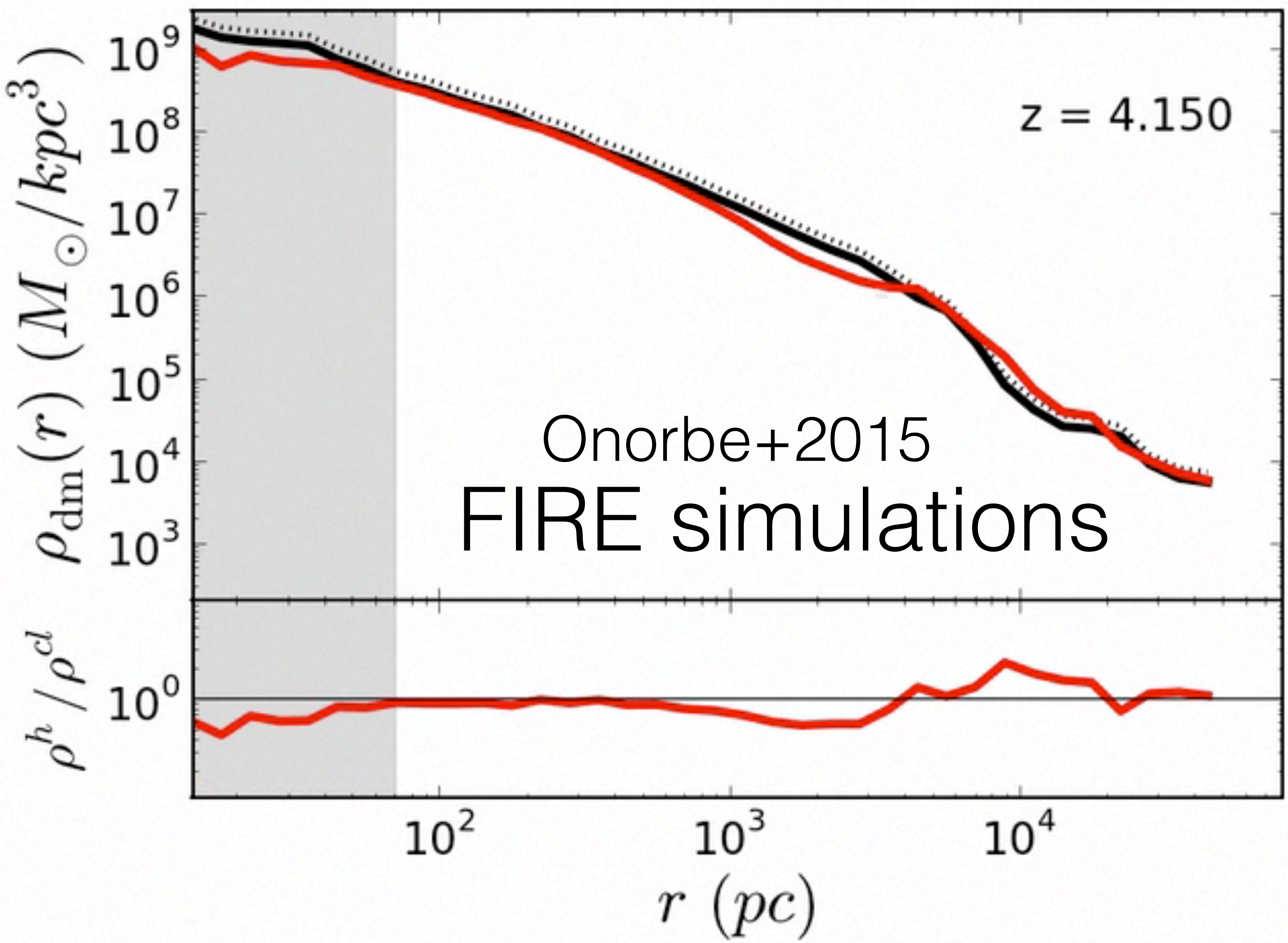
Guedes et al. (2011)

Zoom simulations can resolve densities typical of real star forming regions.

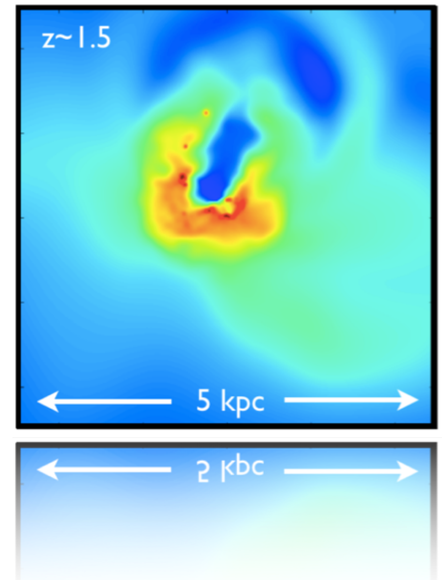
- **star formation is more “bursty”**
- **feedback and galaxy structure ends up being more realistic**



