Dark Matter
Advanced Training Institute

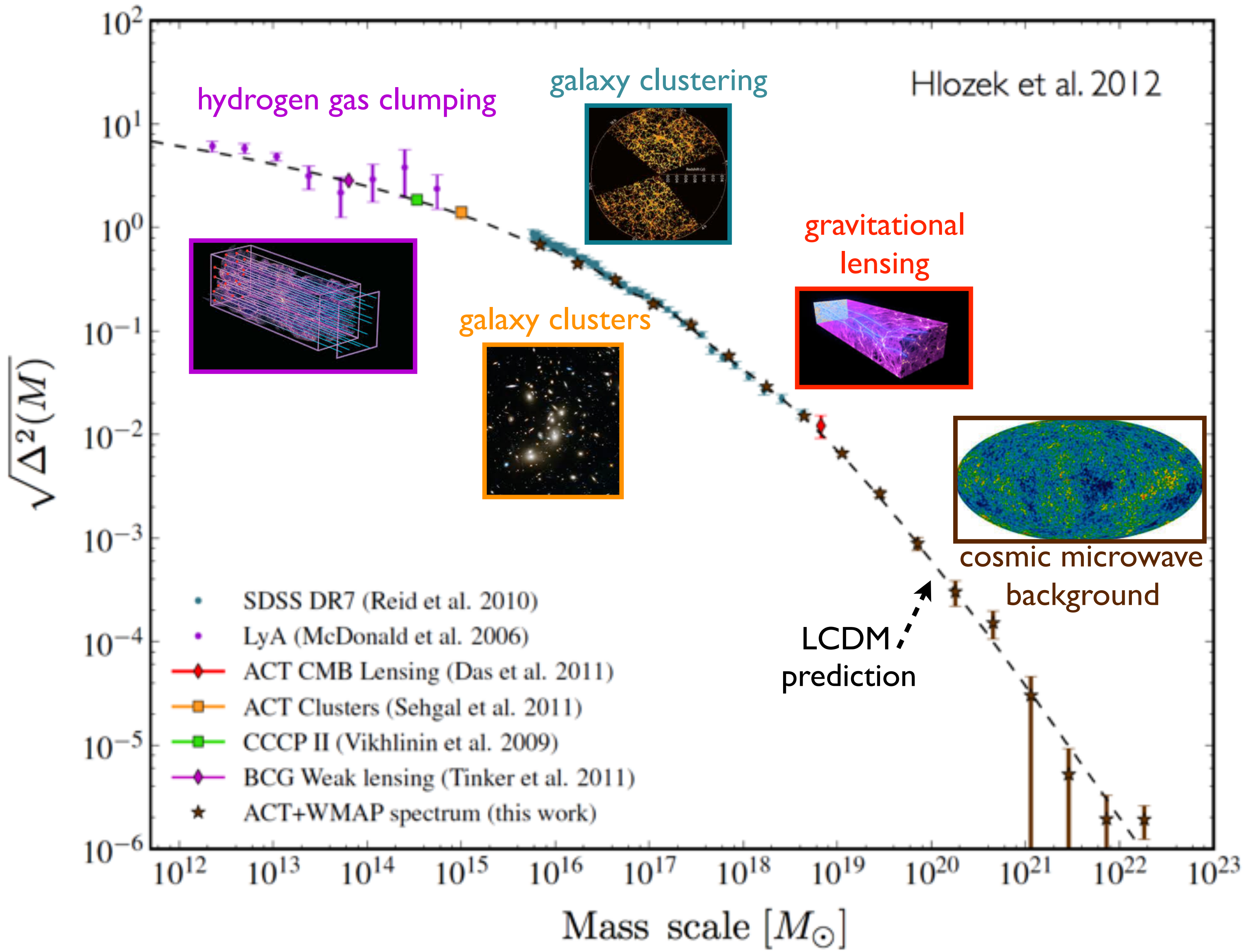
Observations and simulations of structure formation in the Universe

Lecture 1

Simulating the universe in dark matter

James Bullock
UC Irvine

LCDM: CLUSTERING ON (QUASI) LINEAR SCALES



Cosmological Simulation **Initial Conditions** Start with the Power Spectrum

Primordial power spectrum: $$P(k) \propto k^n \text{ with } n \simeq 1$$

Set by early universe physics
(inflation in the standard scenario)

Cosmological Simulation **Initial Conditions** Start with the Power Spectrum

Primordial power spectrum: $P(k) \propto k^n \text{ with } n \simeq 1$

Dimensionless processed linear power spectrum (z=0):

$$\Delta^2(k) \quad = \frac{k^3}{2\pi^2} P(k)\, T^2(k)$$

Cosmological Simulation **Initial Conditions** Start with the Power Spectrum

Primordial power spectrum: $P(k) \propto k^n \text{ with } n \simeq 1$

Dimensionless processed linear power spectrum (z=0):

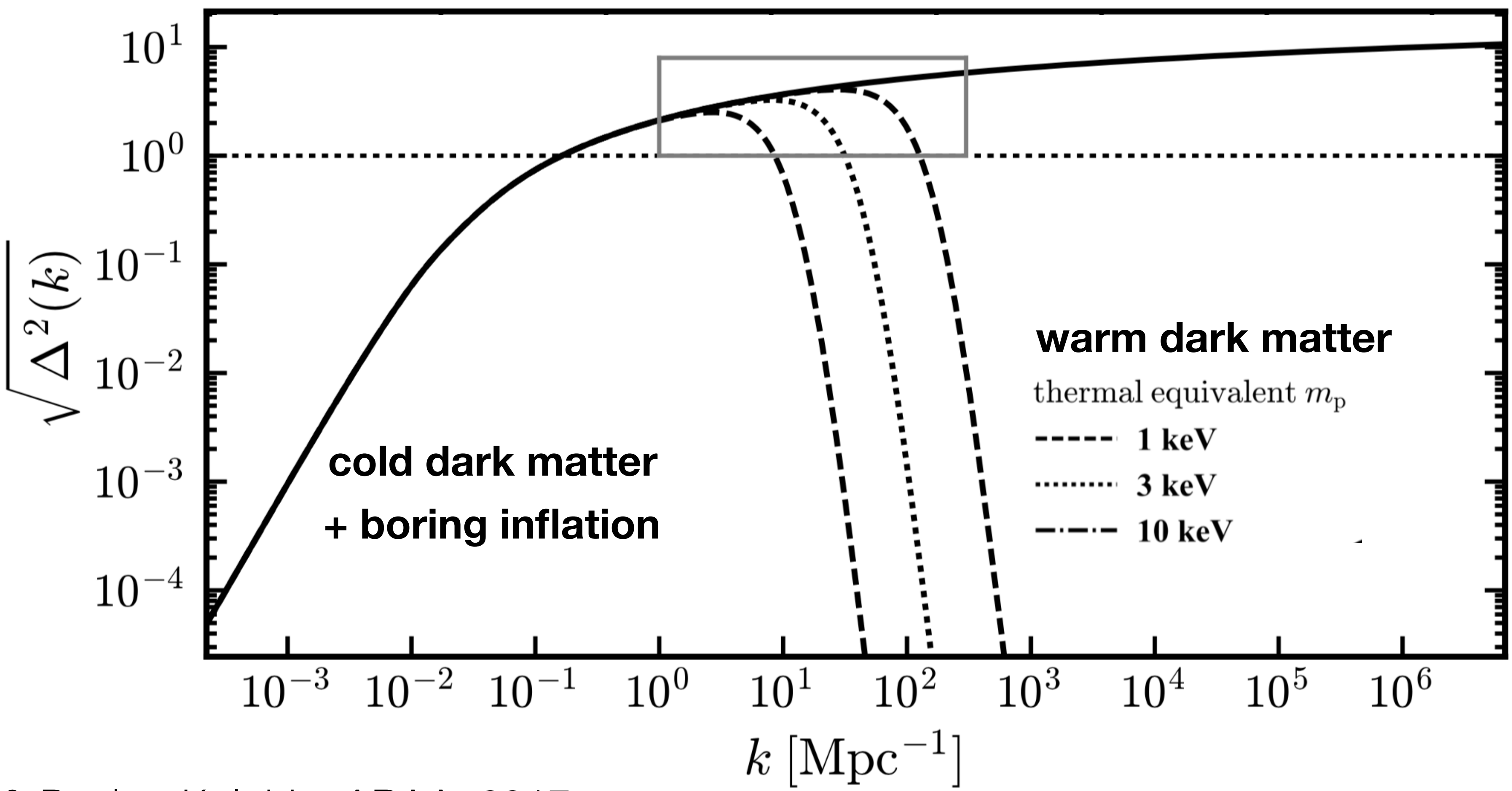
$$\Delta^2(k) = \frac{k^3}{2\pi^2} P(k)\, T^2(k)$$

"Transfer function"

Takes into account perturbation growth after entering horizon

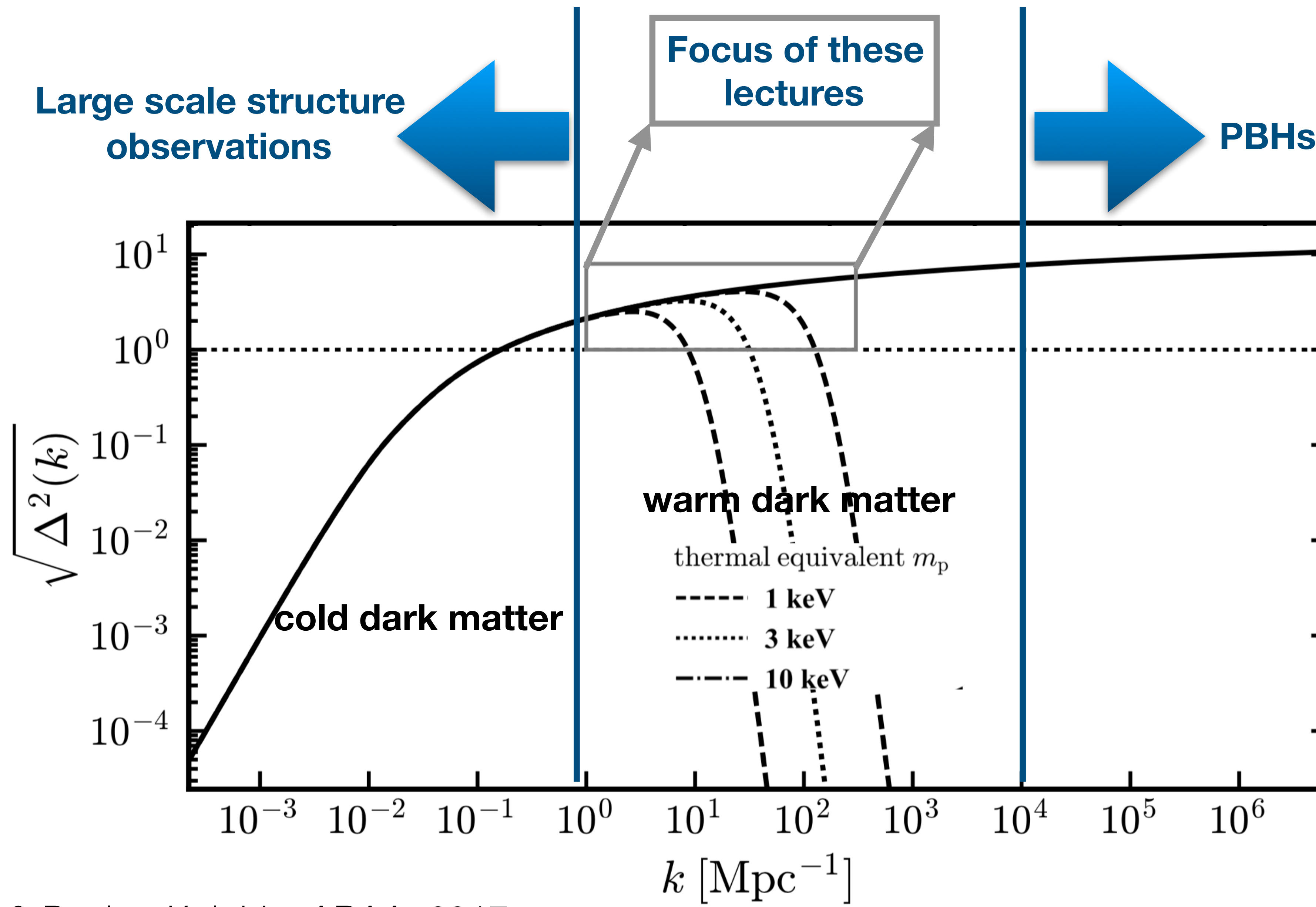
Dark matter microphysics can affect evolution of primordial fluctuations (free-streaming, collisional damping, etc.)

Dimensionless processed linear power spectrum (z=0):



JSB & Boylan-Kolchin, ARAA, 2017

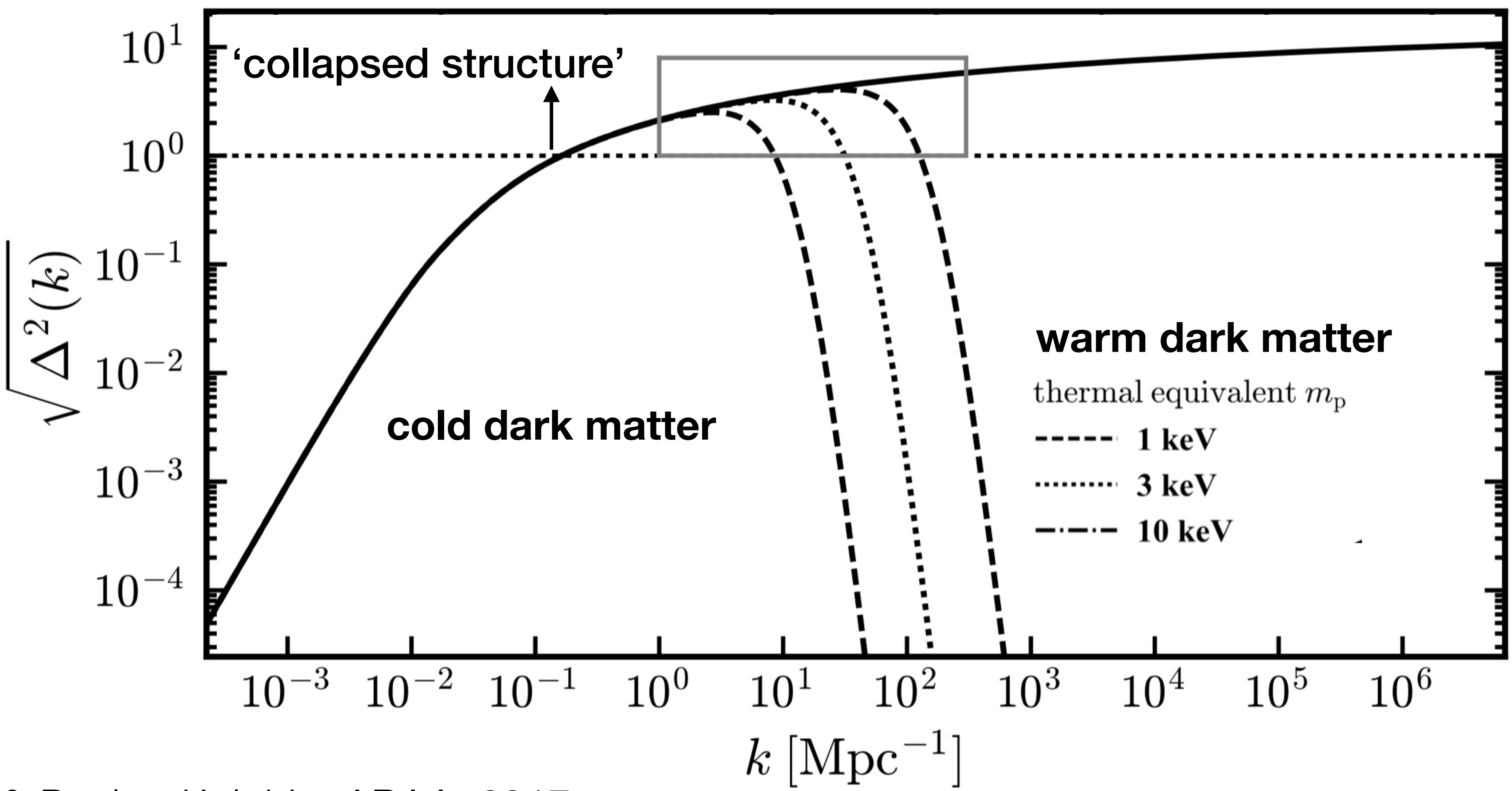
Dimensionless processed linear power spectrum (z=0):



JSB & Boylan-Kolchin, ARAA, 2017

Dimensionless processed linear power spectrum (z=0):

<u>Warning</u>: Calculated using **linear** perturbation theory.
Not an accurate description of real power spectrum where fluctuations > 1.