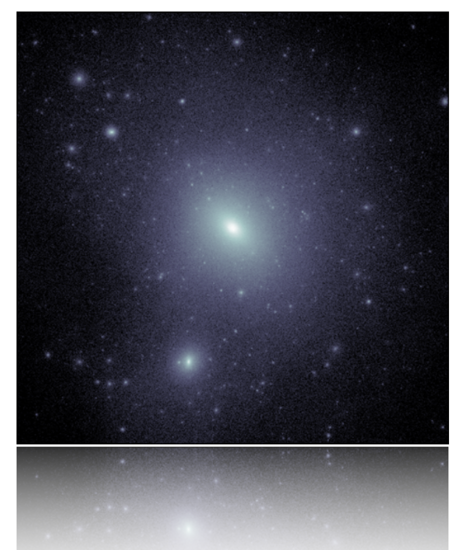
FEEDBACK CAN ALTER DM STRUCTURE



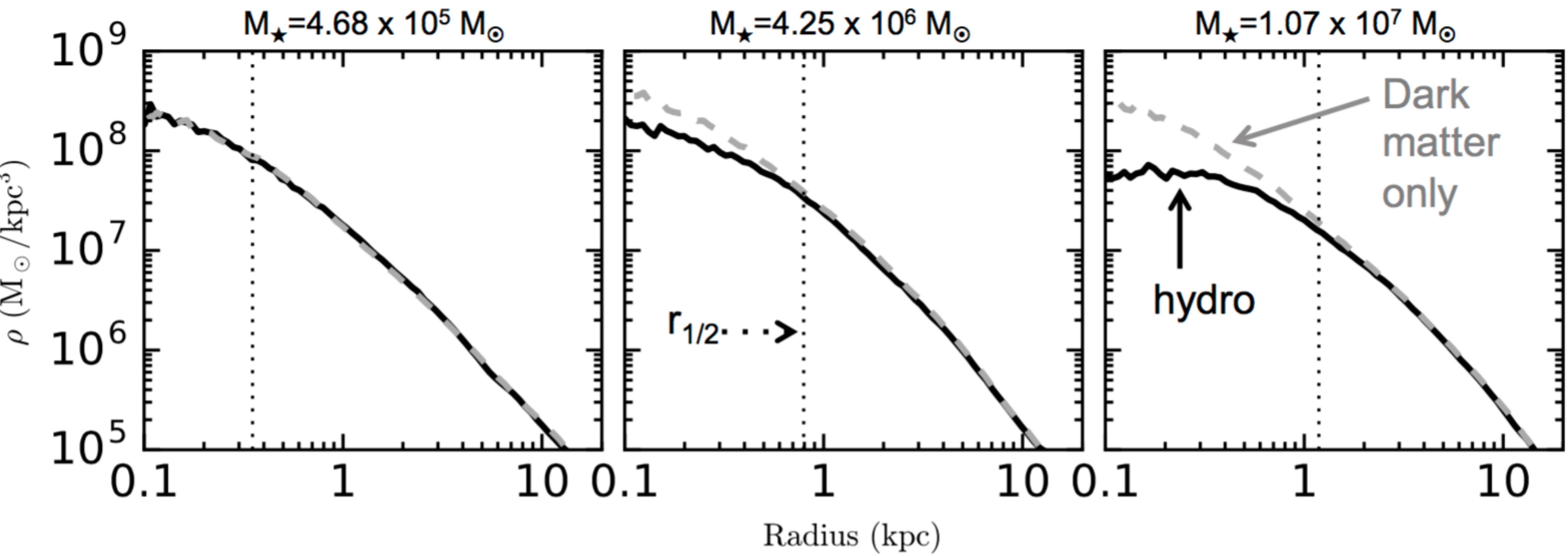
Red = Hydro



Black = only DM

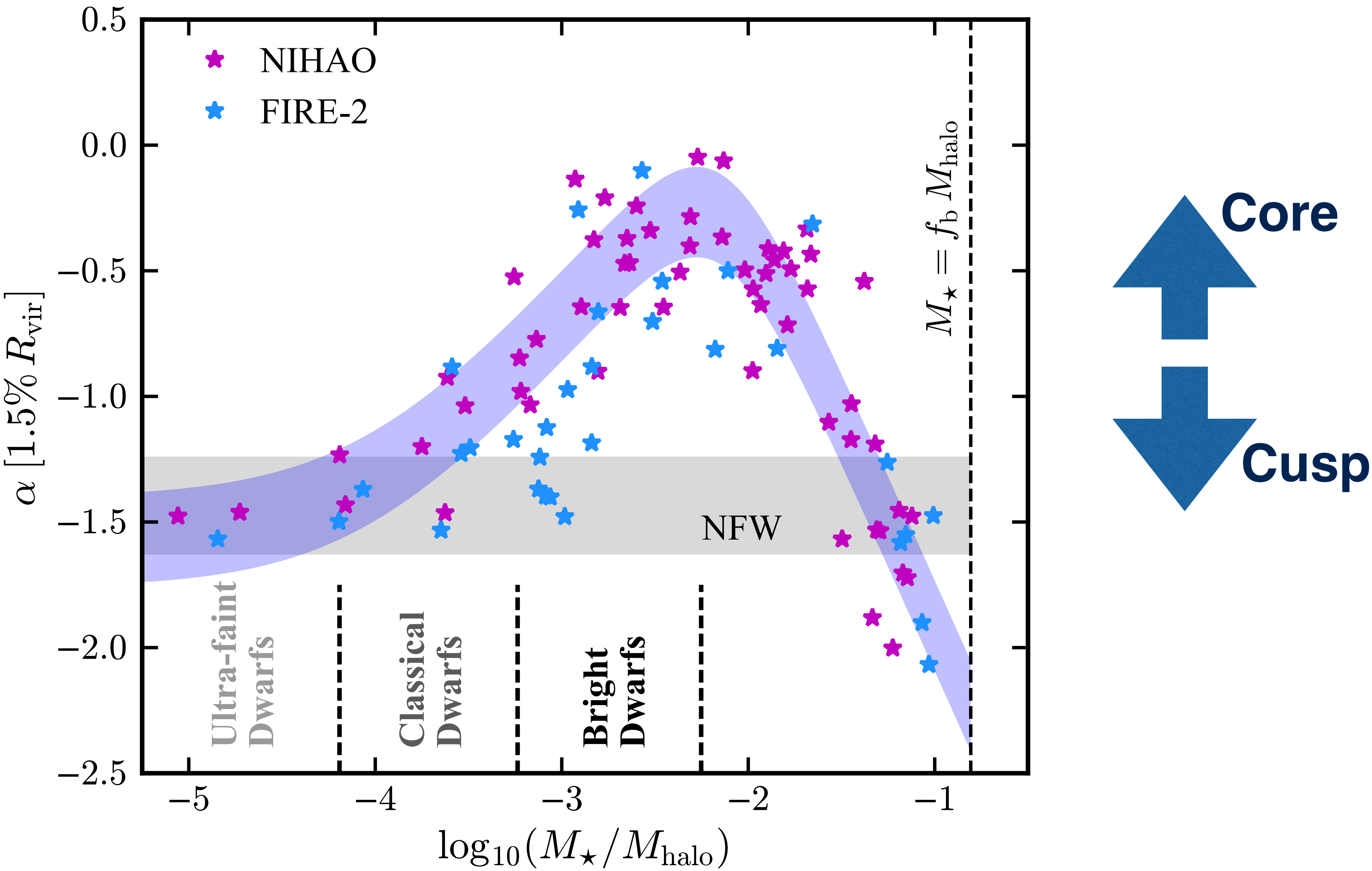


Need >3.e6M_{sun} stars to affect DM density profile



Fitts et al. 2017

Agreement among frienemies



JSB & Boylan-Kolchin, ARAA, 2017

Feedback?

Below $M_{\star} \sim 10^6 \, M_{\odot}$ may not be enough energy from SN to alter DM structure

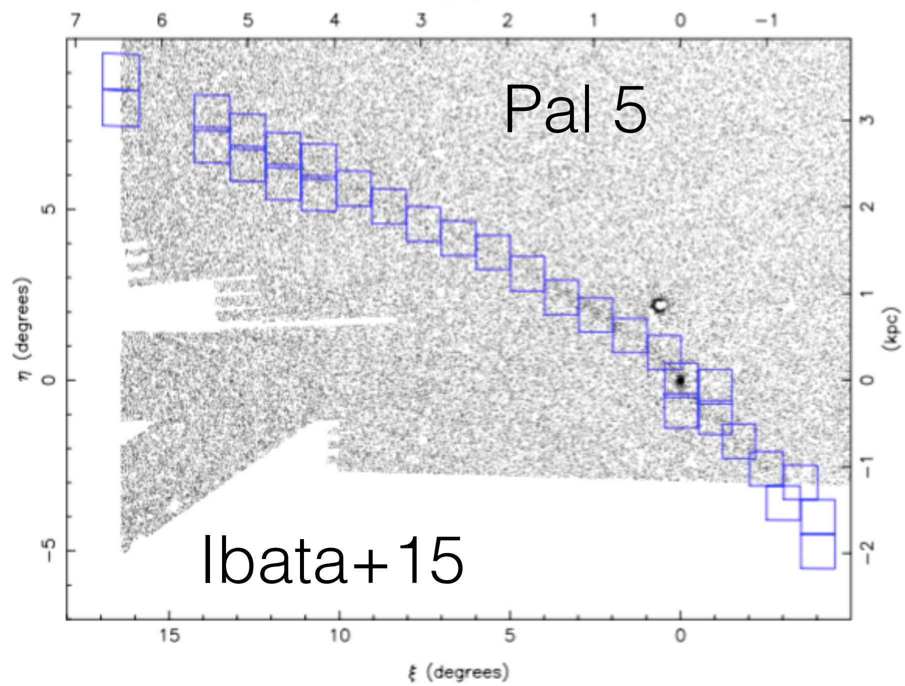
- Precise scale of 'Too Big to Fail'
- Many core-like rotation curves

- can we understand why low stellar mass galaxies seem to have low DM content?

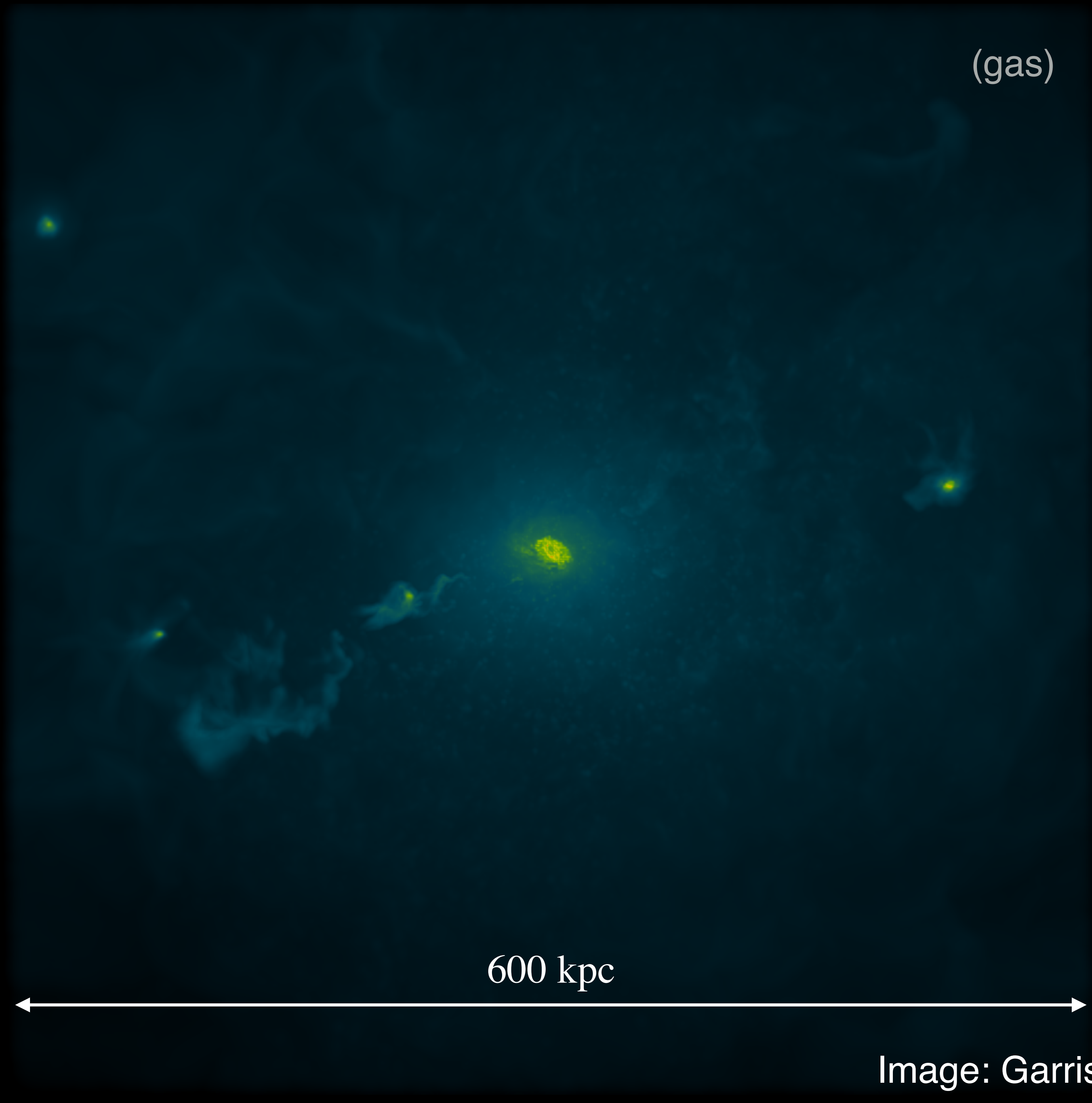
Towards finding **dark** substructure

- Gravitational Lensing - detections ongoing, bright future.
  - Vegetti+12 (gravitational imaging)
  - MacLeod+13;Nierenberg+14 (flux ratios)
  - Hezaveh+13,16 (spatially resolves spectroscopy w/ ALMA)
  - EUCLID (&SKA) should increase sample size of lenses tremendously compared to small sample now.

- Stream heating/punching around Milky Way
  - Erkal & Belokurov 15, Bovy +16; Sanderson



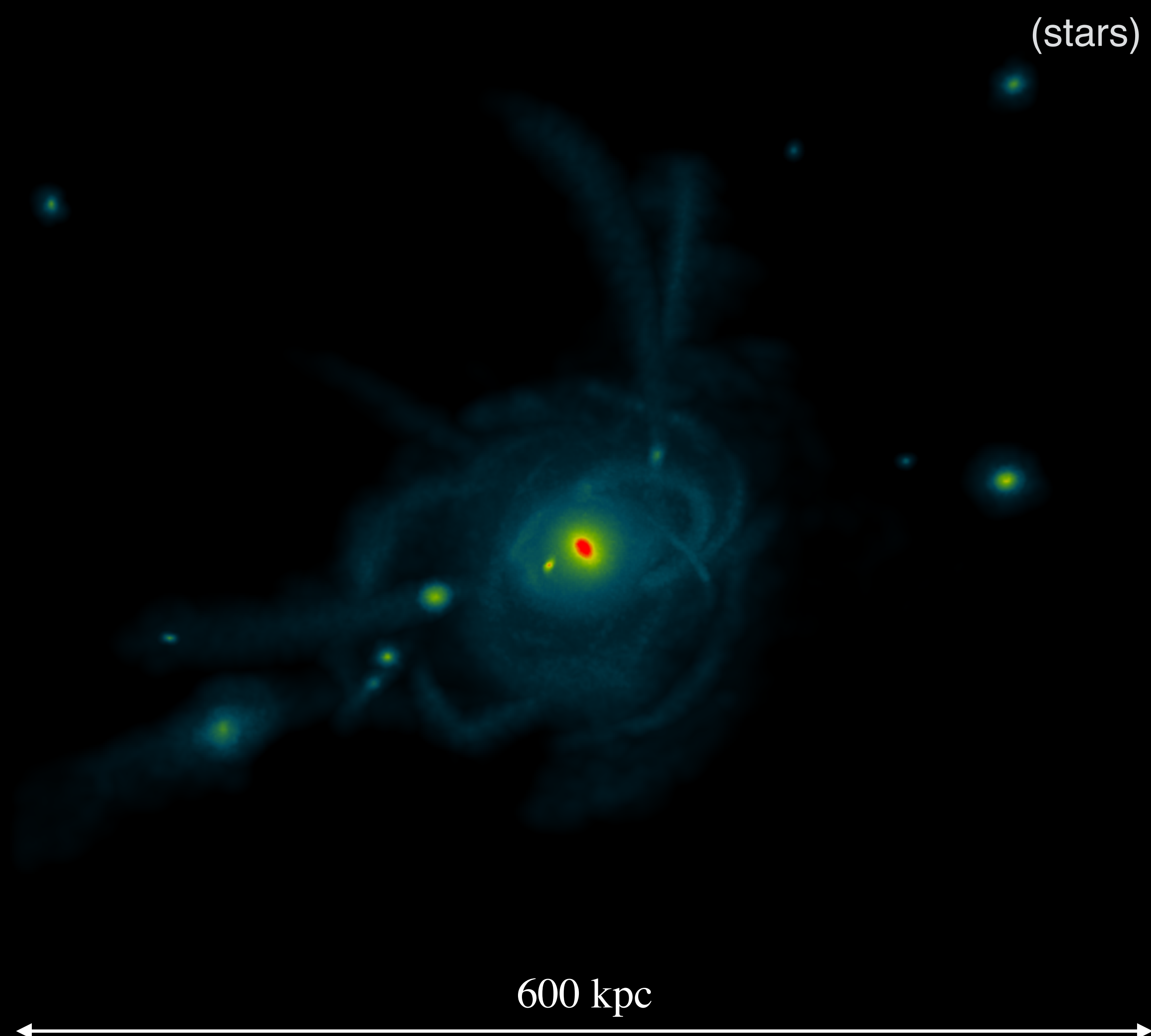
Latte Project: the Milky Way on FIRE (Feedback in Realistic Environments)



Wetzel+2016

Image: Garrison-Kimmel

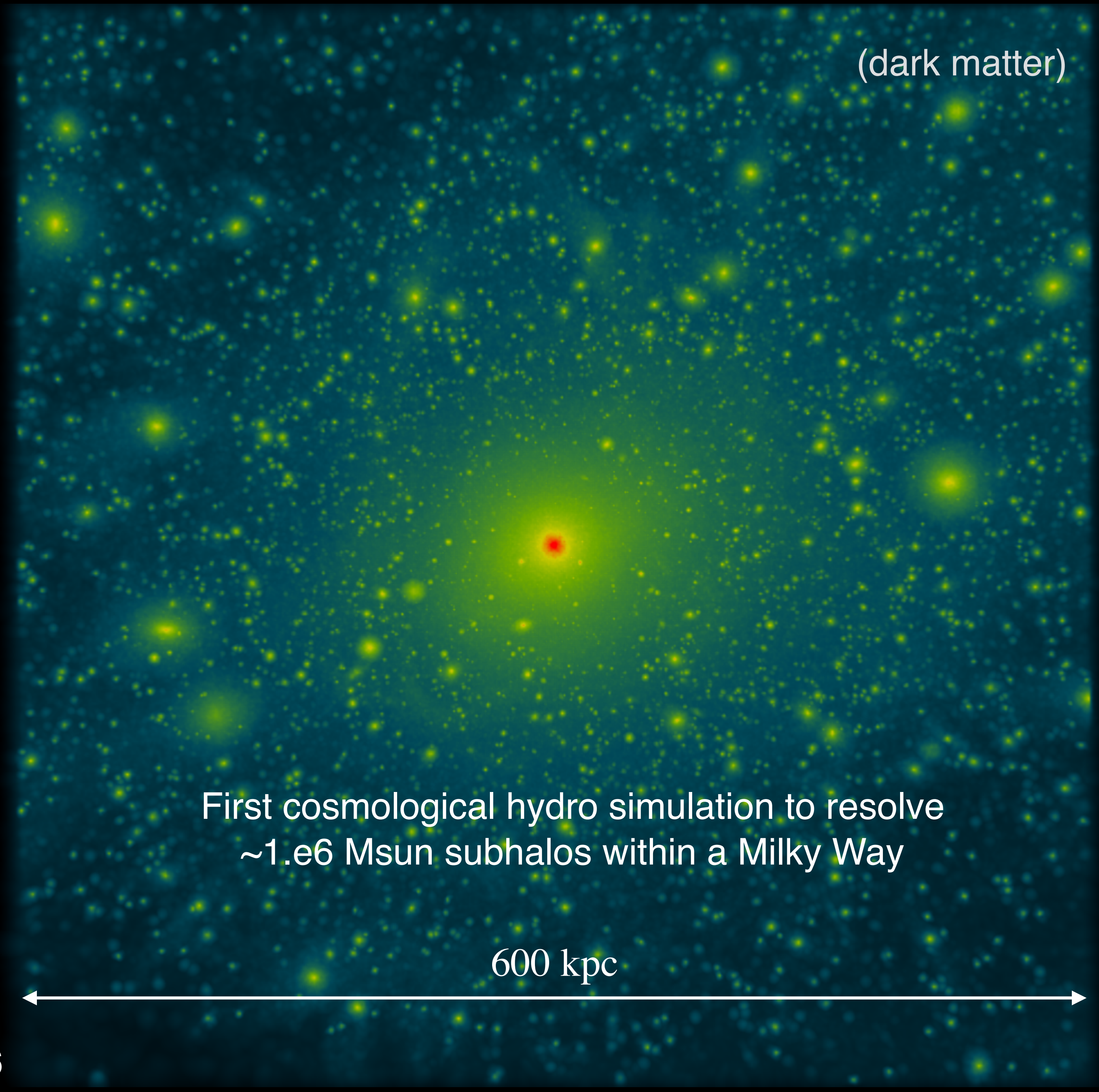
Latte Project: the Milky Way on FIRE (Feedback in Realistic Environments)



Wetzel+2016

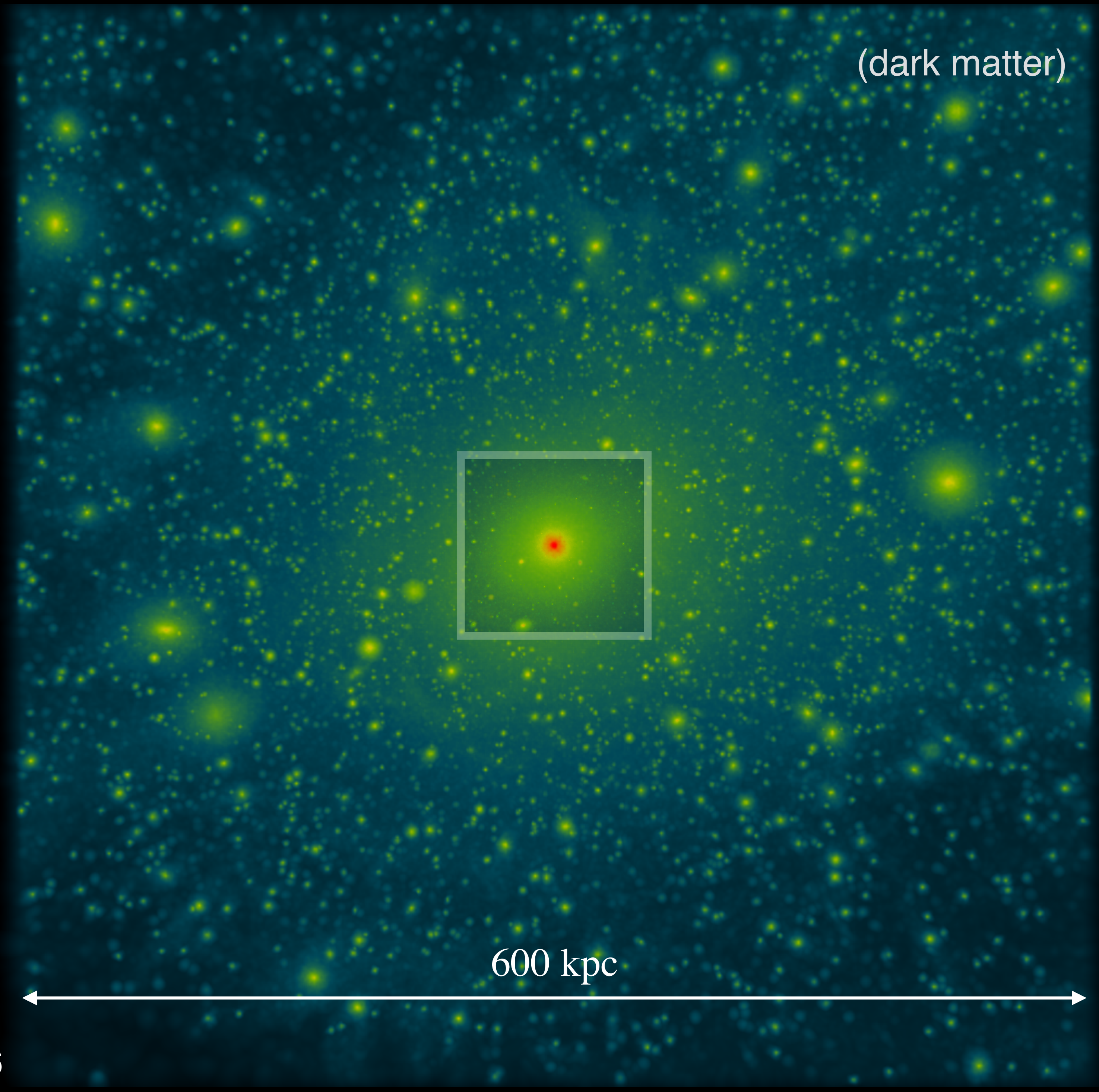
Image: Garrison-Kimmel

Latte Project: the Milky Way on FIRE (Feedback in Realistic Environments)