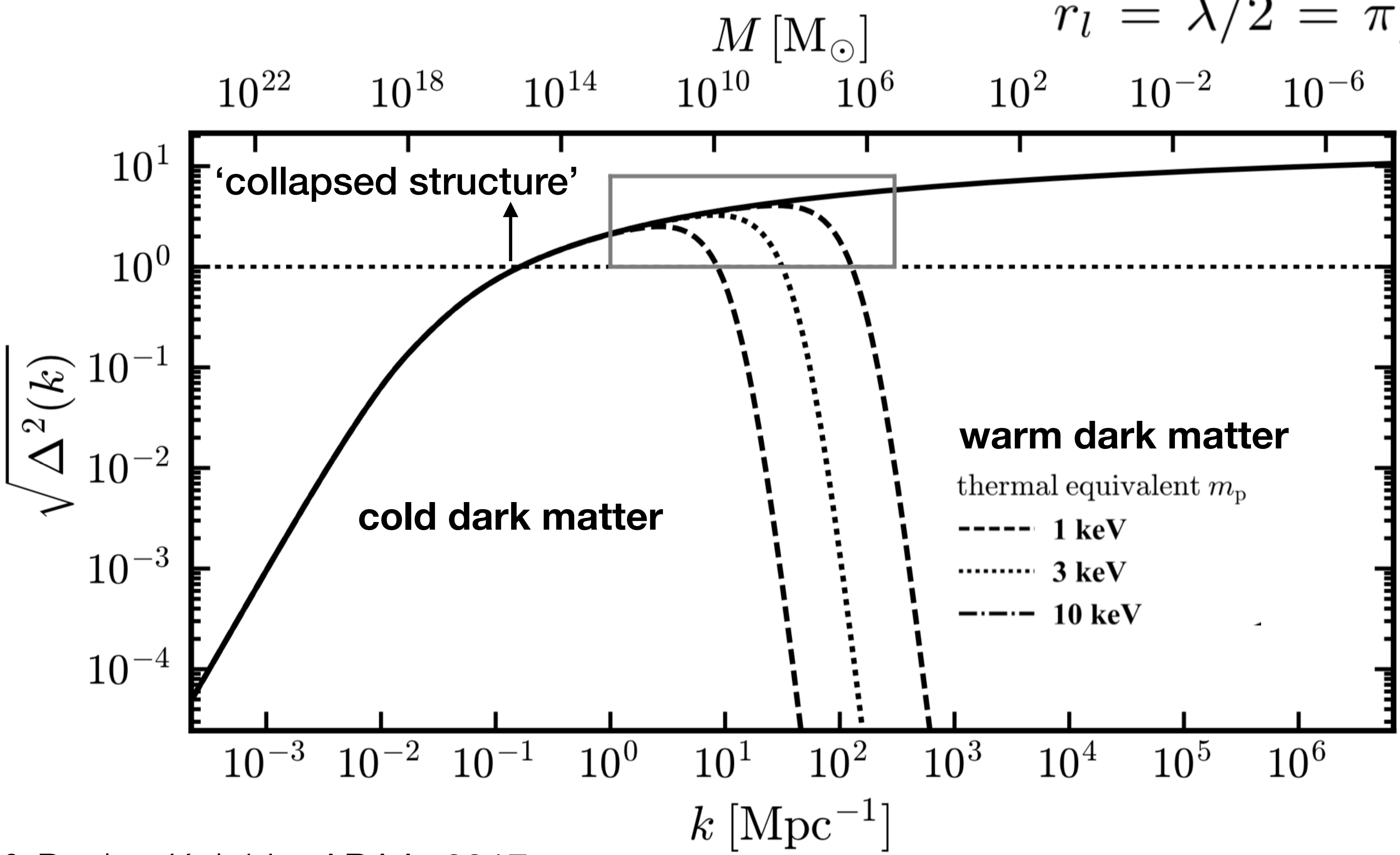
JSB & Boylan-Kolchin, ARAA, 2017

Recast in terms of mass scale

$$M = \frac{4\pi}{3} r_l^3 \rho_m$$

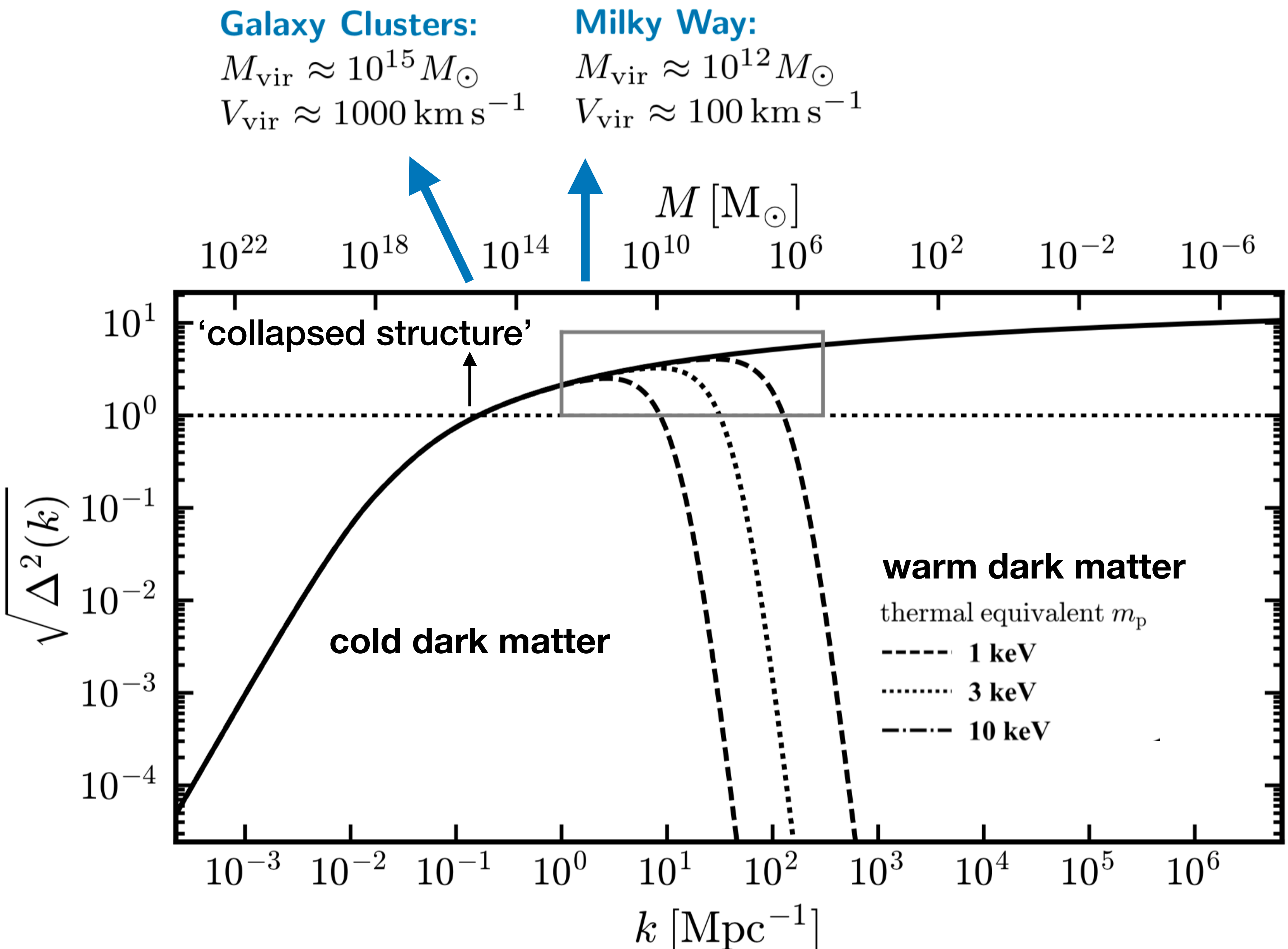
"Fluctuations within spheres of mass M"

$$r_l = \lambda/2 = \pi/k.$$



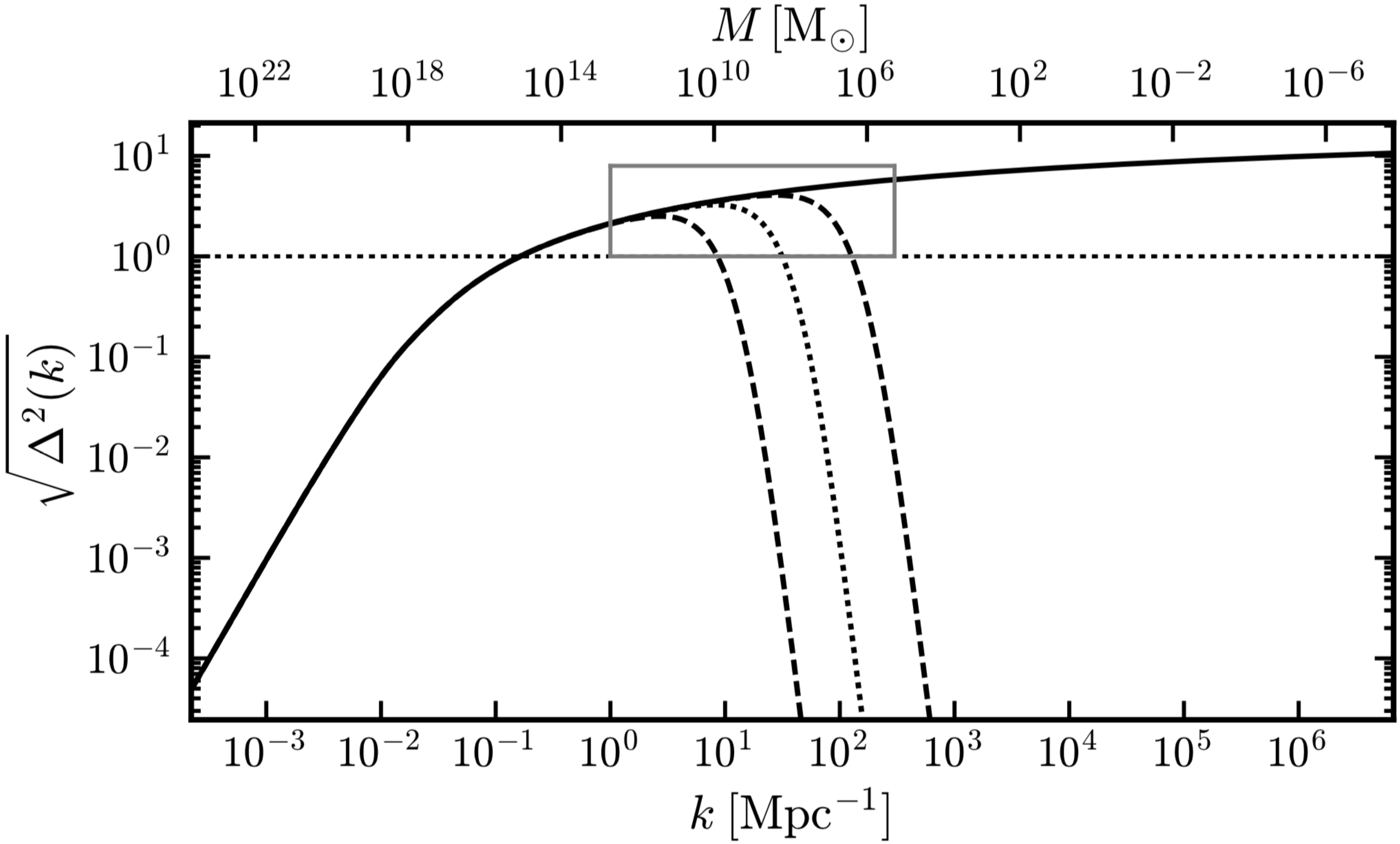
JSB & Boylan-Kolchin, ARAA, 2017

Dimensionless processed linear power spectrum (z=0):