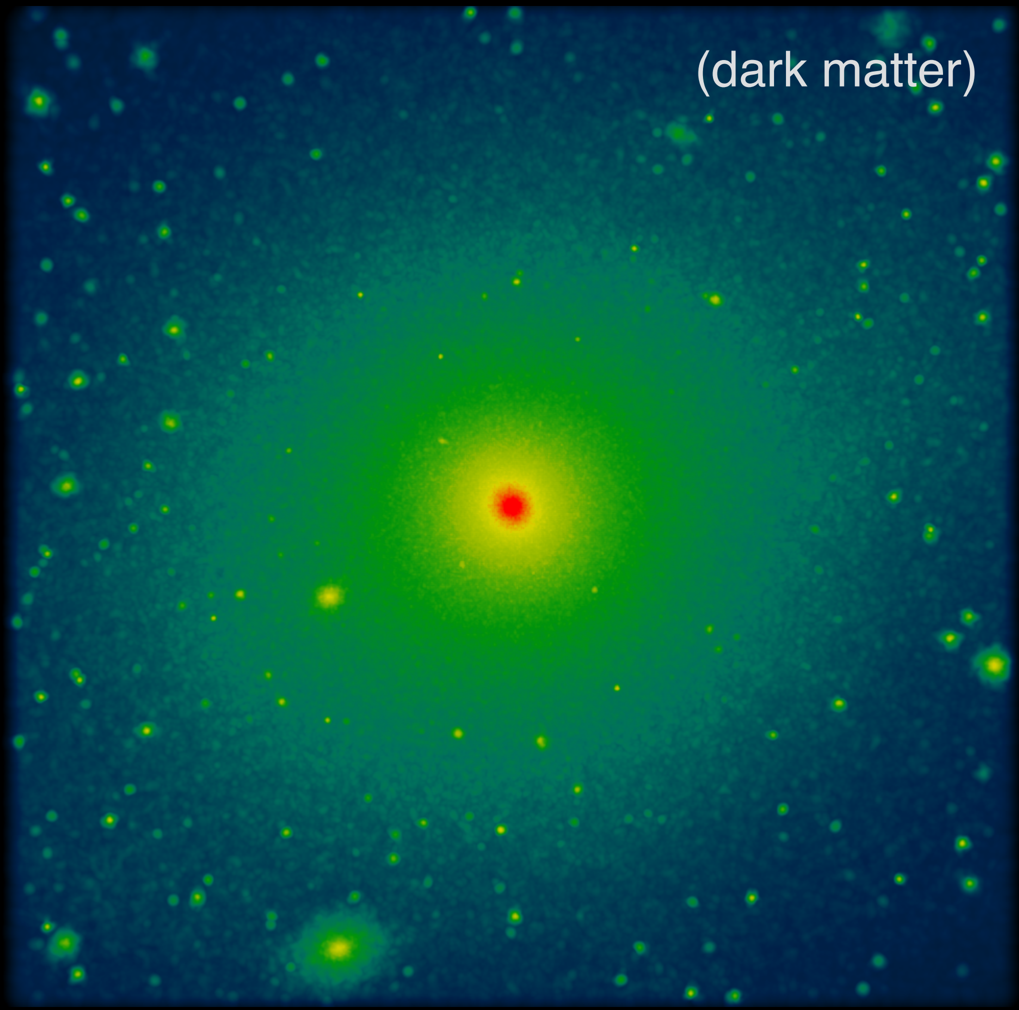
Wetzel+2016

Latte Project: the Milky Way on FIRE (Feedback in Realistic Environments)



Wetzel+2016

FIRE Hydrodynamics

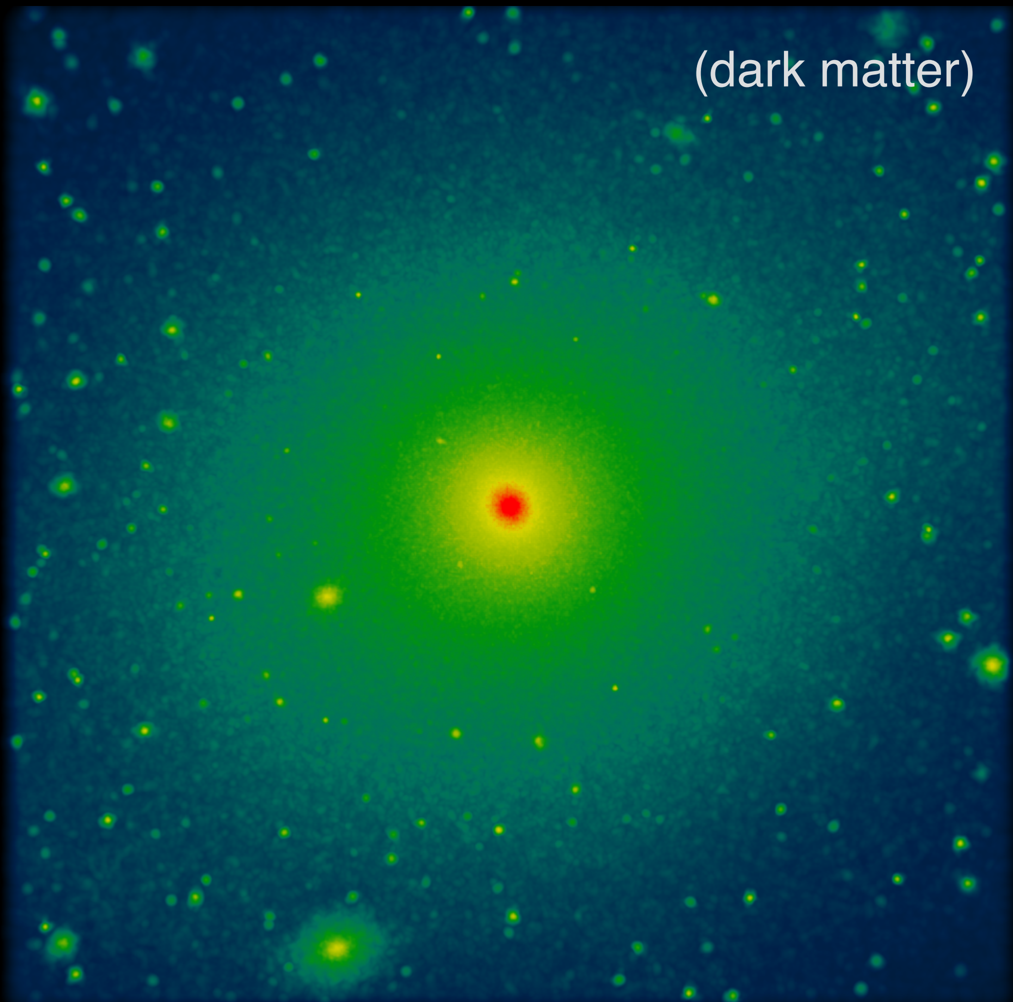


100 kpc

Garrison-Kimmel+2016

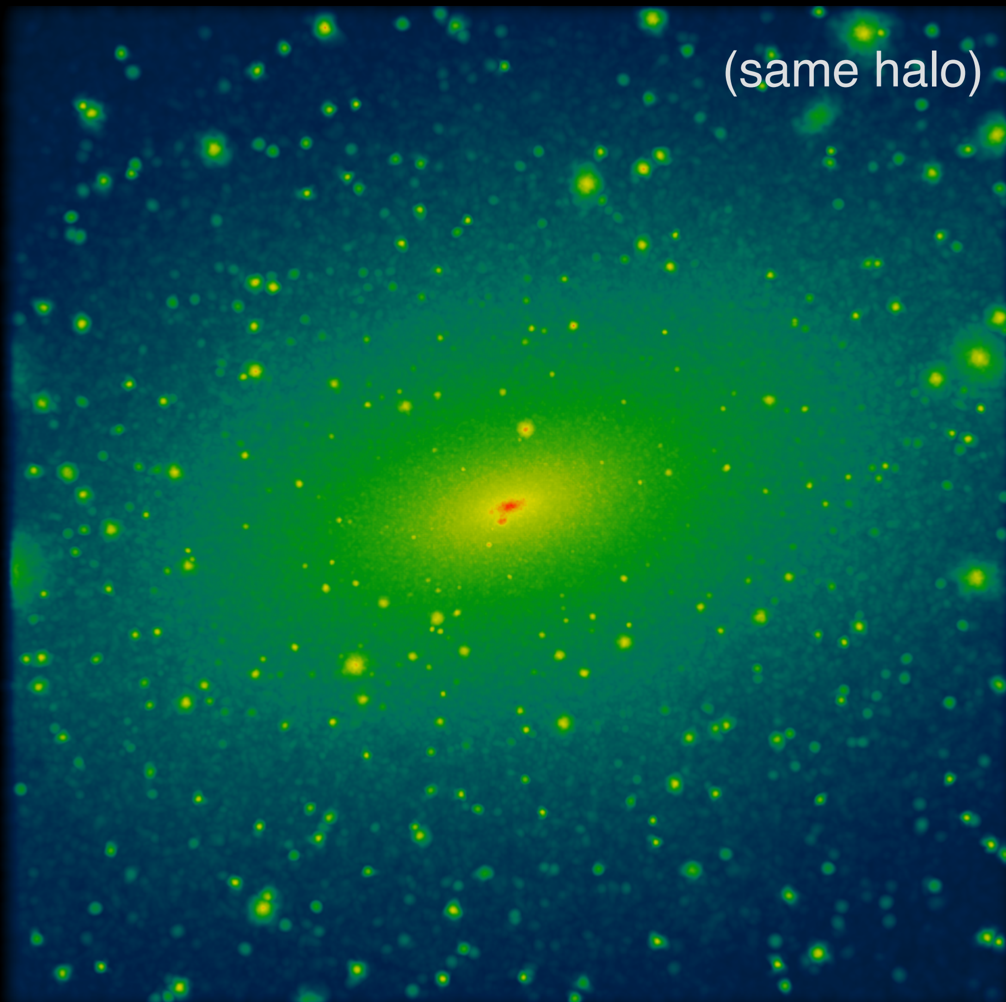
Baryons Matter (A Lot!)