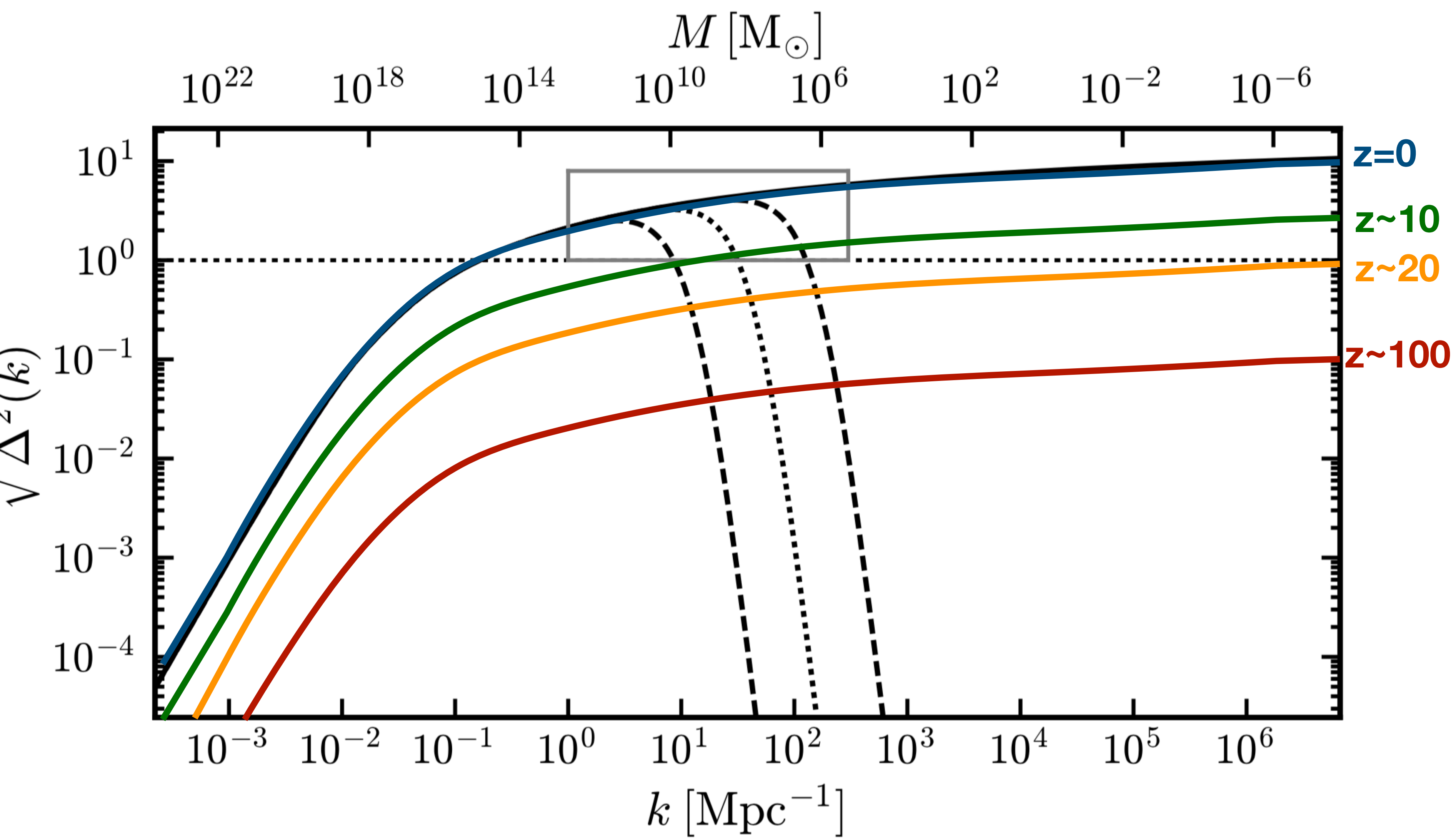


JSB & Boylan-Kolchin, ARAA, 2017

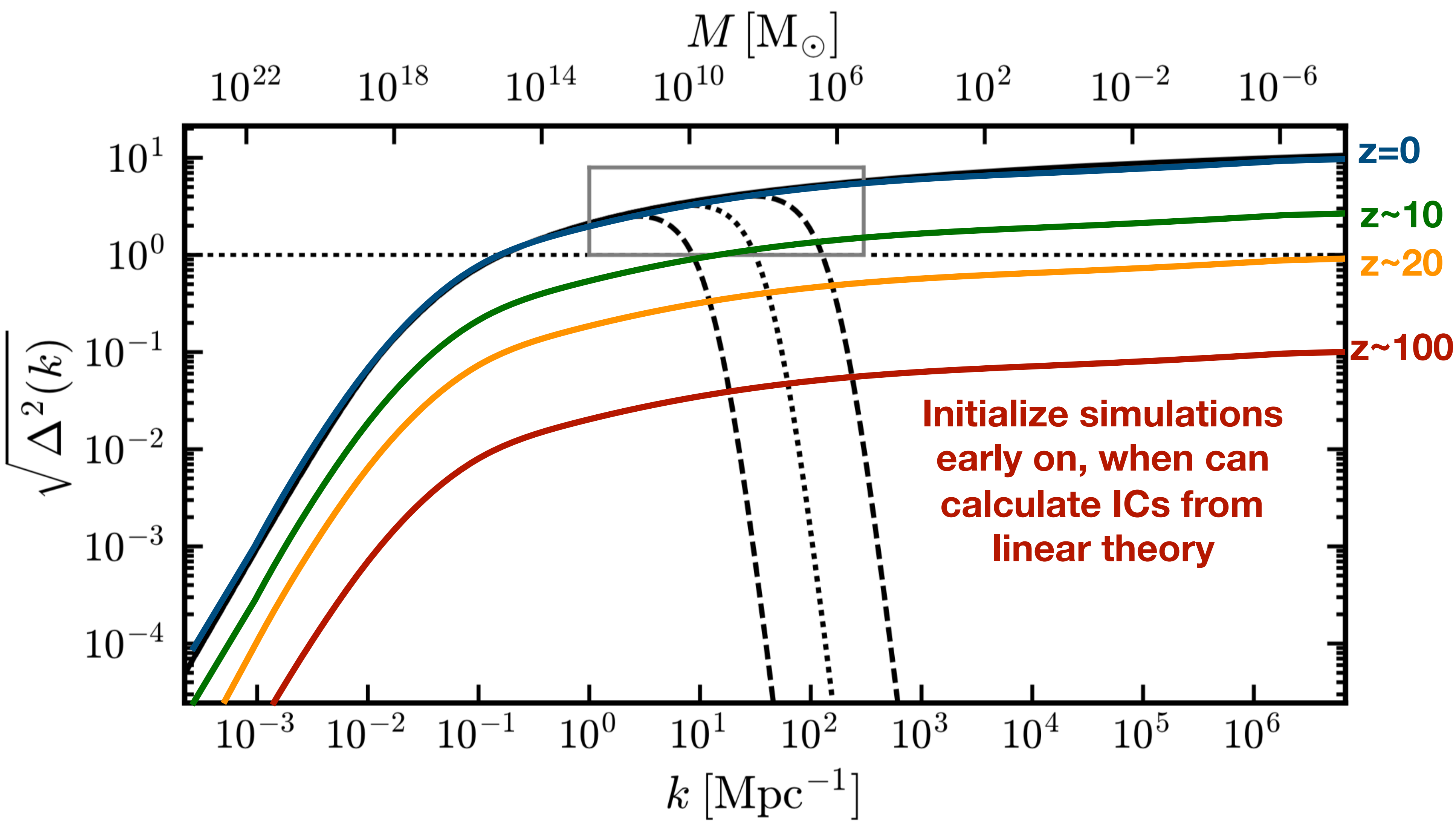
Dimensionless processed linear power spectrum (z=0):

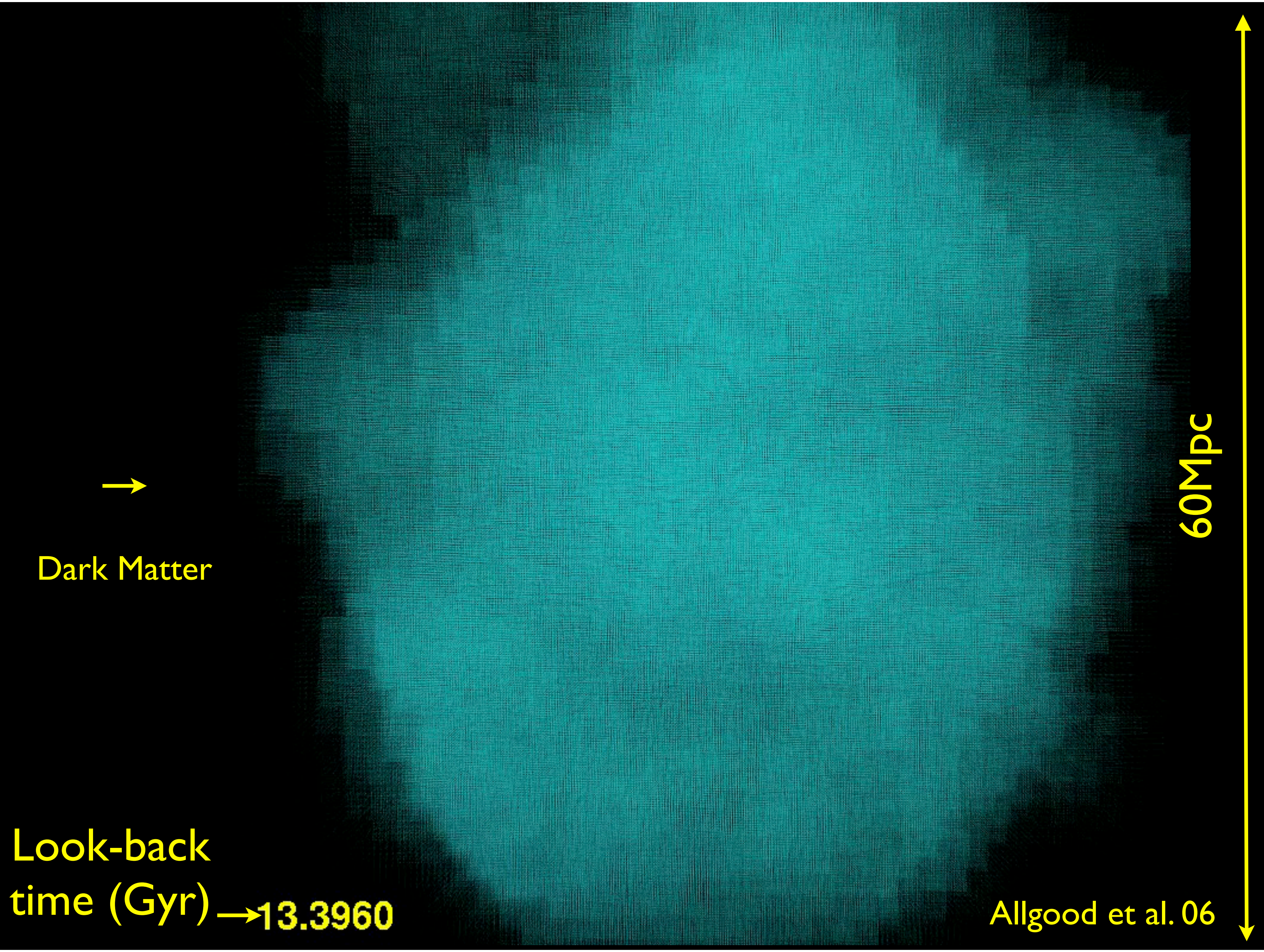


Dimensionless processed linear power spectrum at higher redshift



Dimensionless processed linear power spectrum at higher redshift

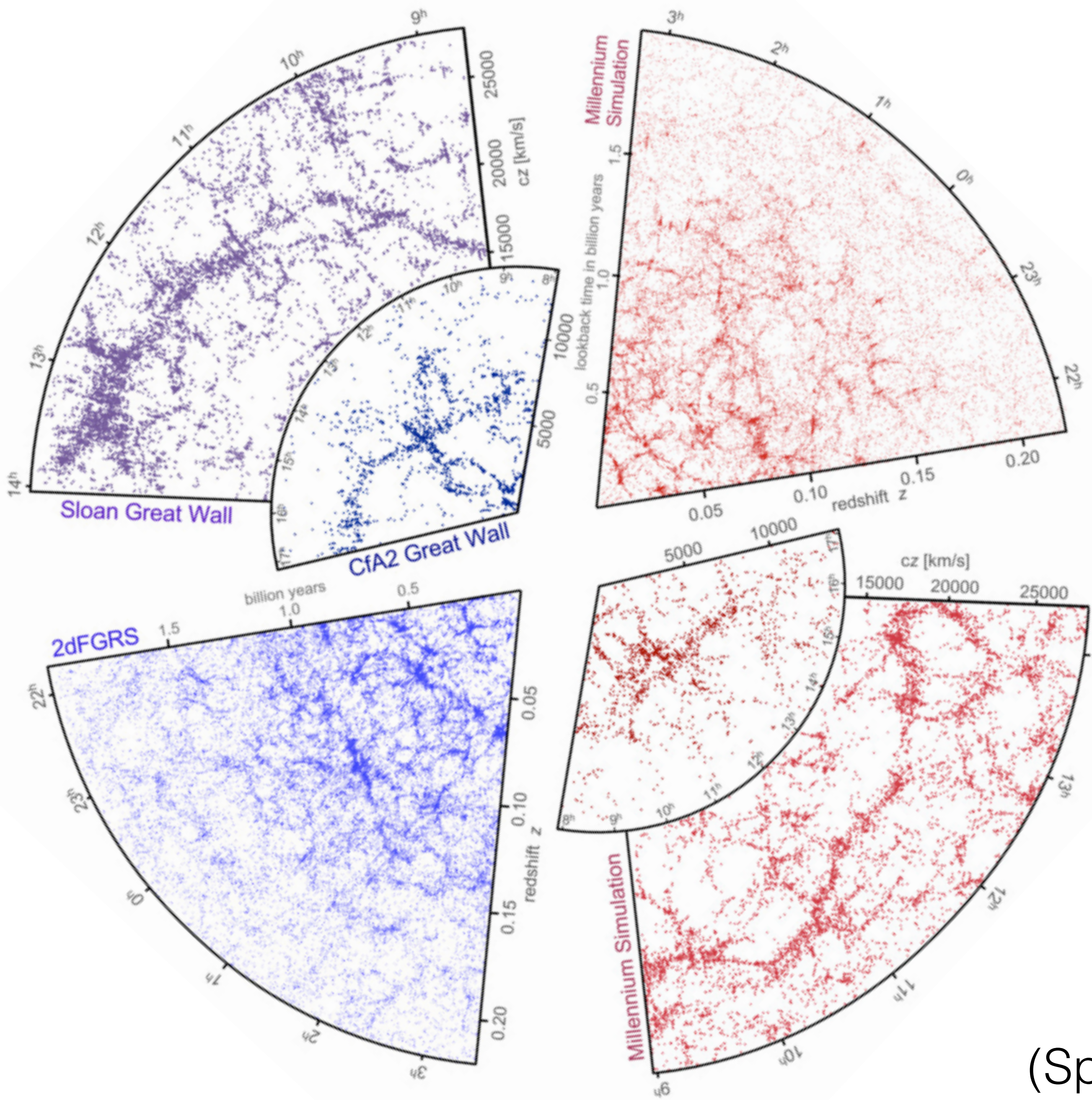




Dark Matter
Look-back time (Gyr) →13.3960
60Mpc
Allgood et al. 06

LCDM: MATCHES LARGE-SCALE UNIVERSE

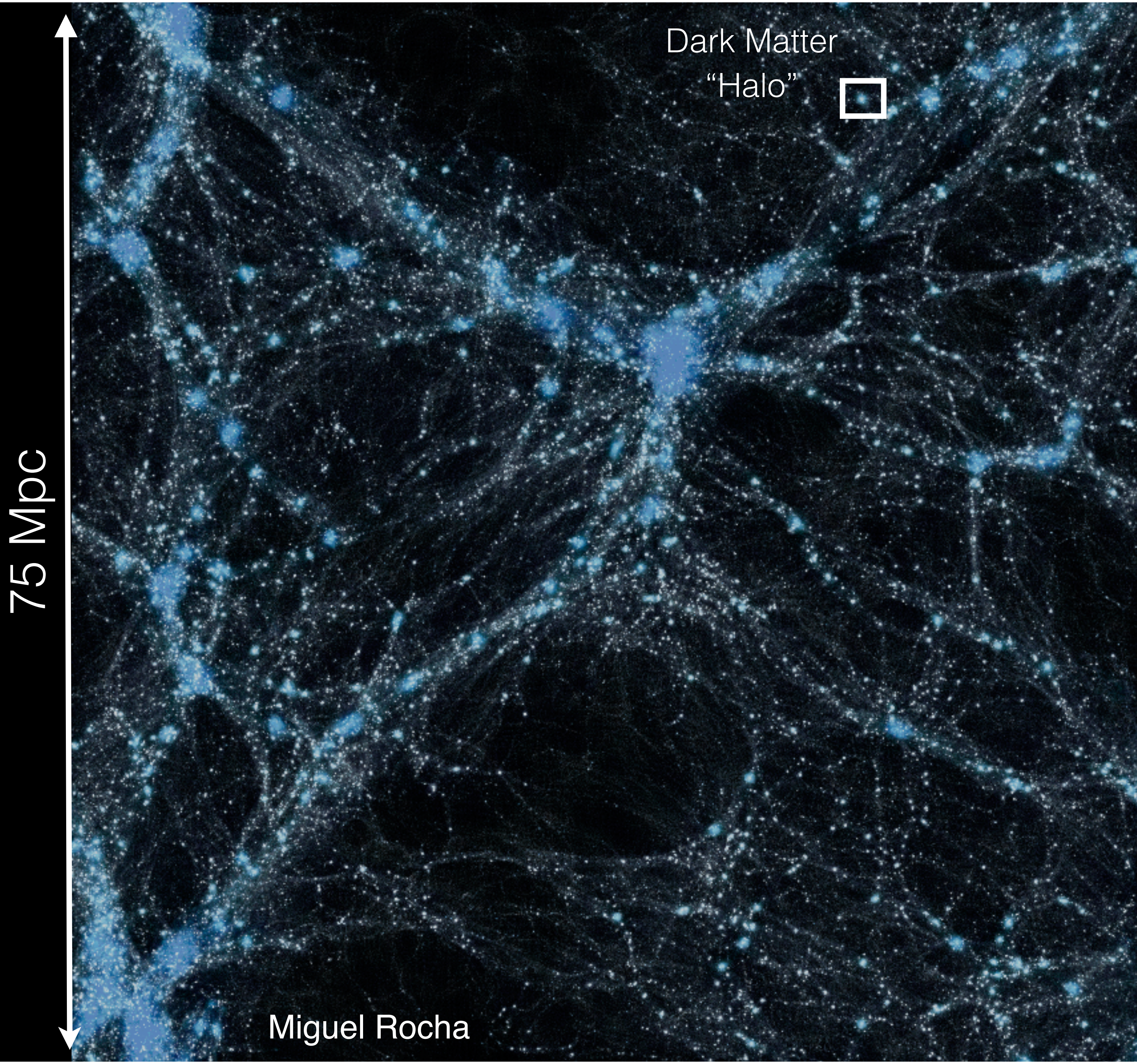
Observed Universe



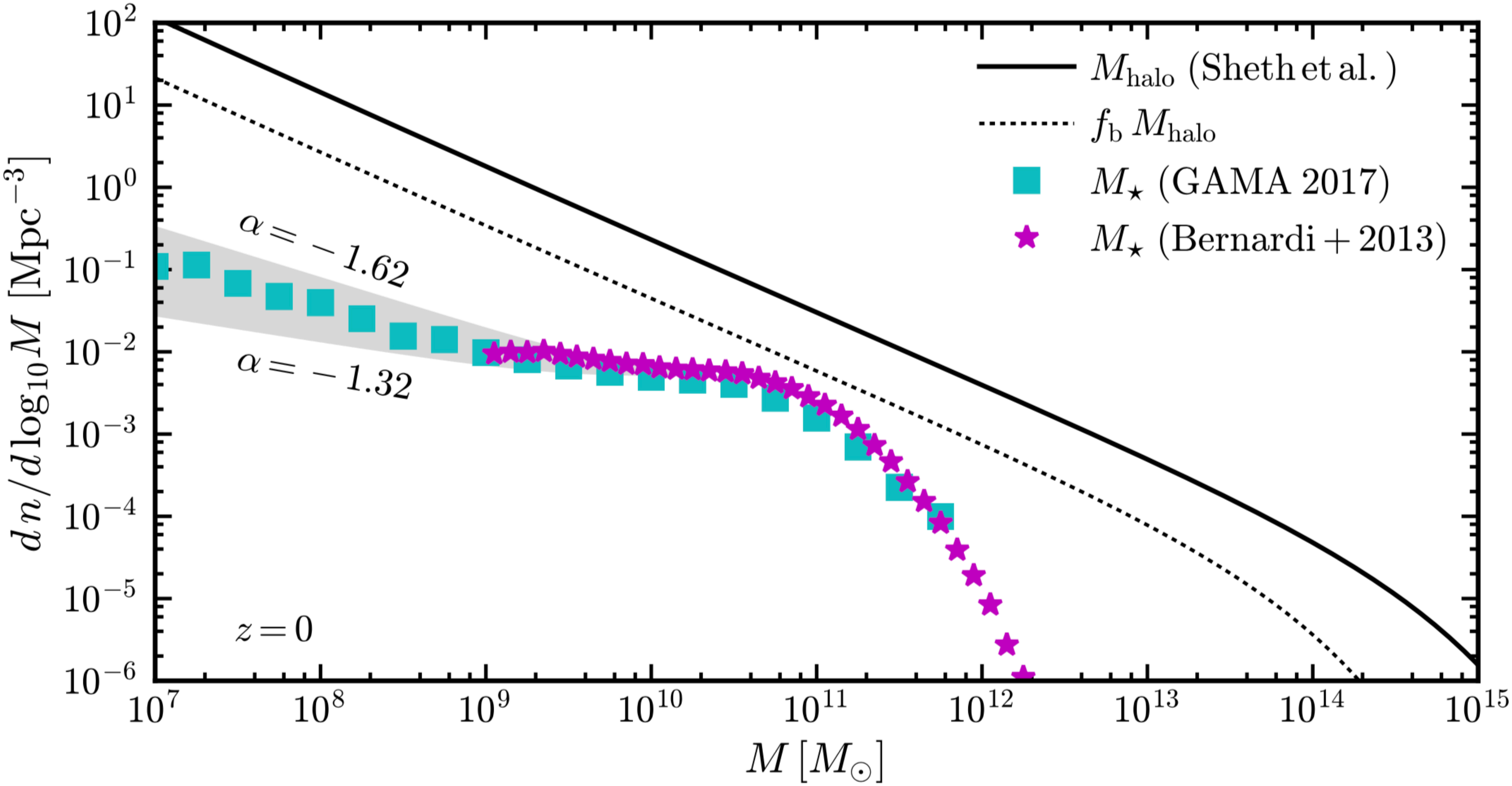
Simulated universe

(Springel + 2005)