FIRE Hydrodynamics



100 kpc

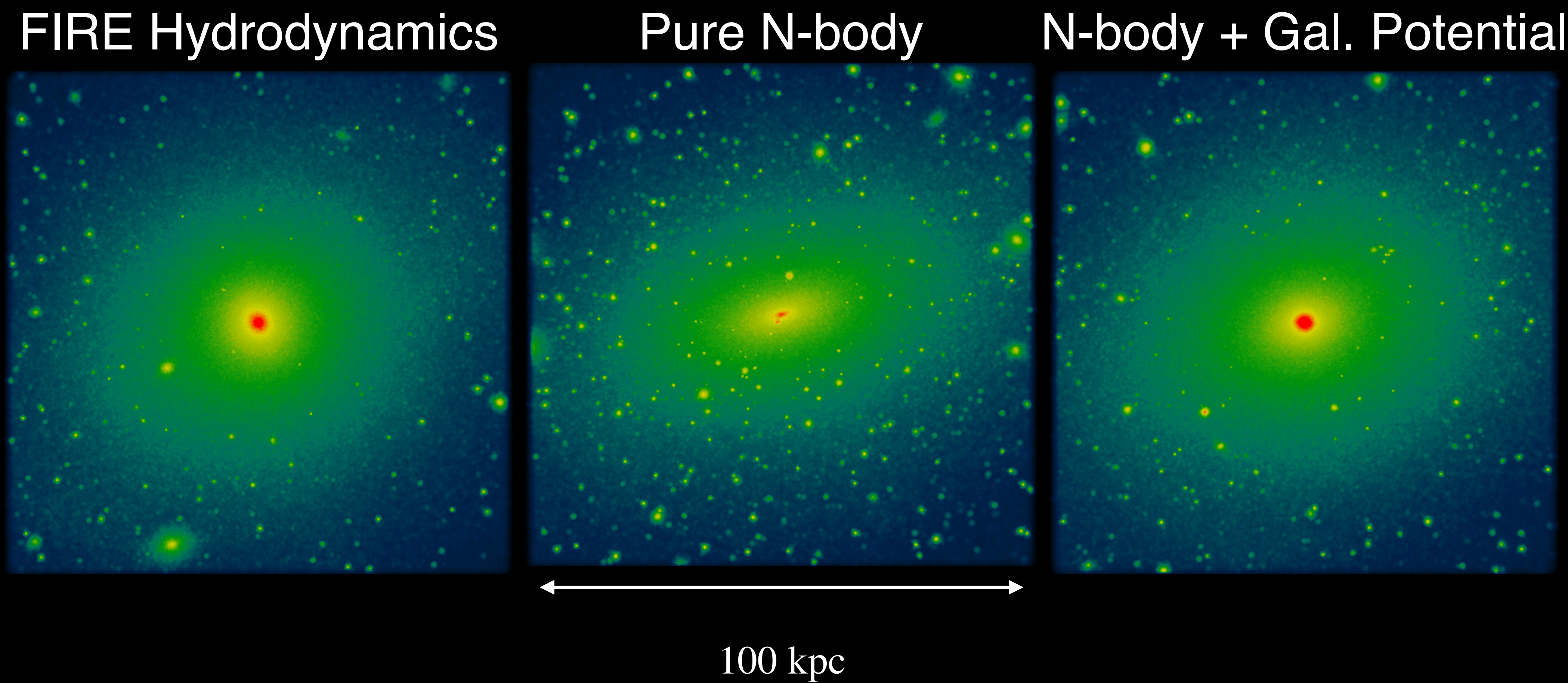
Pure N-Body



100 kpc

Garrison-Kimmel+2016

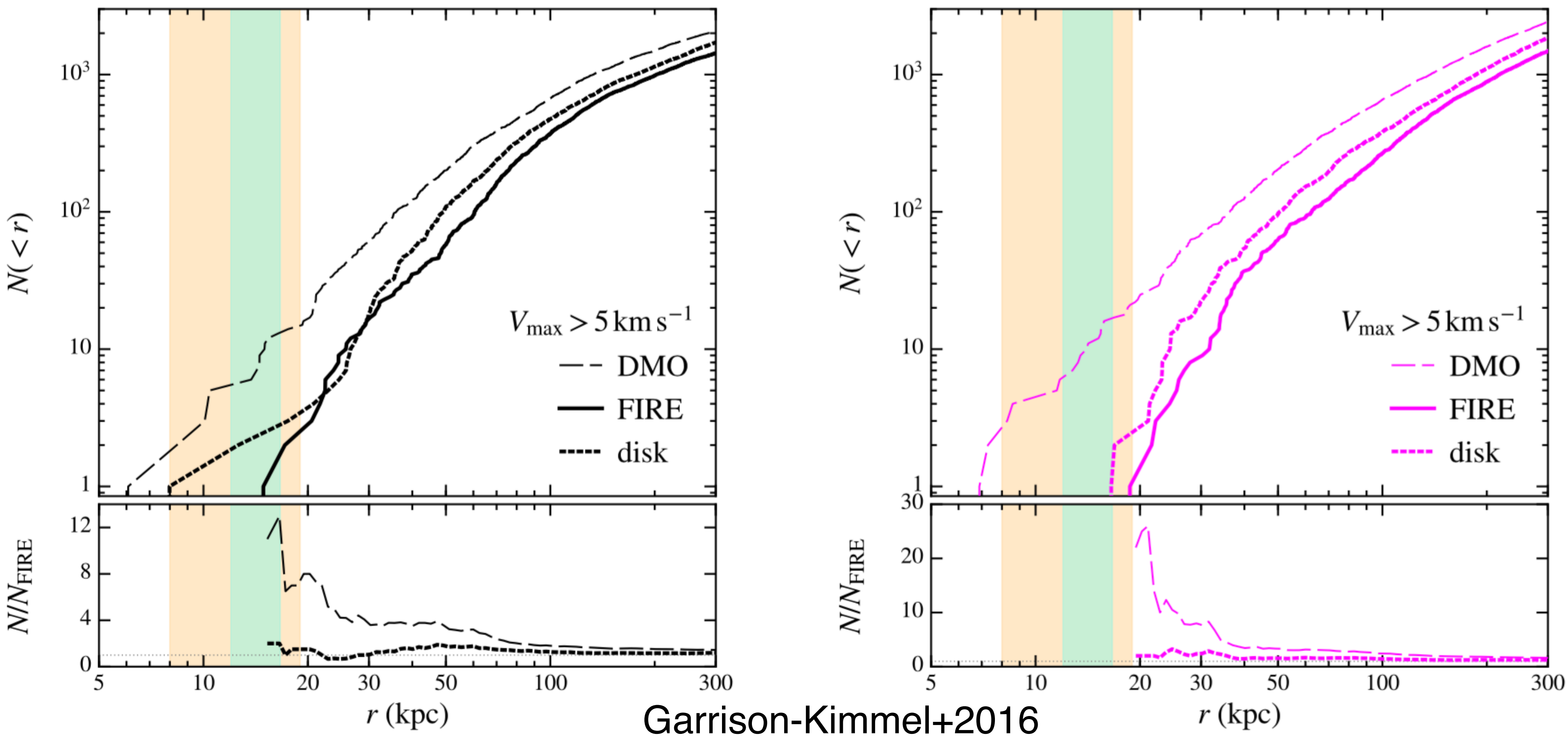
Most important Factor is Central Galaxy Potential