LCDM

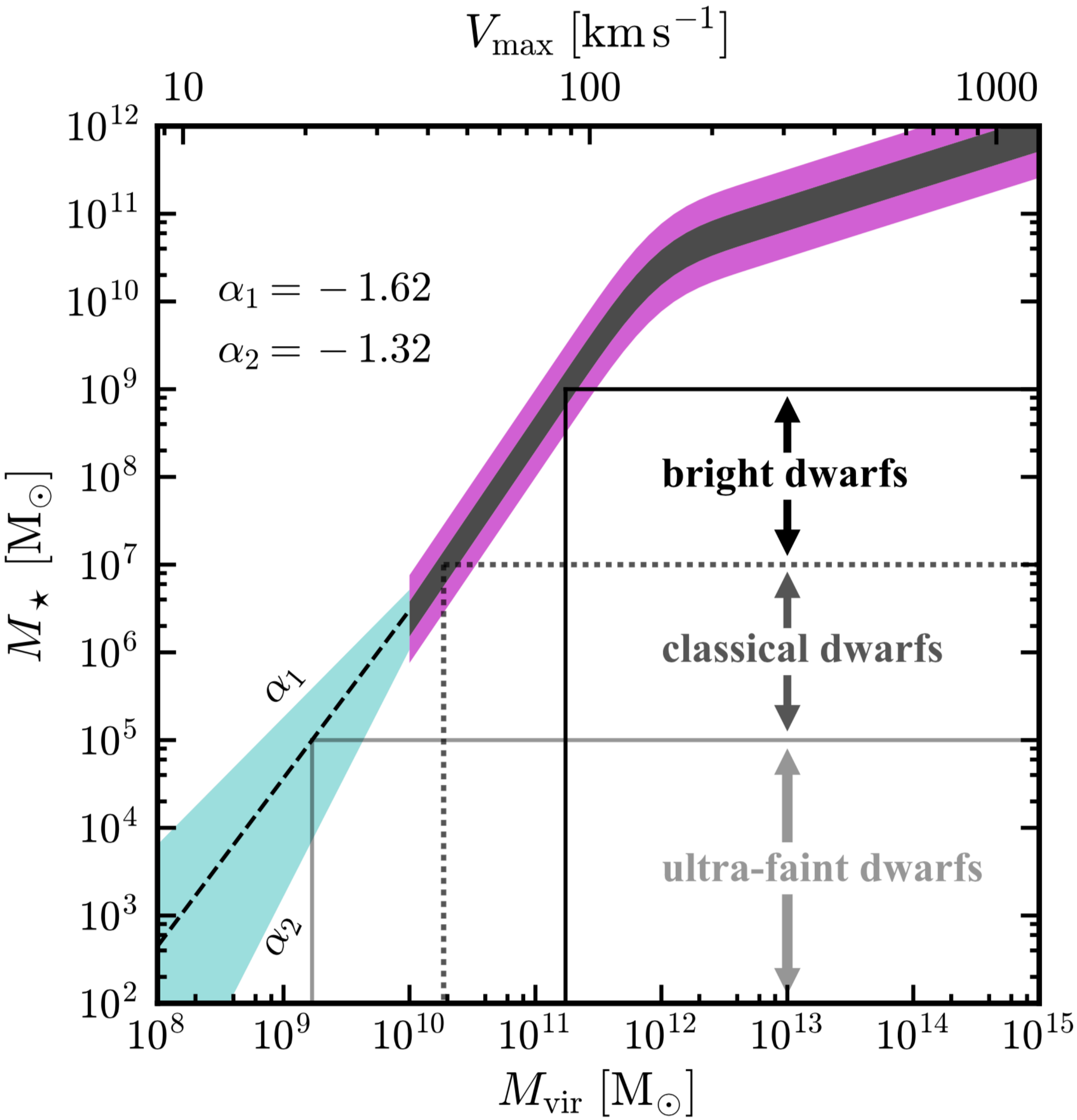


Dark Halo Mass Function vs. Stellar Mass Function



JSB & Boylan-Kolchin, ARAA, 2017

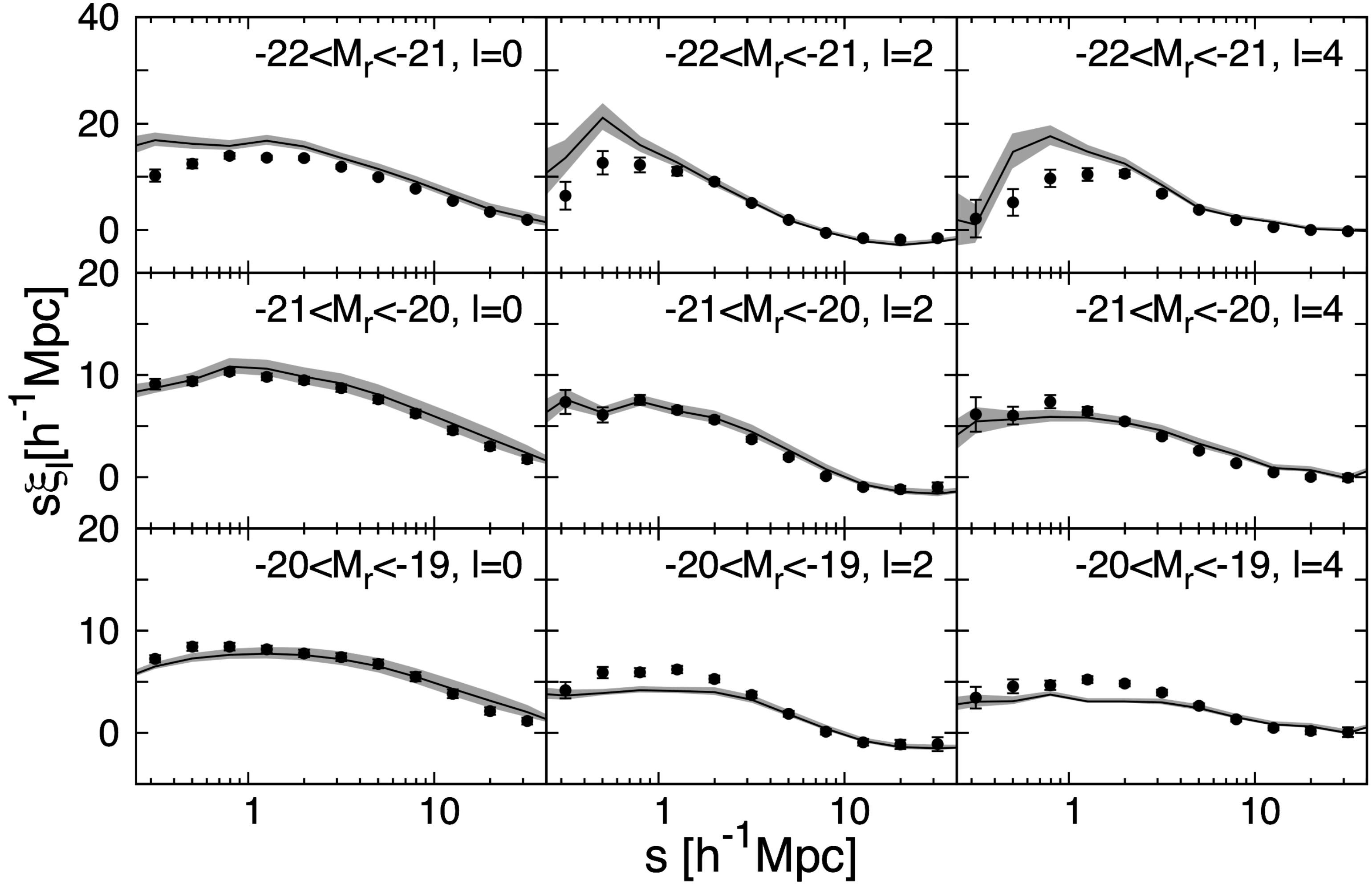
Abundance Matching



JSB & Boylan-Kolchin, ARAA, 2017

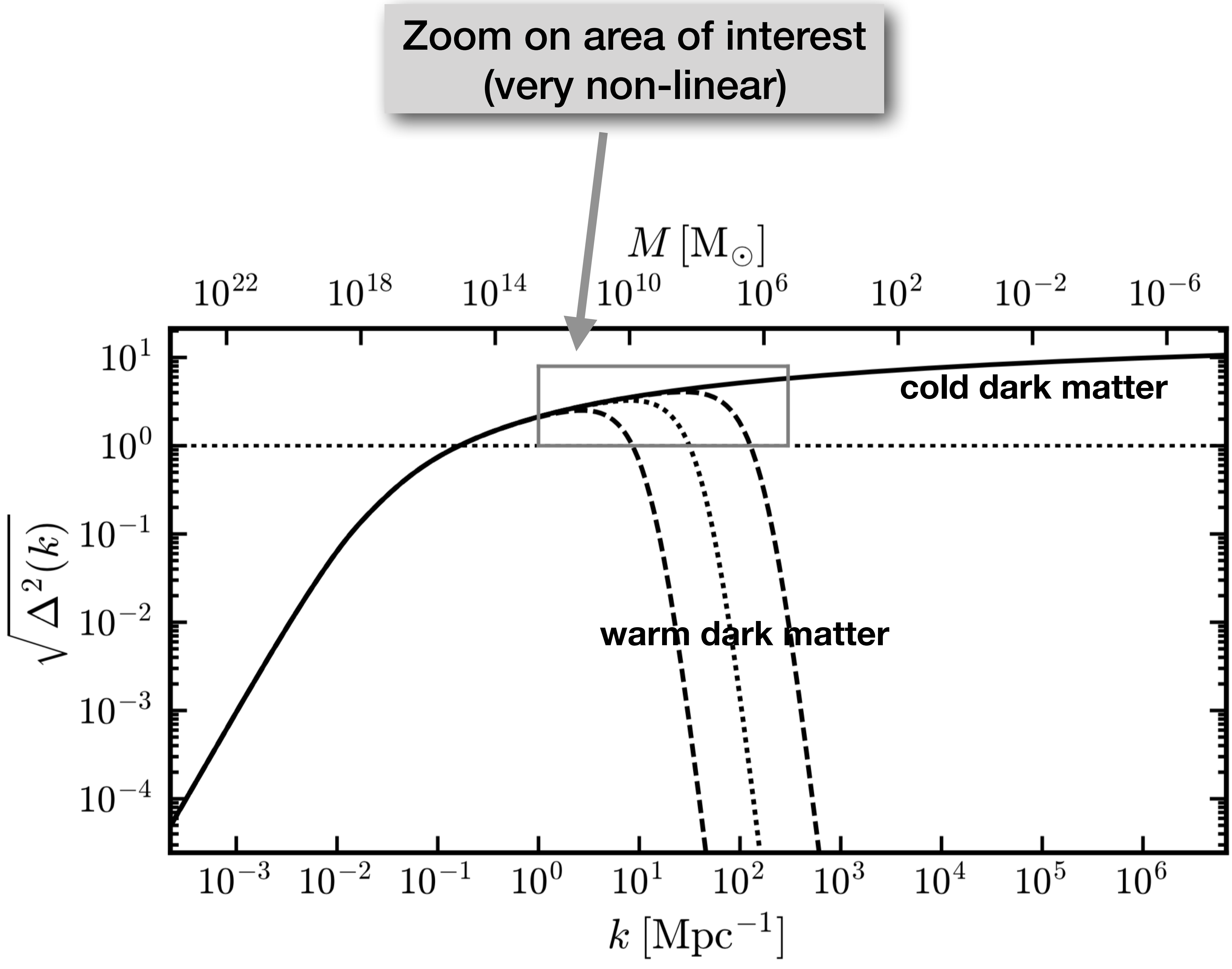
Abundance Matching => Clustering

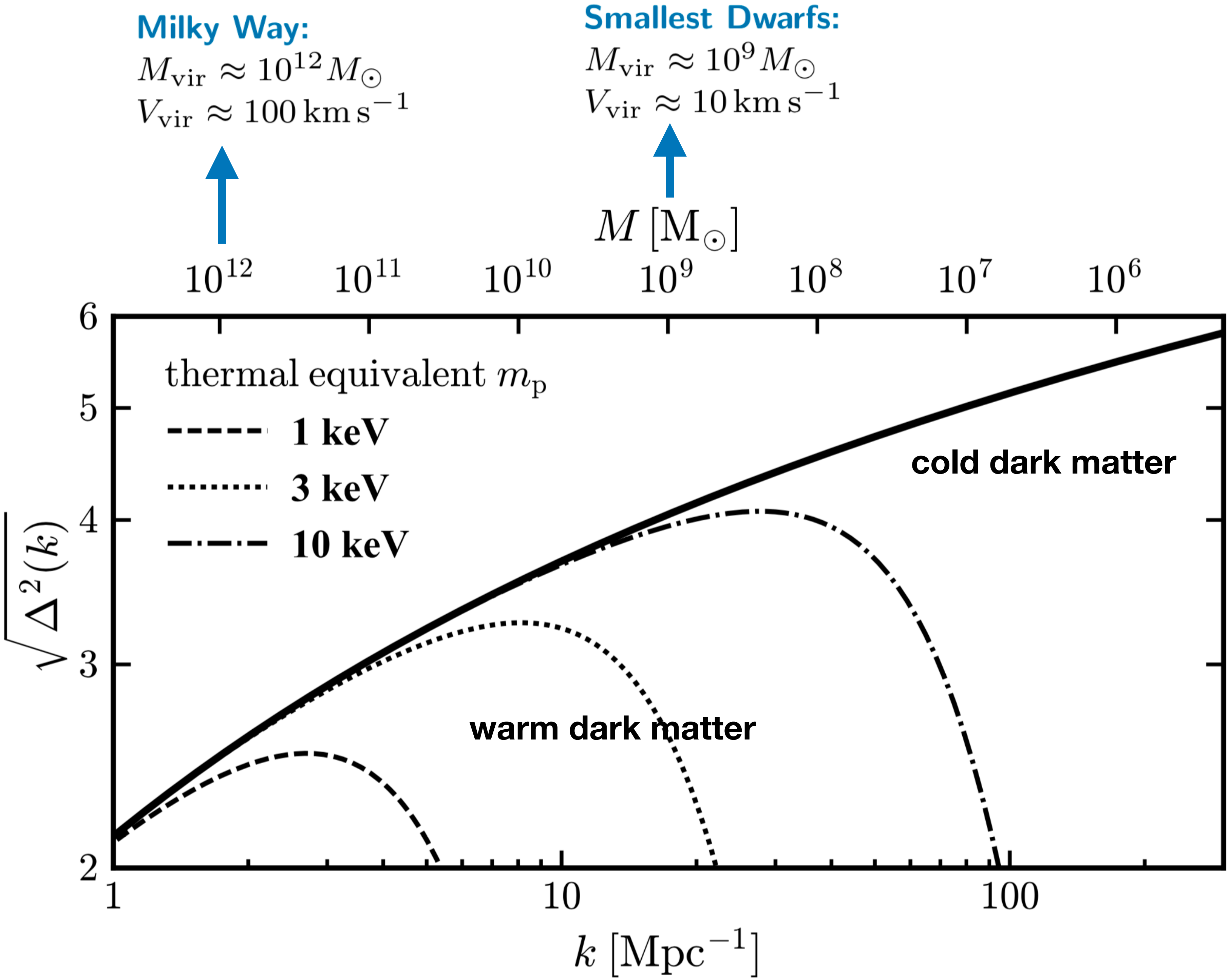
multipole correlation functions sξl(s) (l = 0, 2, 4 from left to right) between SDSS observations (symbols) and halo catalogs (lines)



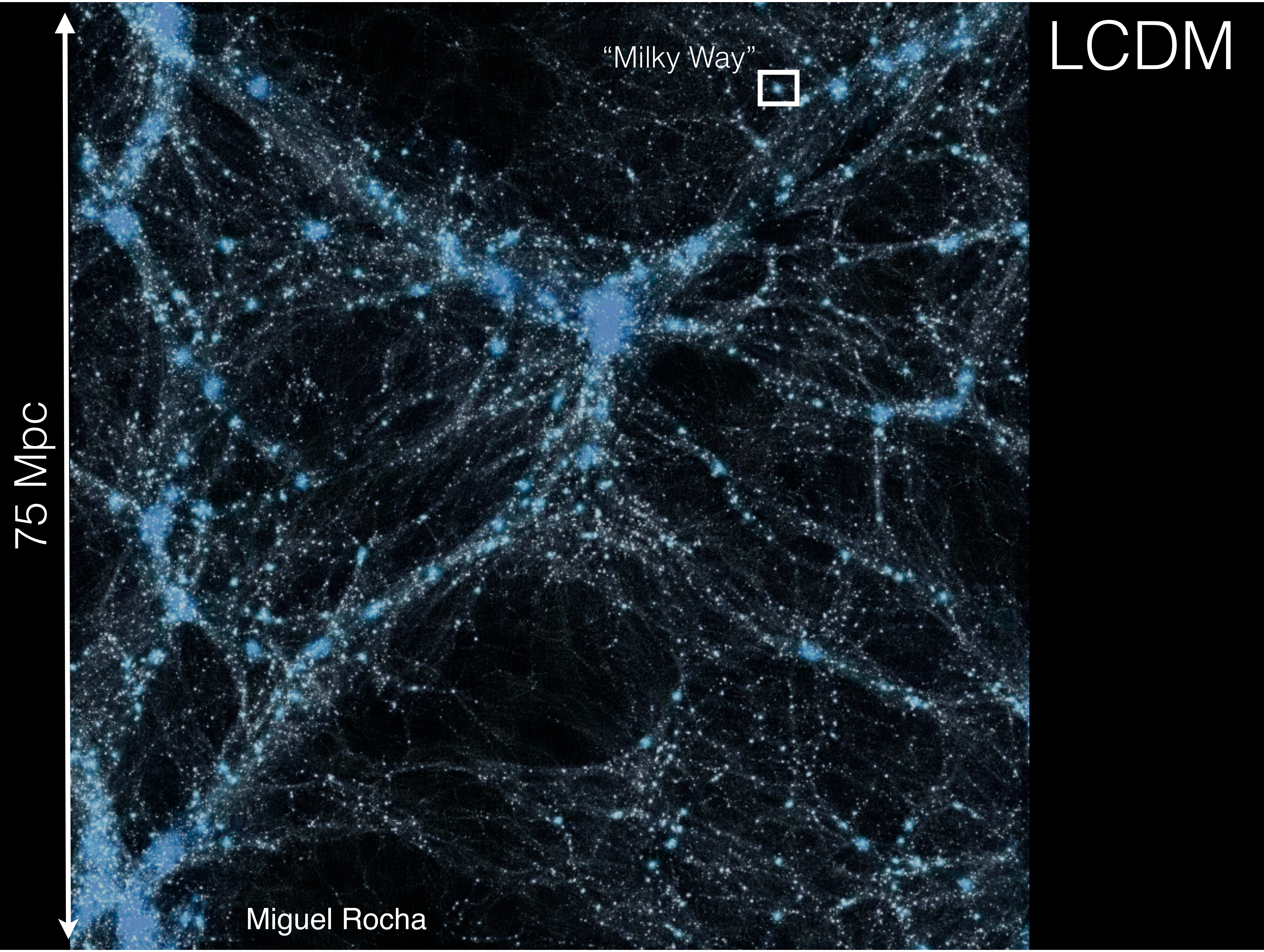
Matches data well at r>1 Mpc

Yamamoto et al. 2015

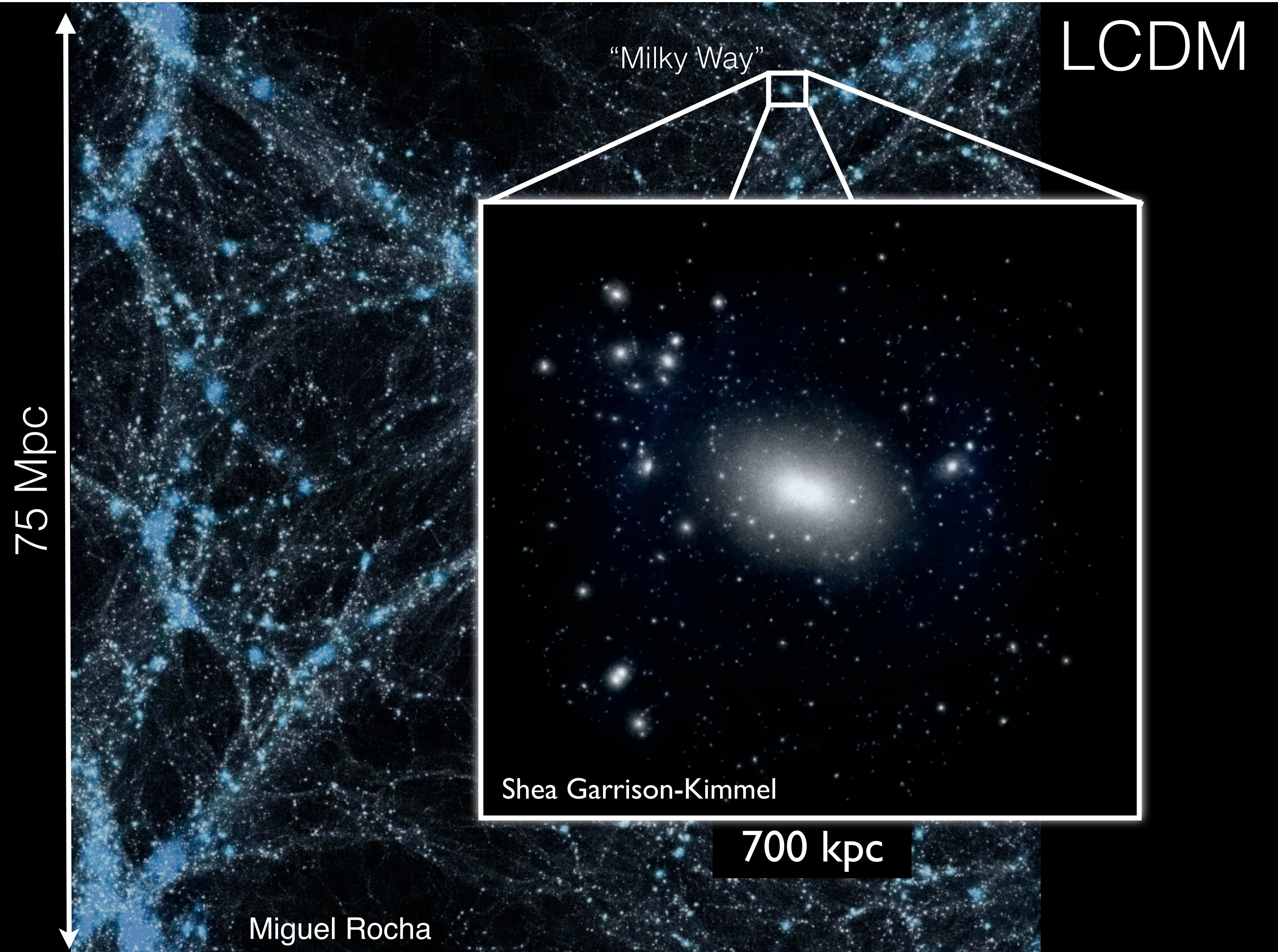

Zoom on area of interest
(very non-linear)
M [M⊙]
10^22
10^18
10^14
10^10
10^6
10^2
10^-2
10^-6
10^1
10^0
10^-1
10^-2
10^-3
10^-4
√Δ²(k)
cold dark matter
warm dark matter
10^-3
10^-2
10^-1
10^0
10^1
10^2
10^3
10^4
10^5
10^6
k [Mpc^-1]