Garrison-Kimmel+2016

Baryons matter for substructure predictions

2 simulations at high resolution

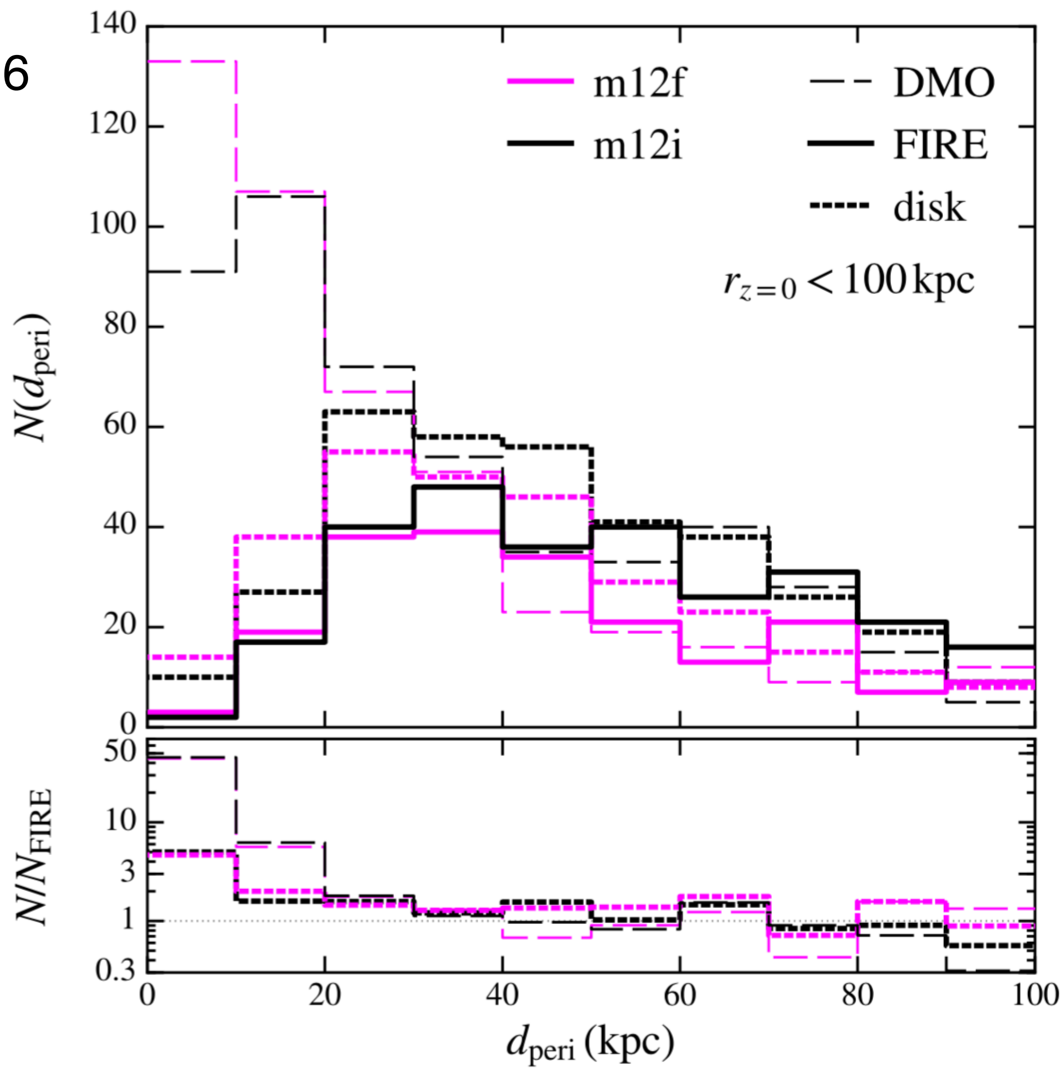


Garrison-Kimmel+2016

up to factor of ~10 reduction w/in radii of interest

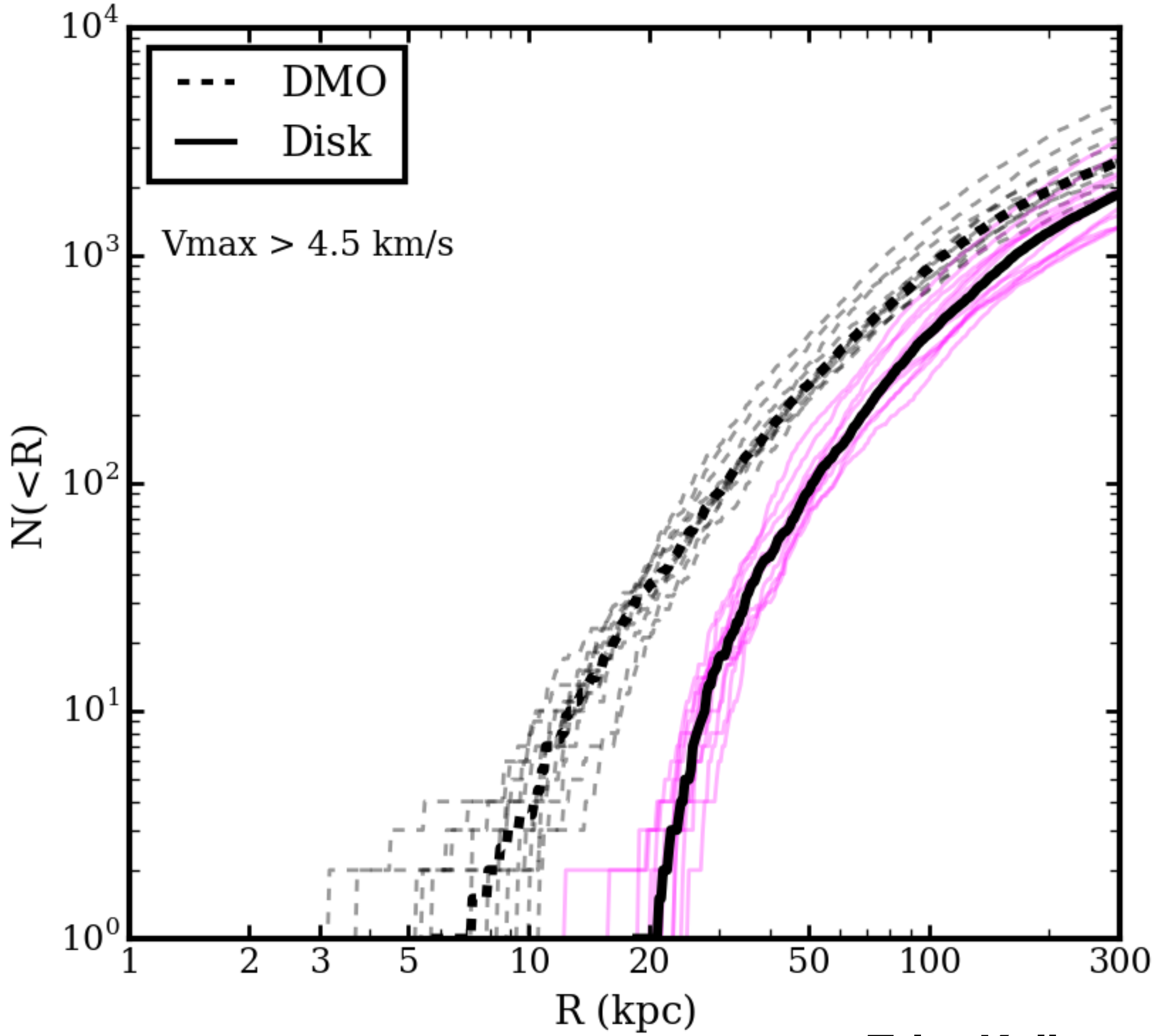
How could the galaxy potential matter so much?

Garrison-Kimmel+2016

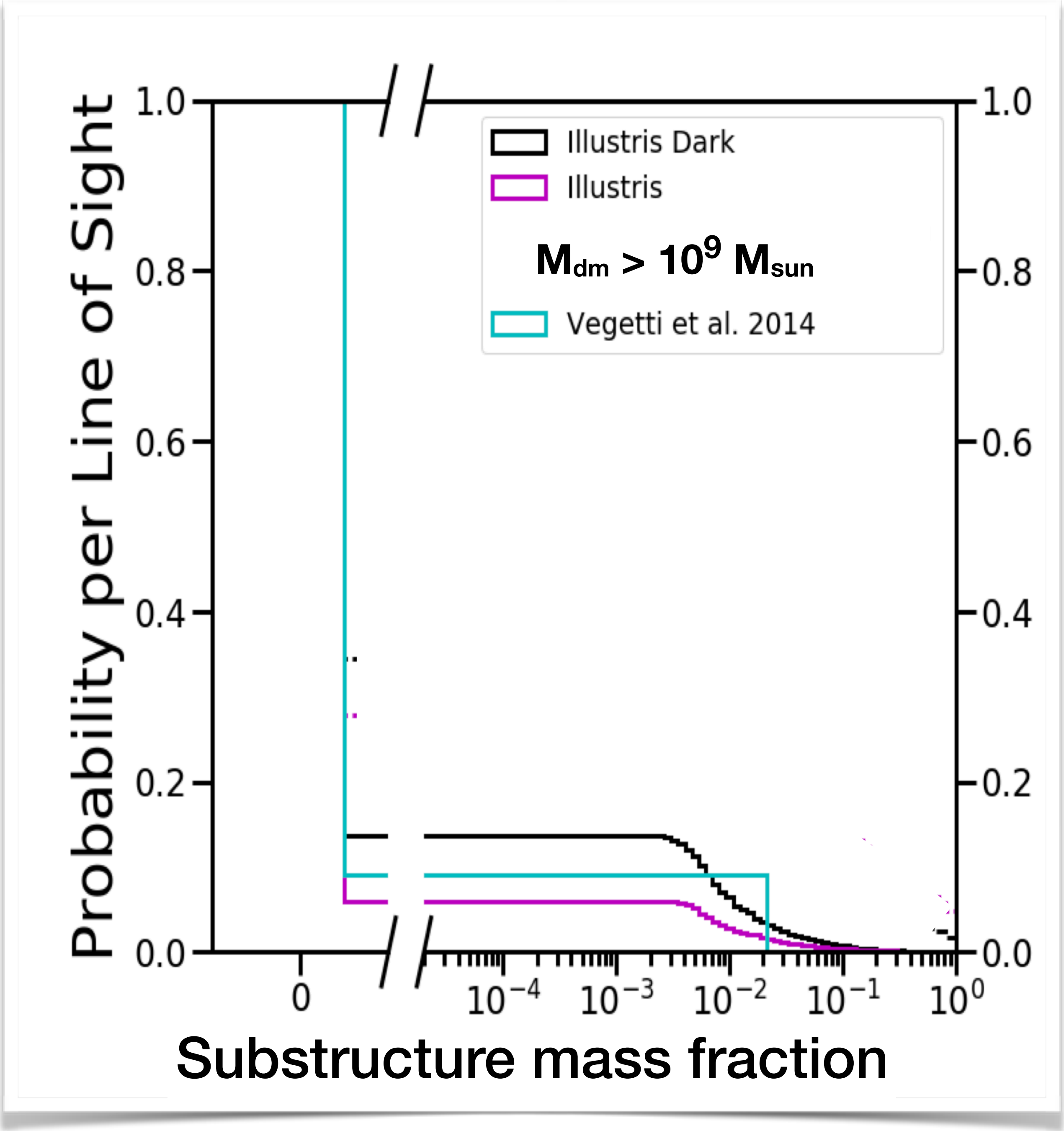


A: Subhalos are on very radial orbits

10 simulations. Tuned Milky Way potential.



Tyler Kelley et al., in prep.



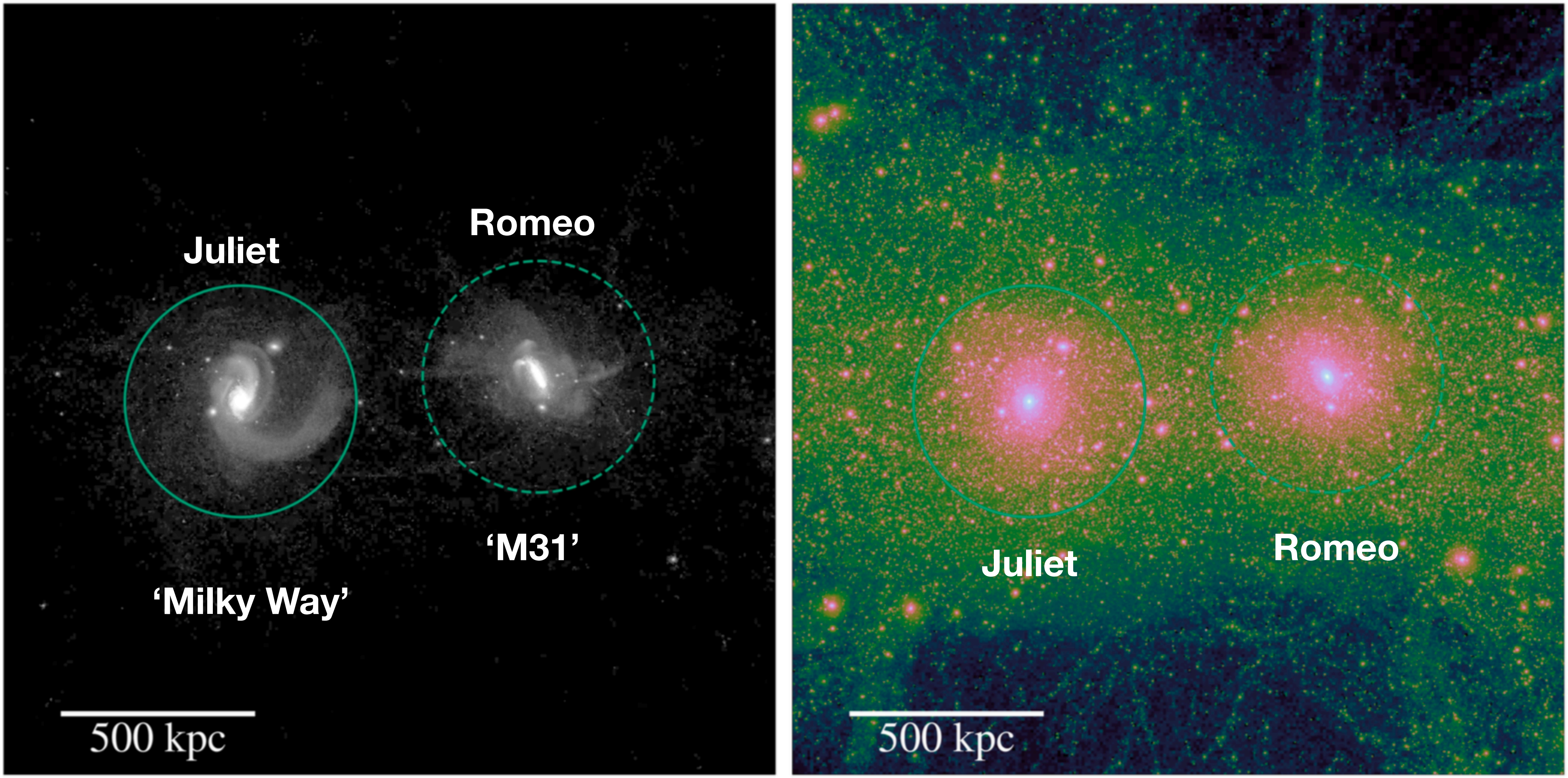
Current substructure lensing constraints are consistent with expected disruption