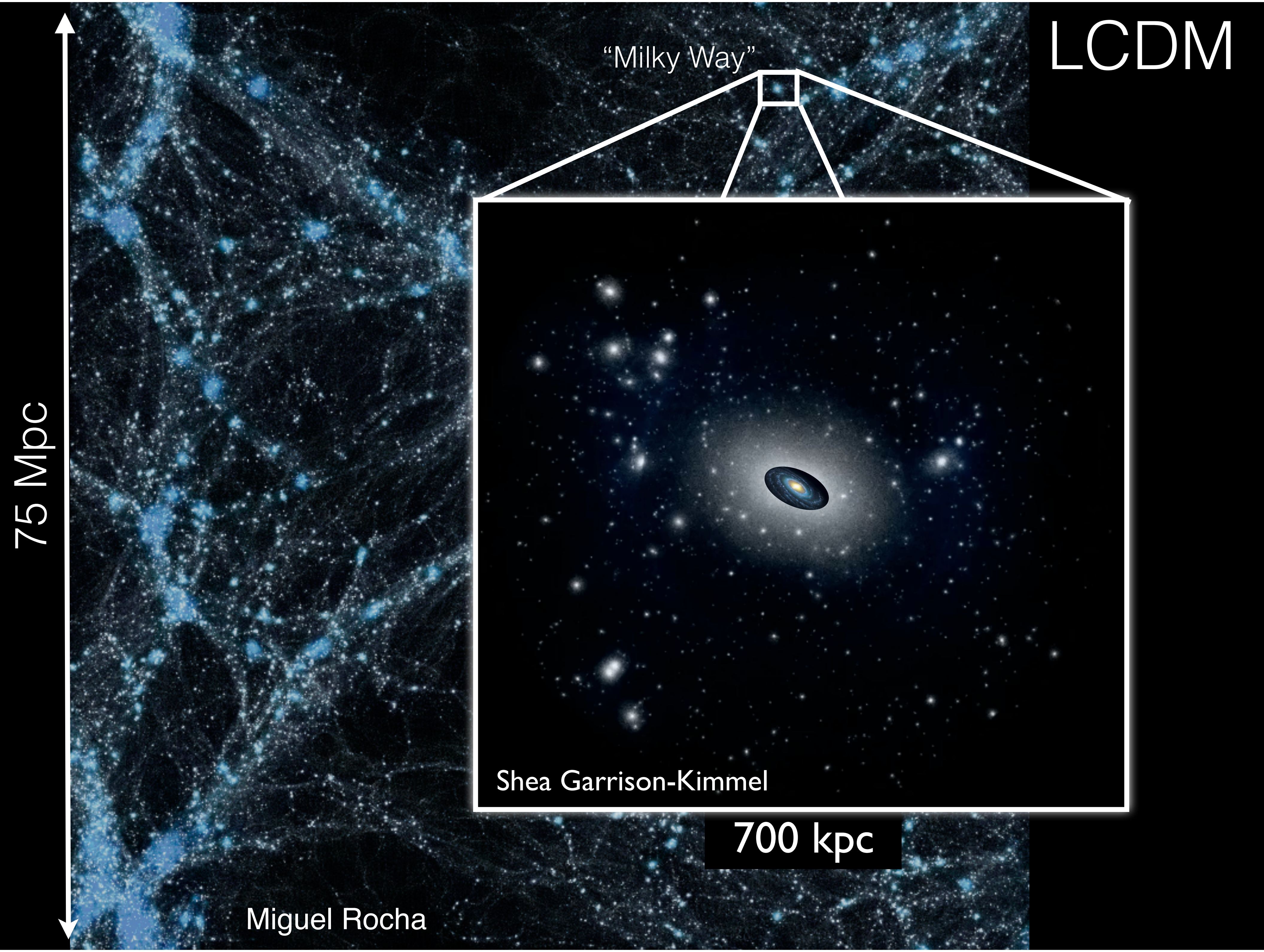
JSB & Boylan-Kolchin, ARAA, 2017



LCDM
"Milky Way"
75 Mpc
Miguel Rocha

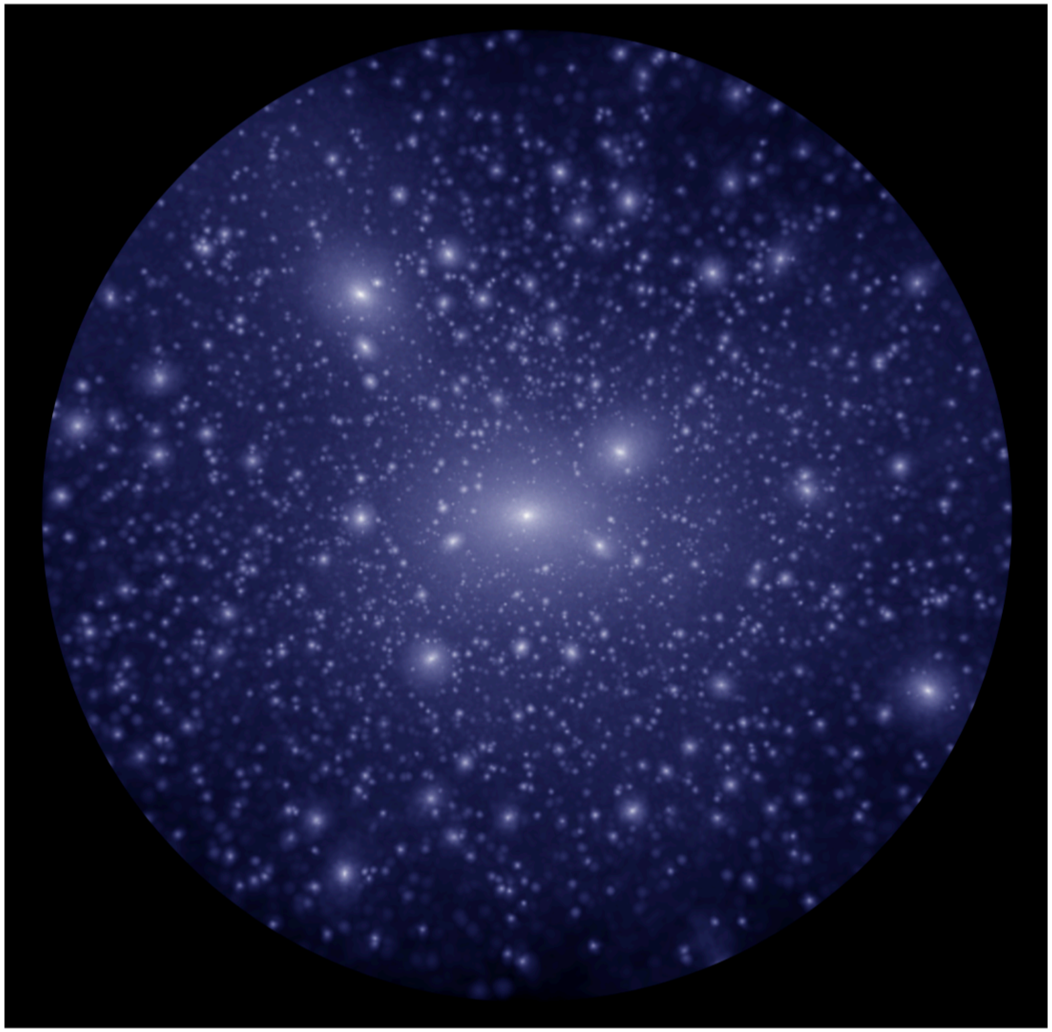


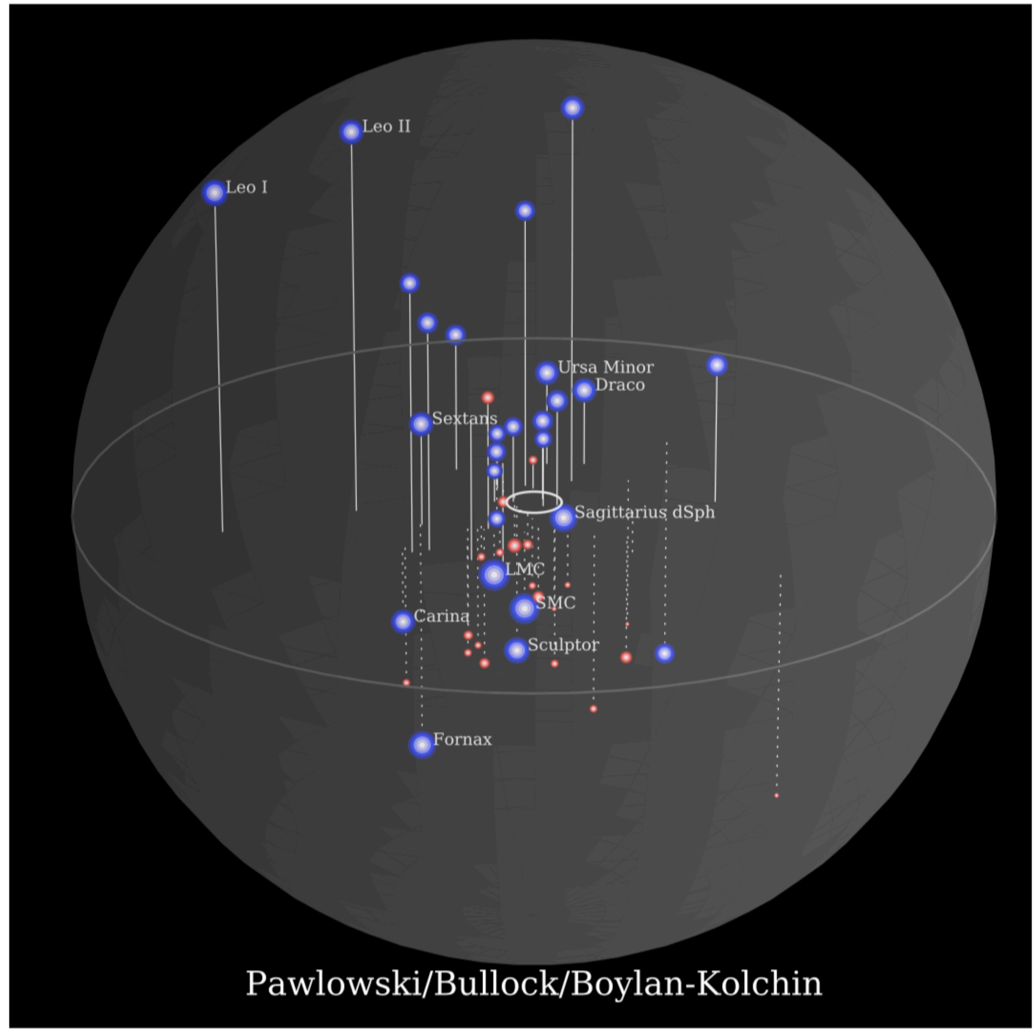
LCDM
"Milky Way"
75 Mpc
Shea Garrison-Kimmel
700 kpc
Miguel Rocha



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

Missing Satellites Problem



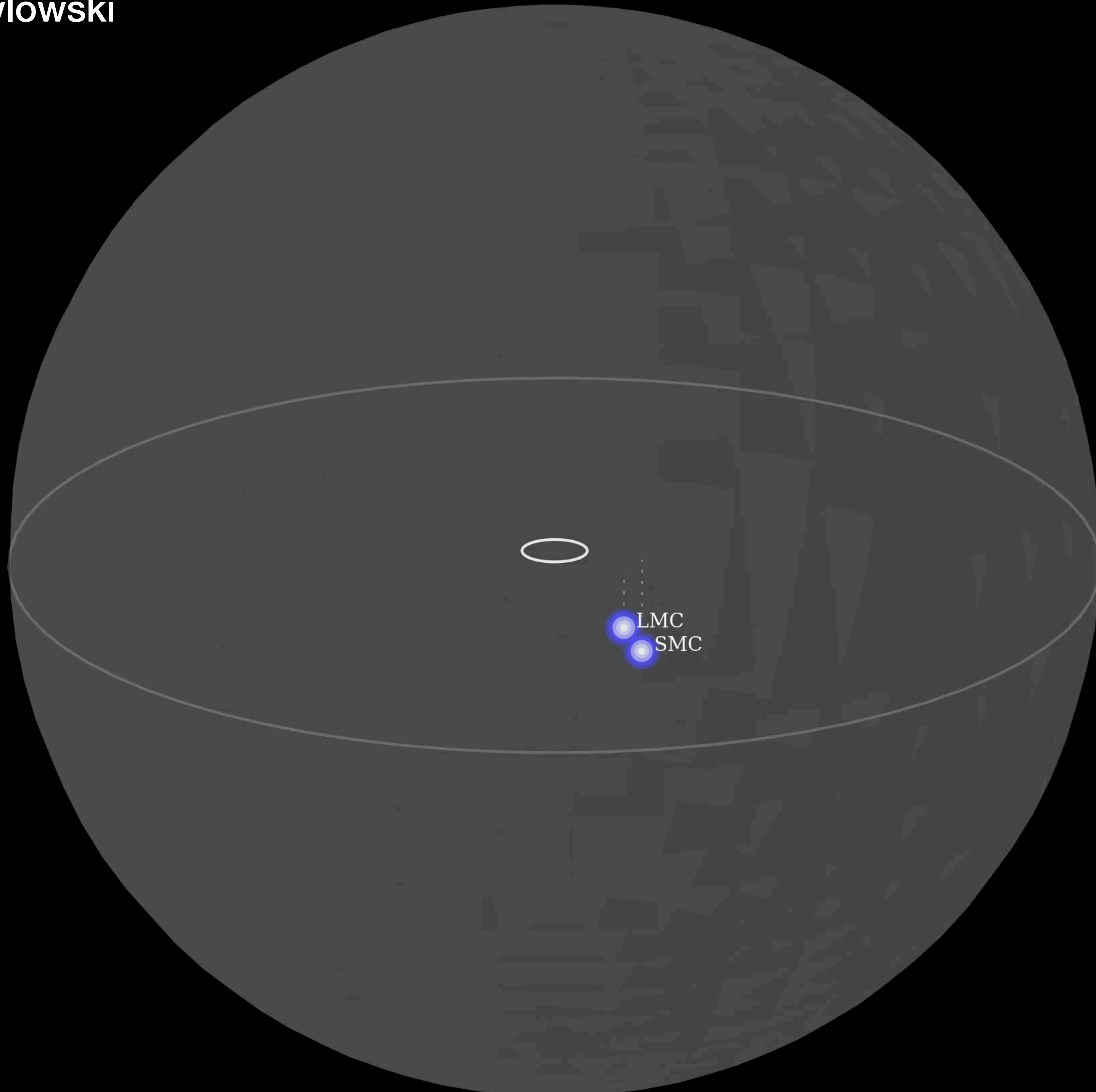


Milky Way:

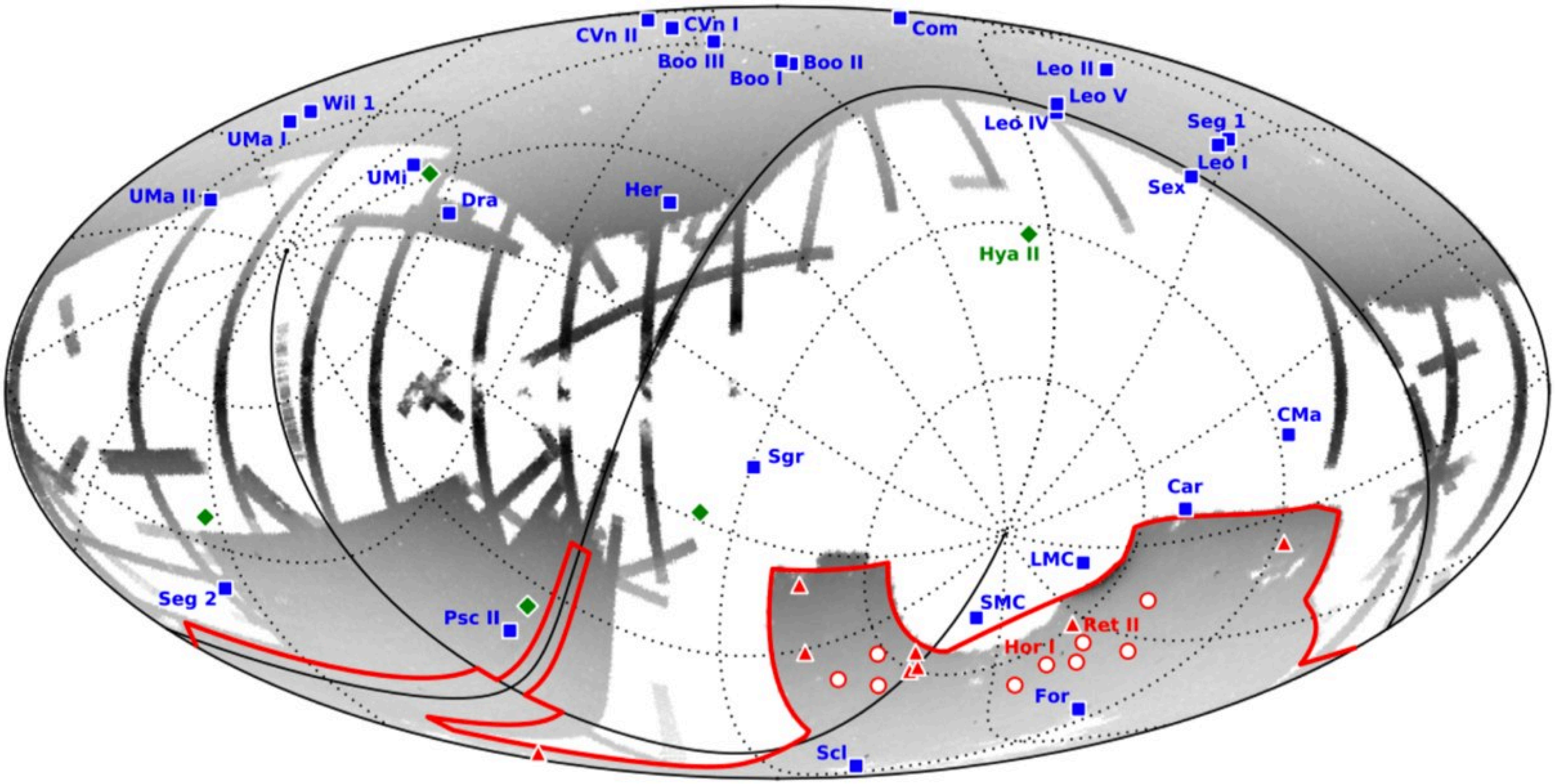
$M_{\rm vir} \approx 10^{12} M_\odot$

$V_{\rm vir} \approx 100\,{\rm km\,s^{-1}}$

Klypin et al. 1999; Moore et al. 1999



Year 1916



CVn II
CVn I
Com
Boo III
Boo II
Boo I
Leo II
Leo V
Wil 1
Leo IV
Seg 1
UMa I
Leo I
UMi
Sex
UMa II
Dra
Her
Hya II
CMa
Sgr
Car
LMC
Seg 2
SMC
Psc II
Ret II
Hor I
For
Scl

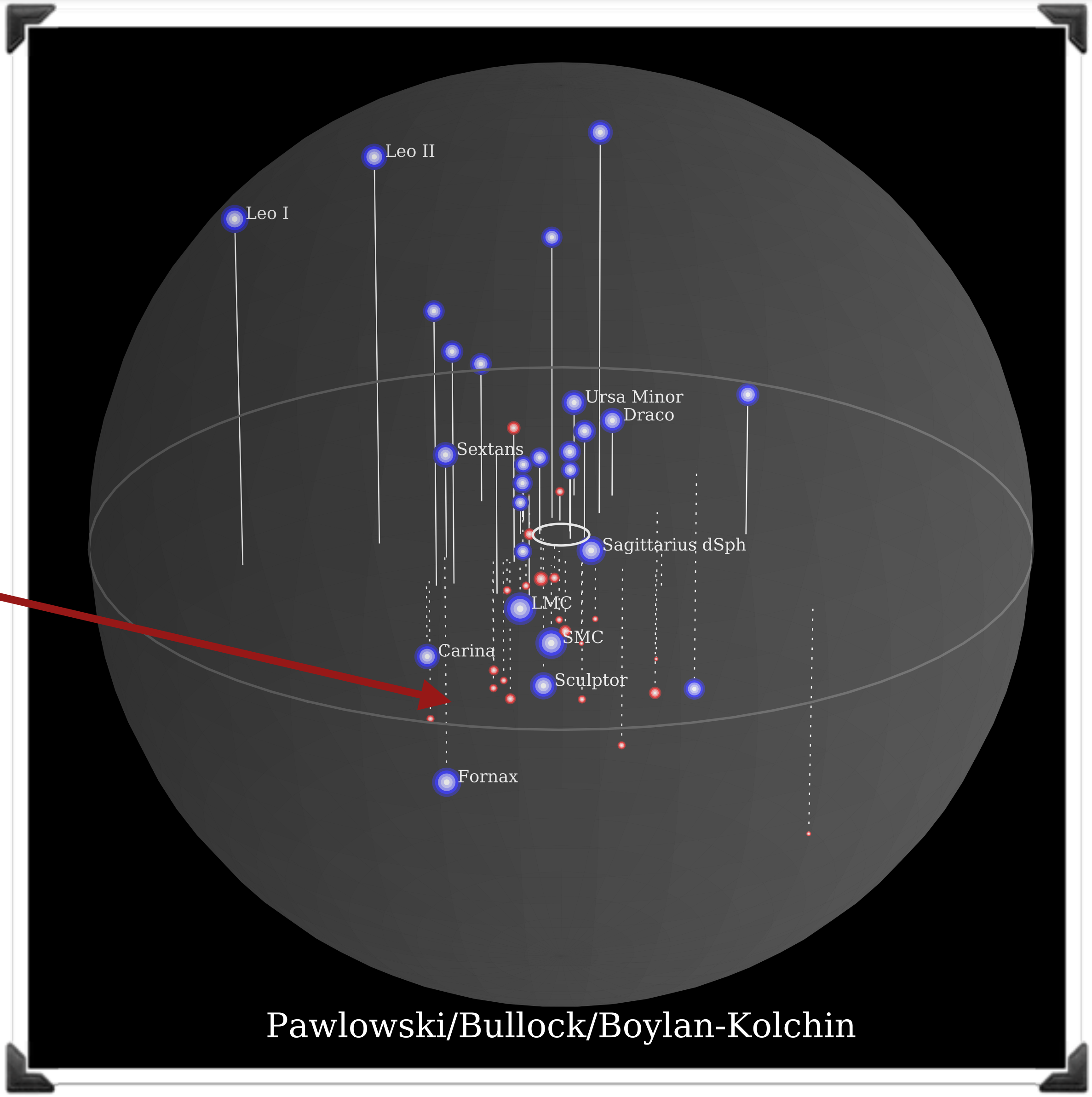
SDSS, DES, etc.