Graus+2017

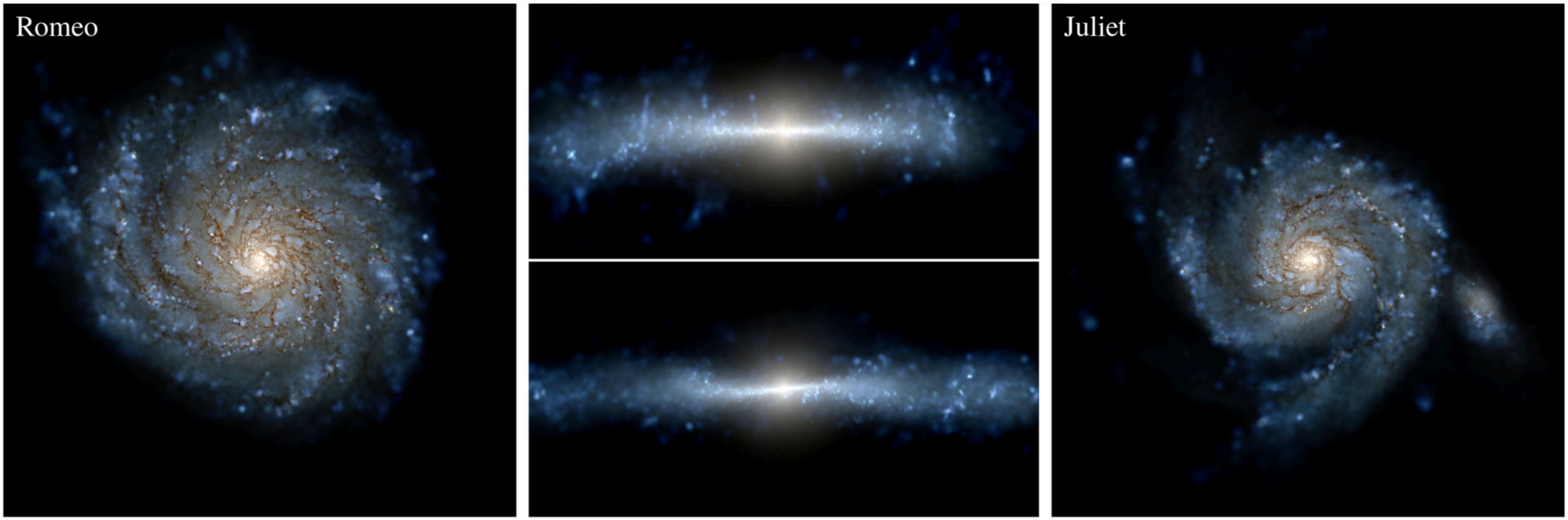
“zoom” FIRE simulation of “Local Group”

Garrison-Kimmel et al. 2018

Stars **Dark Matter**



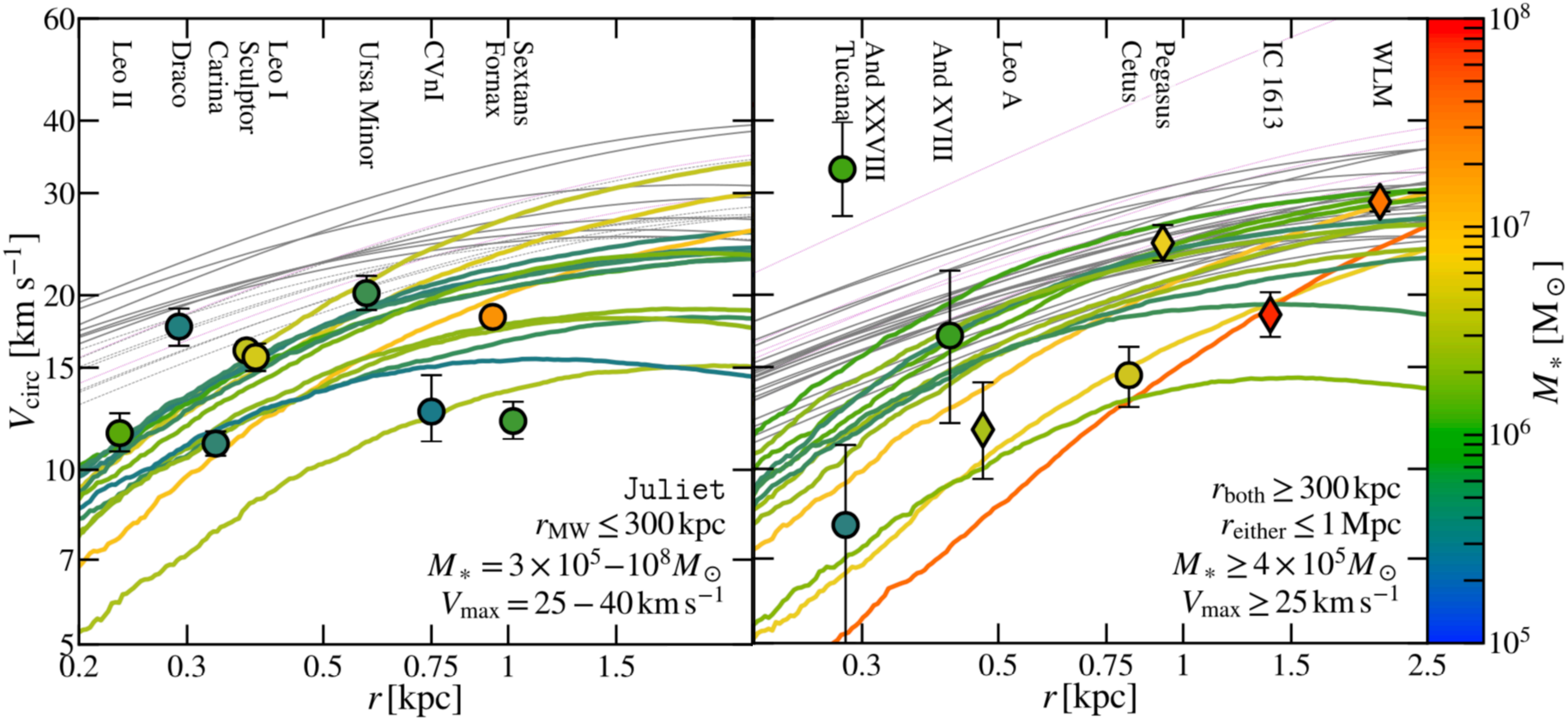
Garrison-Kimmel et al. 2018



Garrison-Kimmel et al. 2018

“solves”
TBTF in the **Milky Way**

“alleviates”
TBTF in the **Local Group**



Garrison-Kimmel et al. 2018

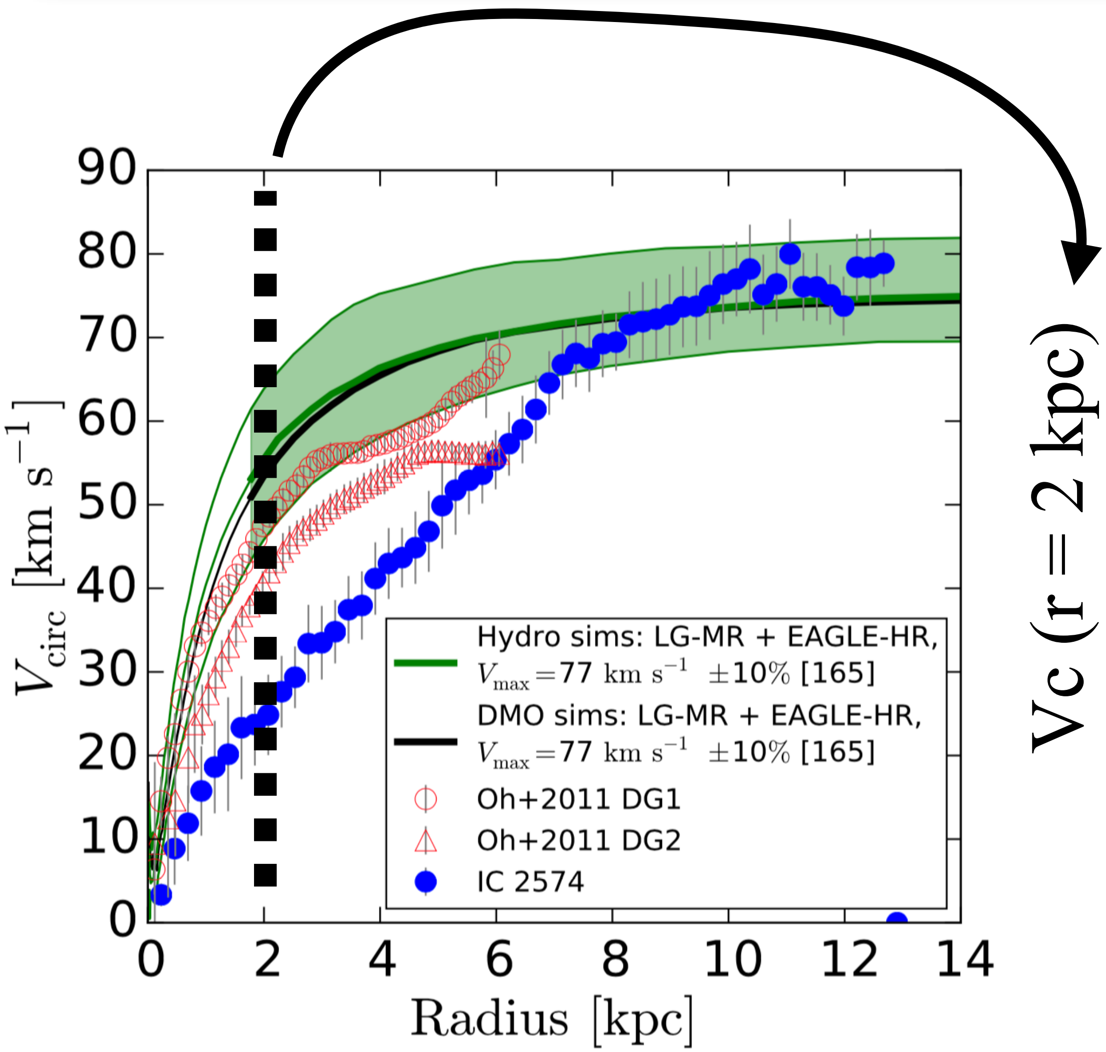
See also: D’Onghia et al. 2010; Sawala et al. 2017; Brooks & Zolotov 2014