2018: ~50 satellite galaxies

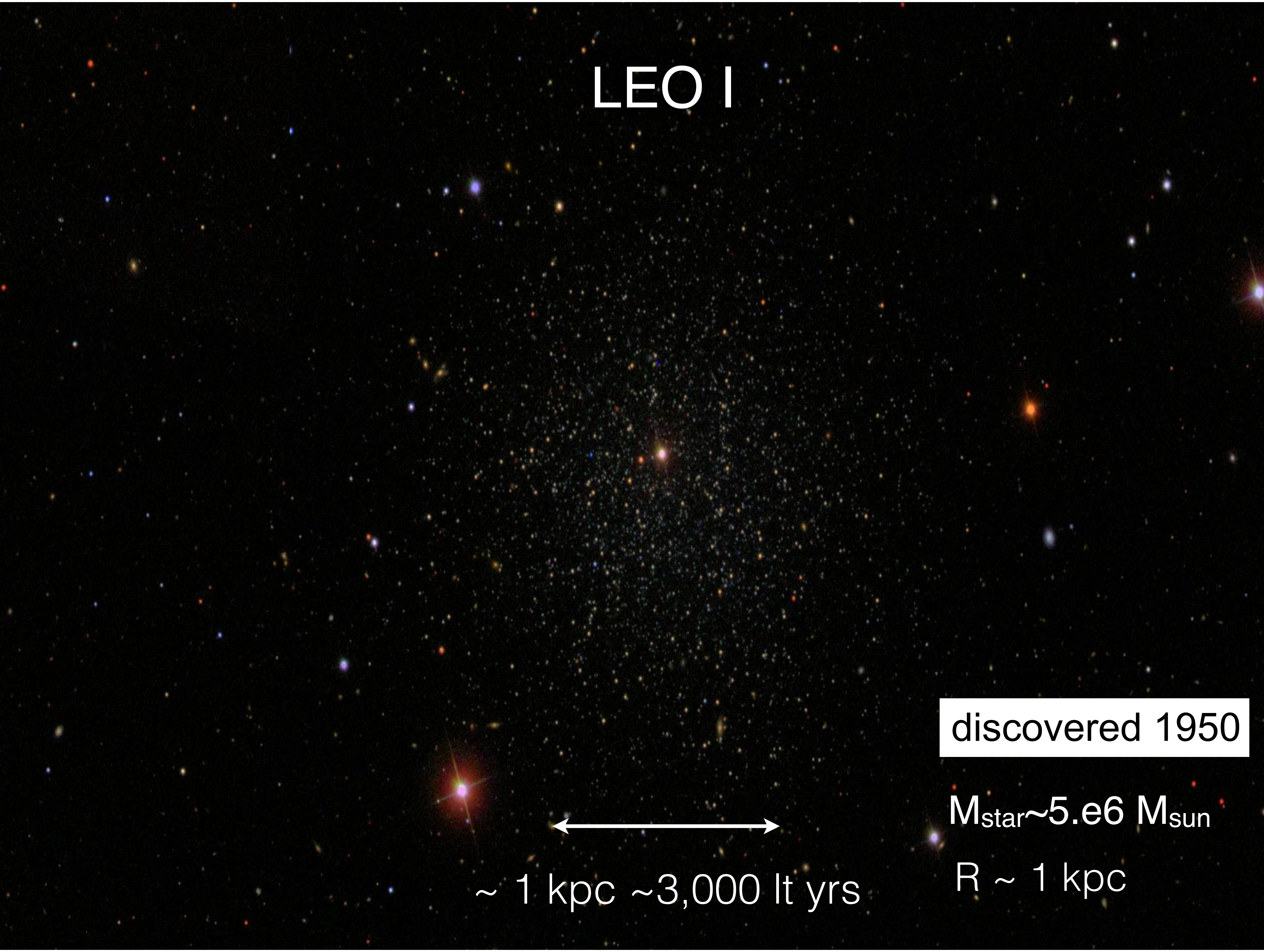
Five-fold increase in last in 14 yrs

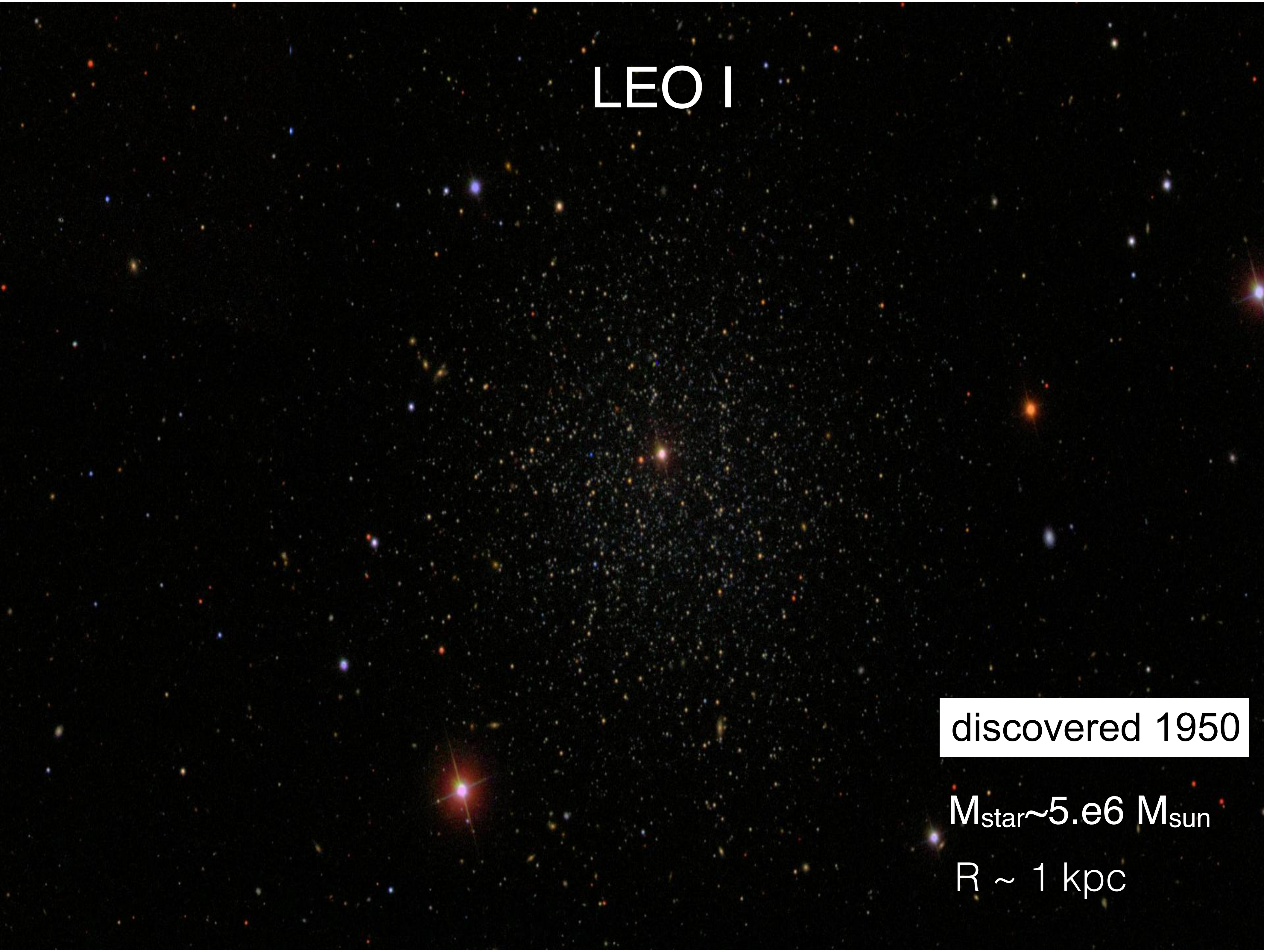
Red points are newest from Dark Energy Survey

LSST will discovery many more



Willman et al. 2005; Zucker et al. 2006; Belokurov et al. 2007
Koposov et al. 2015a; Bechtol et al. 2015; Kim et al. 2015


LEO I
discovered 1950
M_{star}~5.e6 M_{sun}
R ~ 1 kpc
~ 1 kpc ~3,000 lt yrs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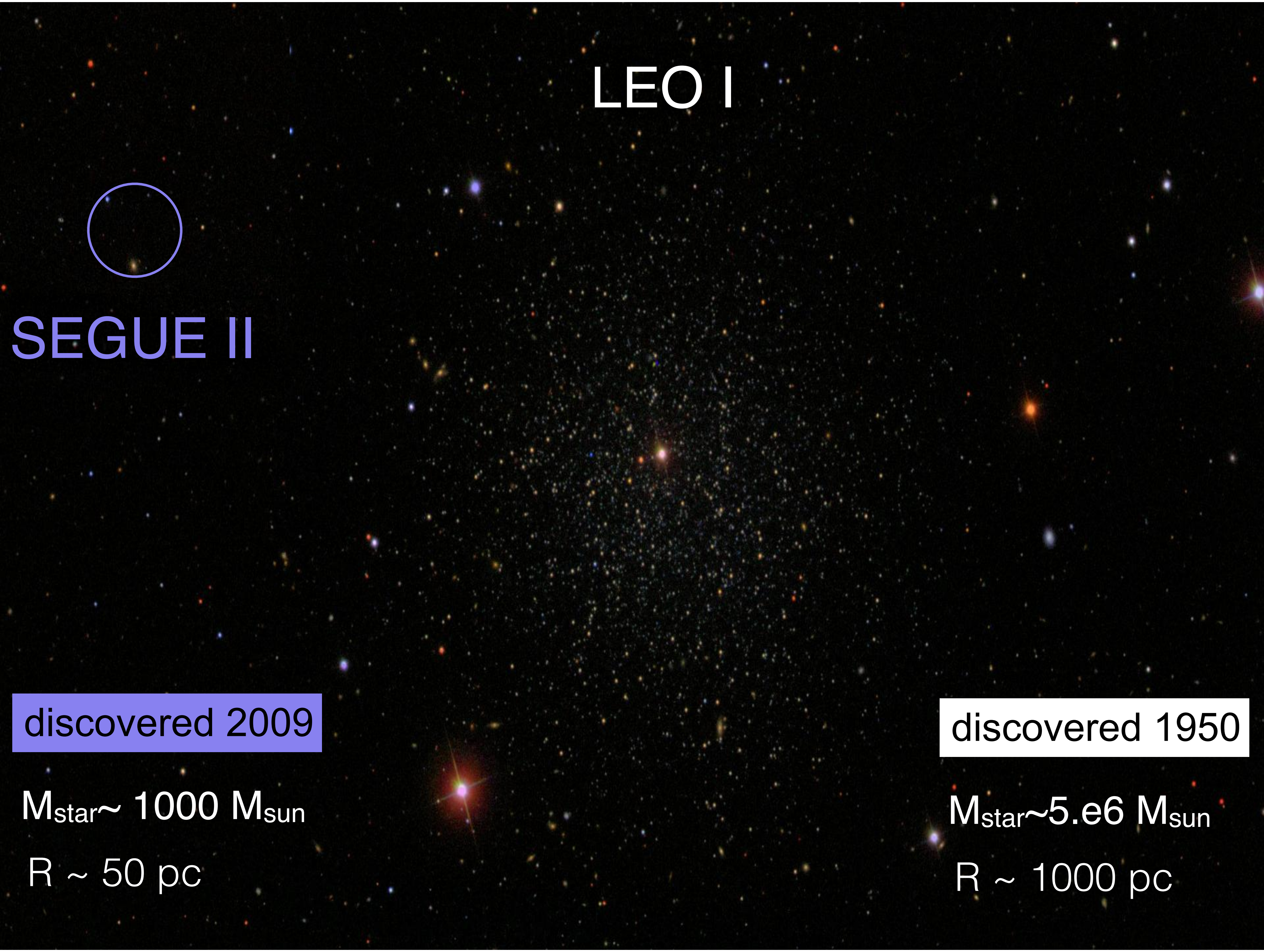
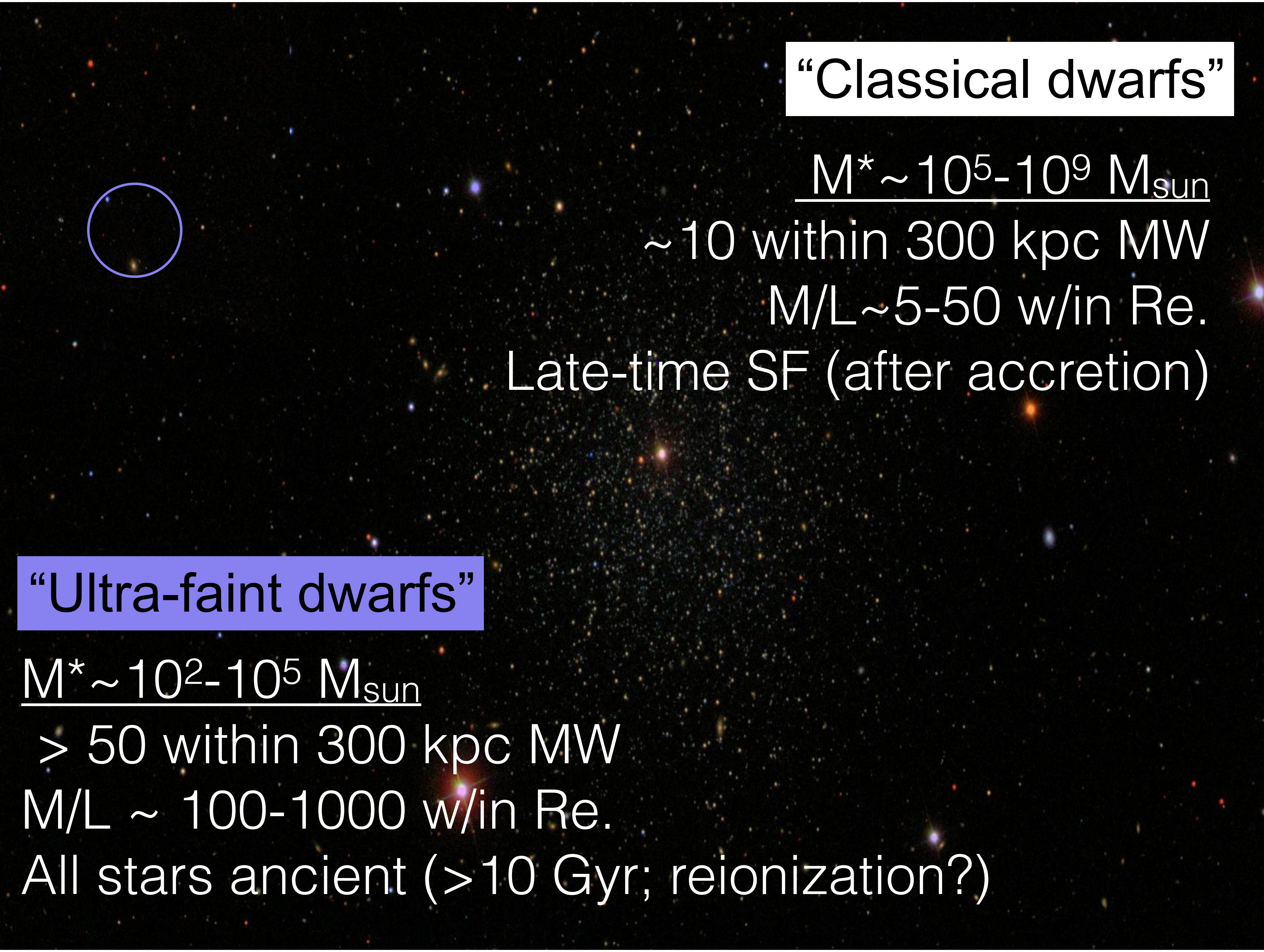

LEO I
SEGUE II
discovered 2009
Mstar~ 1000 Msun
R ~ 50 pc
discovered 1950
Mstar~5.e6 Msun
R ~ 1000 pc