CONCLUSIONS

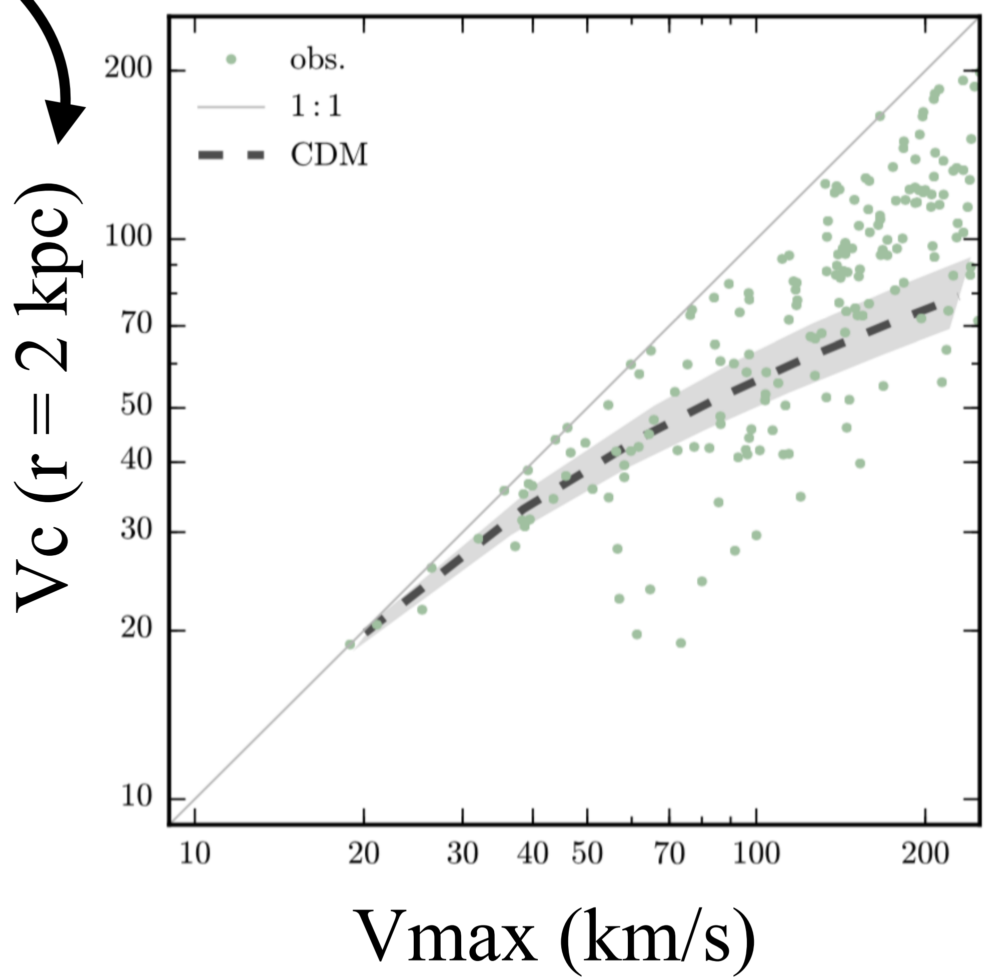
- Standard Cold Dark Matter cosmology (LCDM)
  - Describes large-scale universe remarkably well
- Problems exist on small scales. For example:
  - Cores of galaxies are under-dense compared to predictions
  - The “Too Big To Fail” problem is an extreme version of this
  - Feedback from stars might solve
- Big Questions
  - Do very low-mass dwarfs ($M<10^6 M_{sun}$) have cores or cusps?
  - Can we find truly dark substructure with frequency predicted?

Interesting problems I didn't mention…

Are rotation curves too “diverse”?

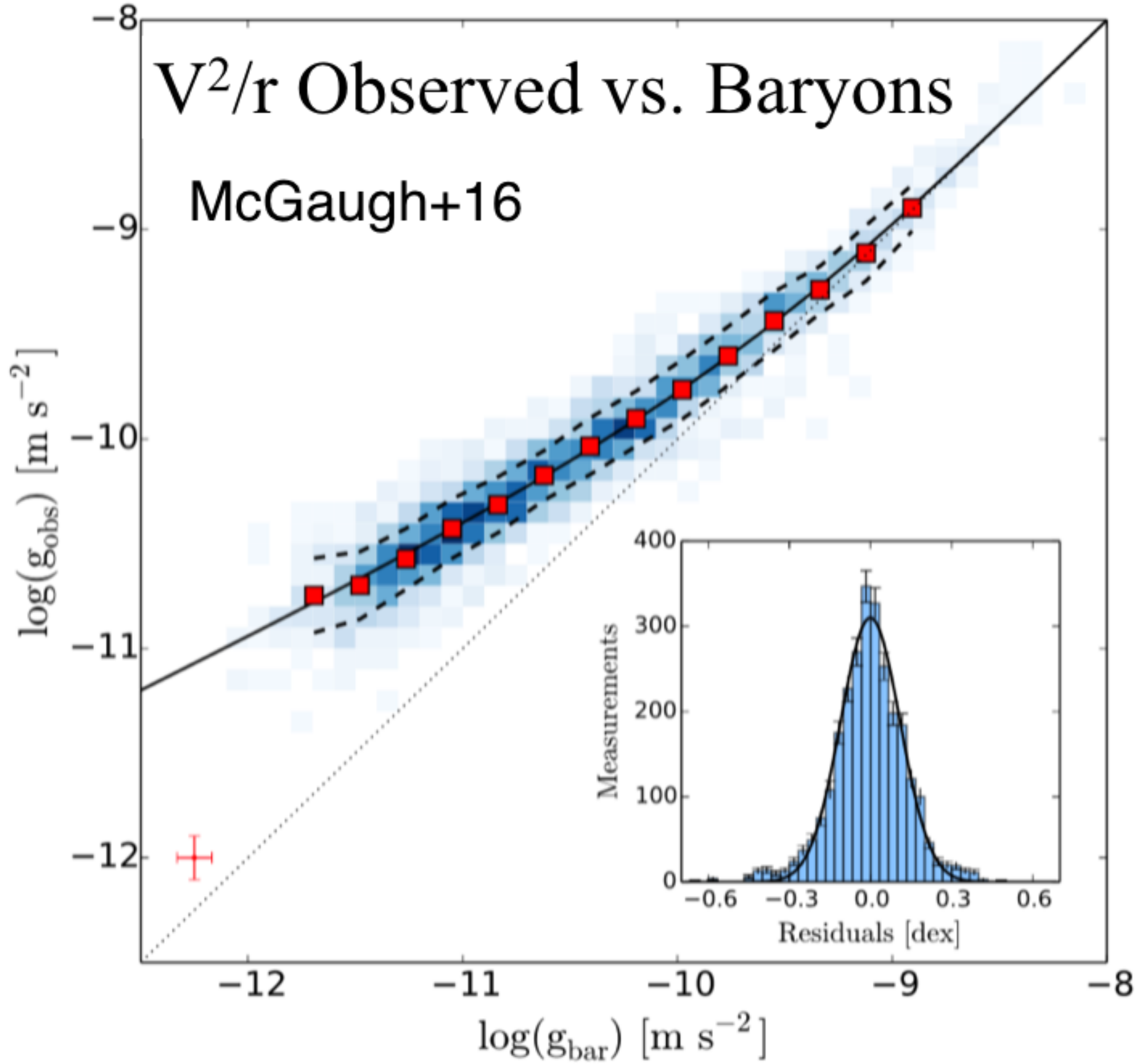


Oman+2015



P. Creasey

Radial Acceleration Relation

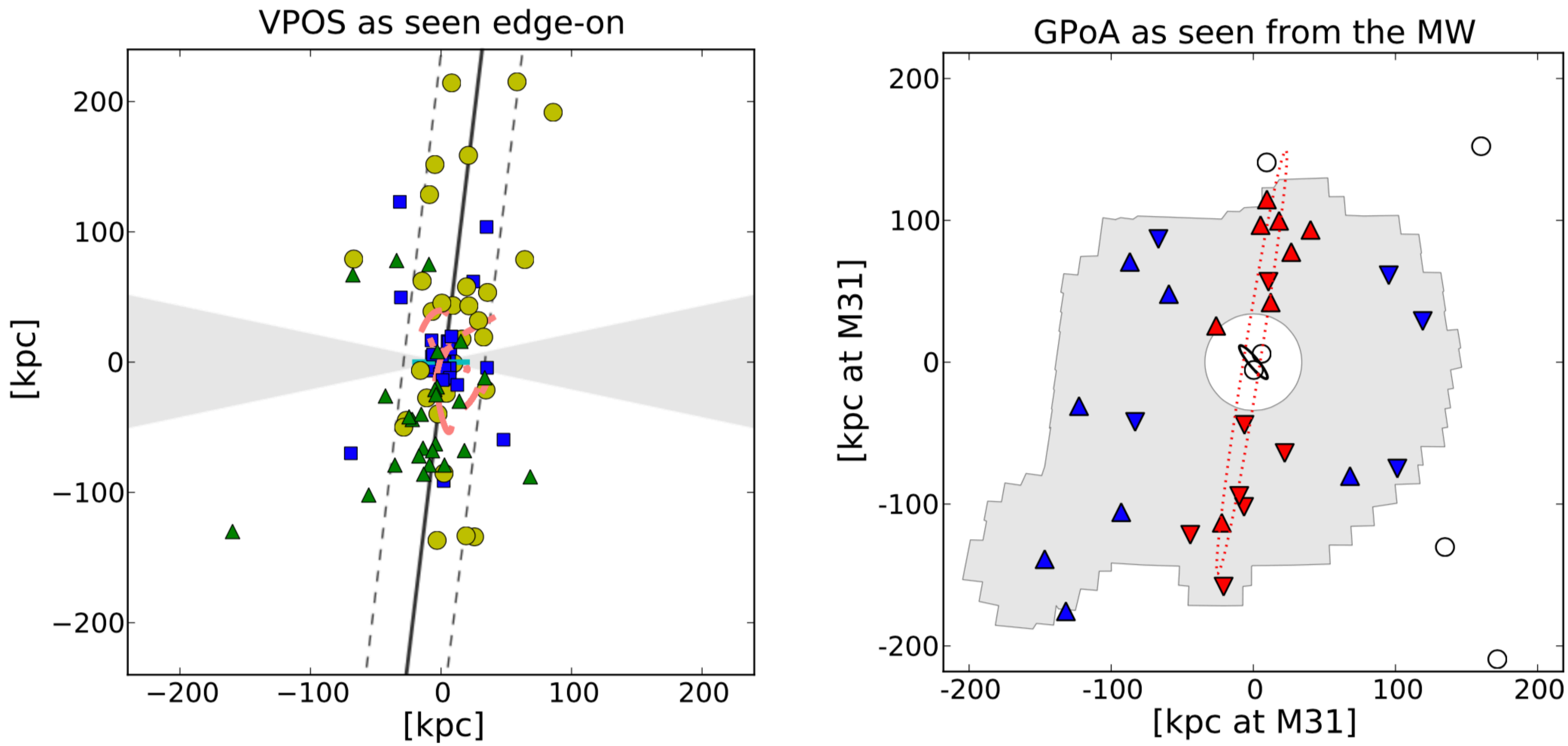


Observed acceleration

Baryonic acceleration

See Di Cintio & Lelli 2016; Keller & Wadsley 2016; Ludlow+16; Desmond 2017; Navarro+17 for CDM takes on RAR

Rotating planes of satellites



satellite galaxies around the Centaurus A galaxy

Muller et al. 2018