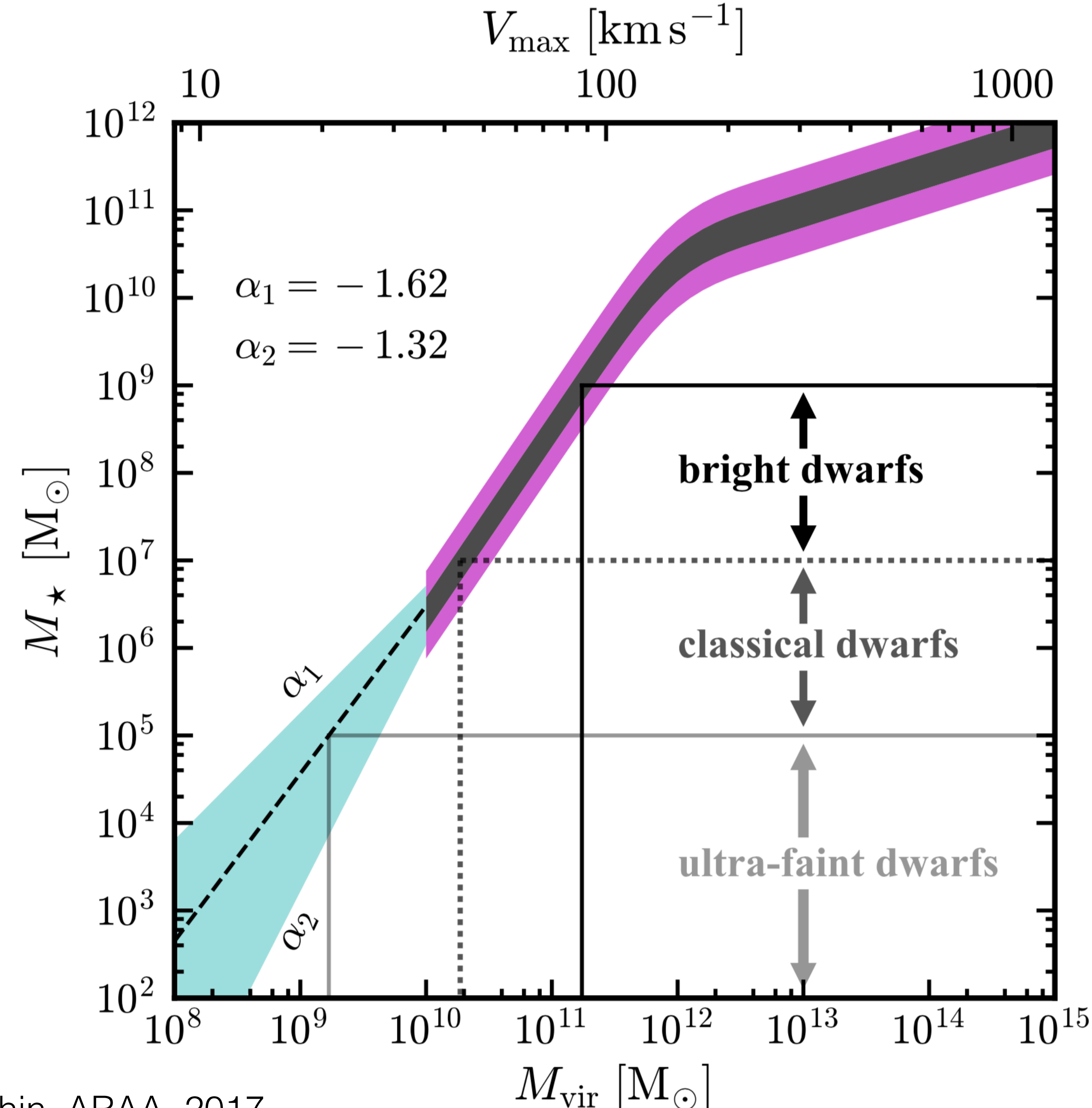


“Classical dwarfs”
$M^* \sim 10^5$-10^9 M_{sun}
~10 within 300 kpc MW
M/L~5-50 w/in Re.
Late-time SF (after accretion)
“Ultra-faint dwarfs”
$M^* \sim 10^2$-10^5 M_{sun}
> 50 within 300 kpc MW
M/L ~ 100-1000 w/in Re.
All stars ancient (>10 Gyr; reionization?)

Bright Dwarfs:
$M_\star \approx 10^8 M_\odot$
$M_{\rm vir} \approx 10^{11} M_\odot$
$M_\star / M_{\rm vir} \approx 10^{-3}$

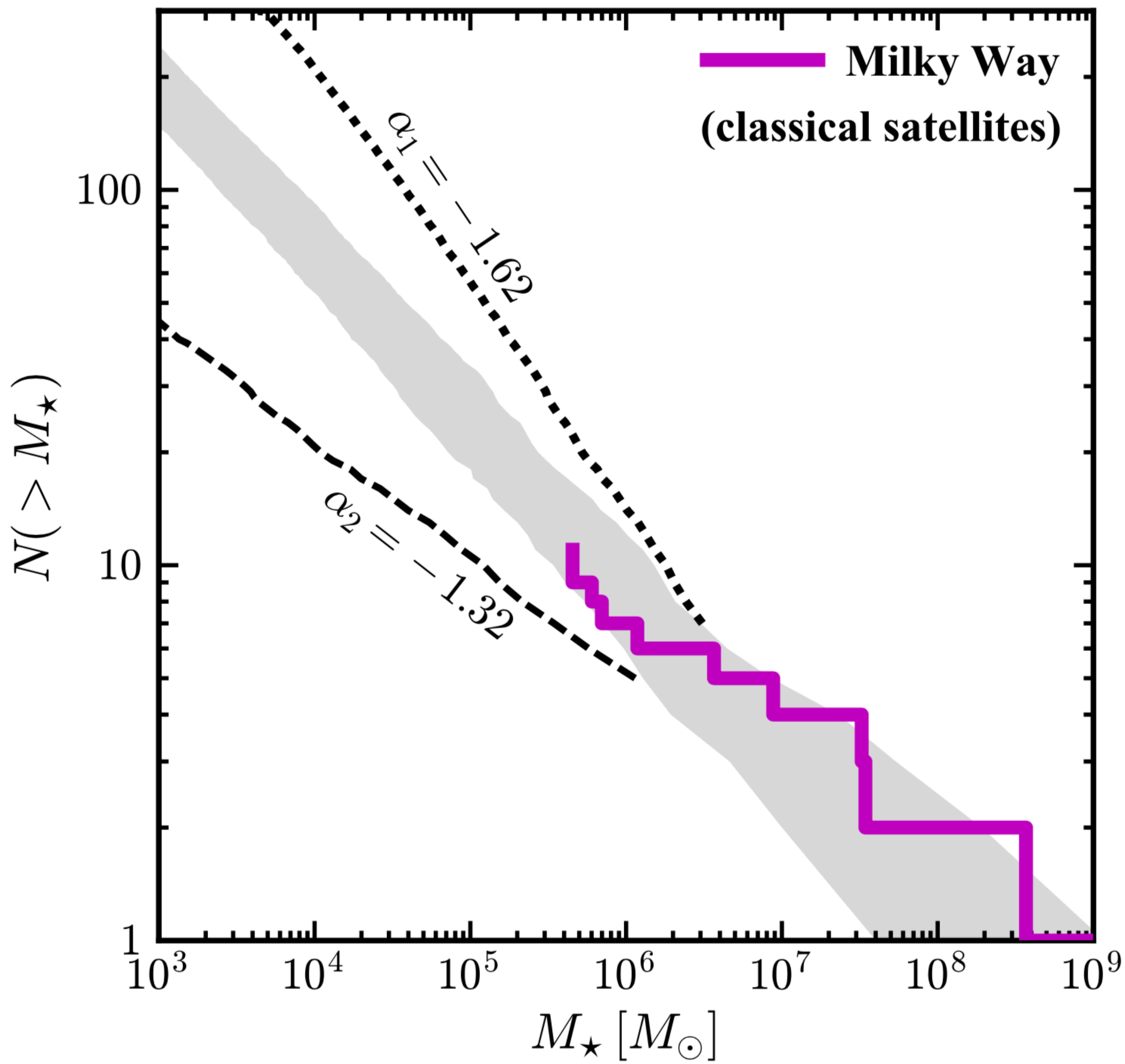
Classical Dwarfs:
$M_\star \approx 10^6 M_\odot$
$M_{\rm vir} \approx 10^{10} M_\odot$
$M_\star / M_{\rm vir} \approx 10^{-4}$

Ultra-faint Dwarfs:
$M_\star \approx 10^4 M_\odot$
$M_{\rm vir} \approx 10^9 M_\odot$
$M_\star / M_{\rm vir} \approx 10^{-5}$



JSB & Boylan-Kolchin, ARAA, 2017

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



JSB & Boylan-Kolchin, ARAA, 2017

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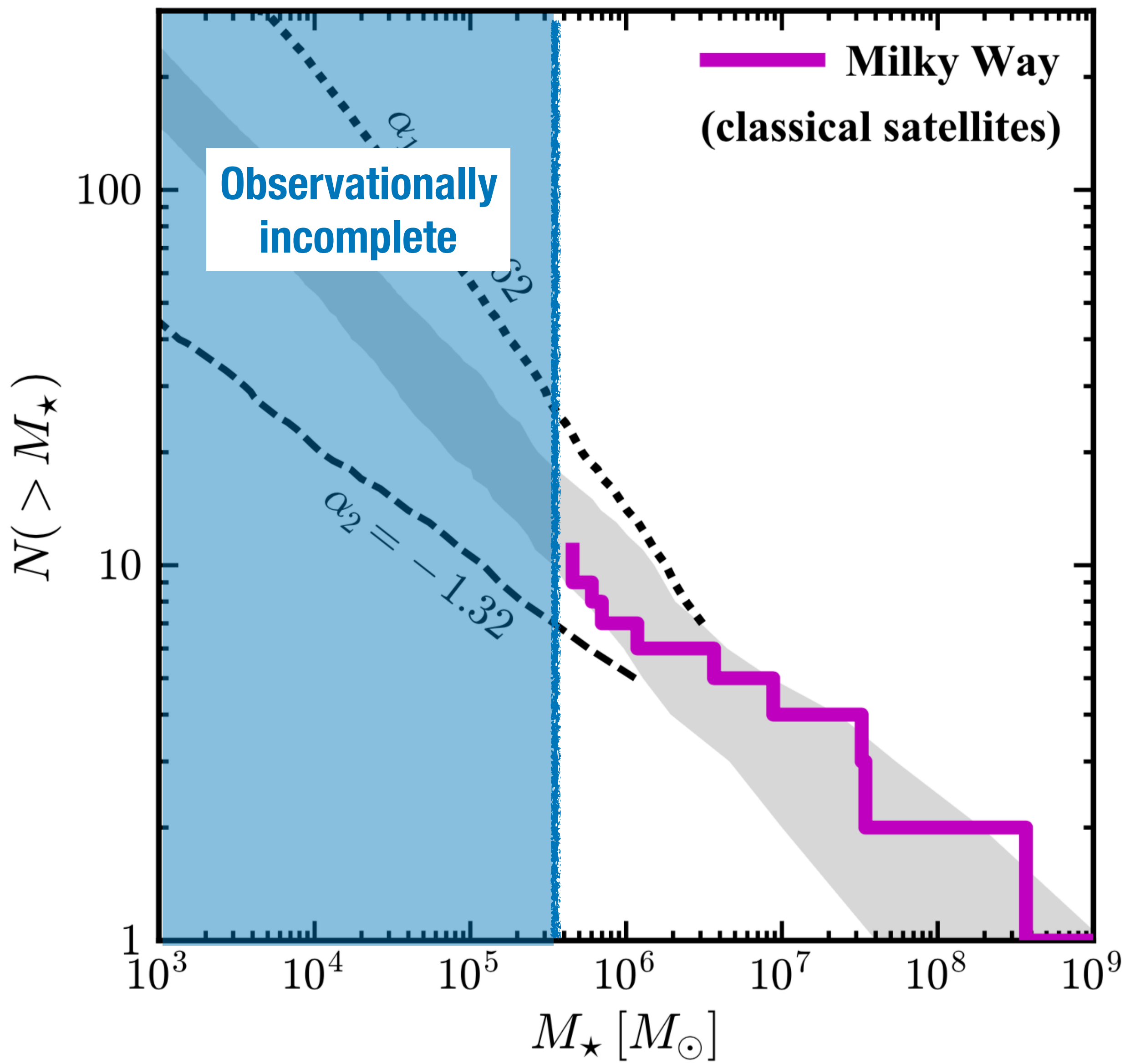
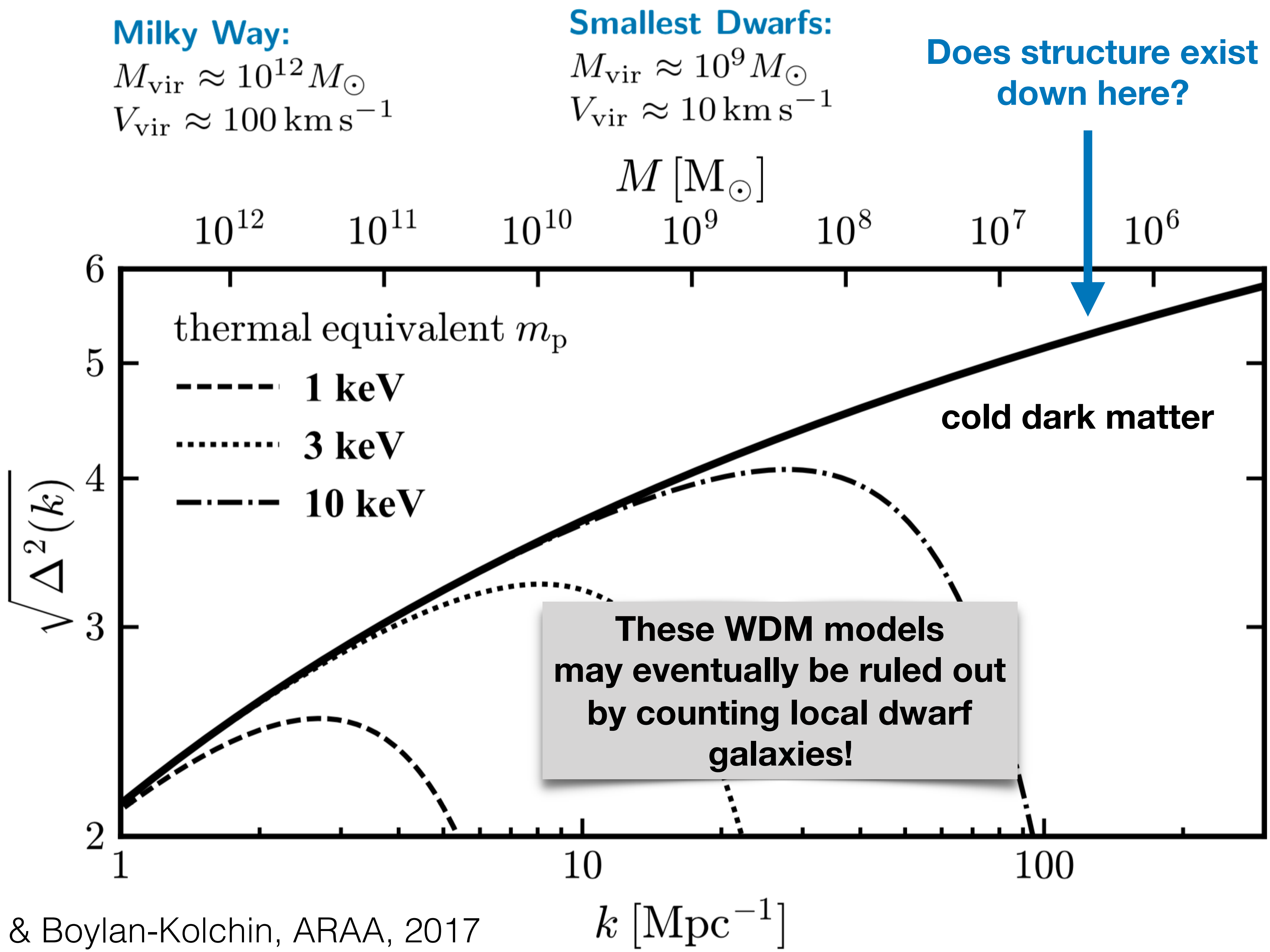
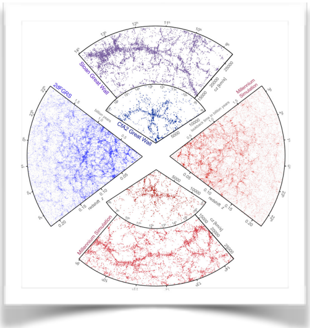


JSB & Boylan-Kolchin, ARAA, 2017

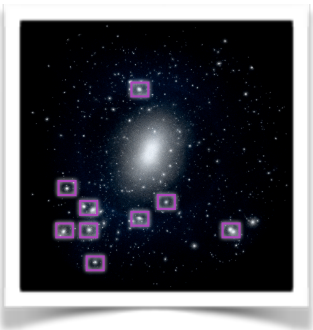


JSB & Boylan-Kolchin, ARAA, 2017

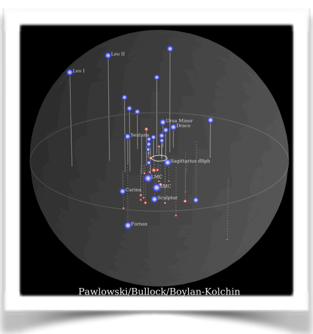
Summary So Far:



1. Cold Dark Matter Simulations reproduce structure (clustering) of universe on large scales (mass scales larger than ~ 10^{12} M_{sun} ~ Milky Way halo mass)



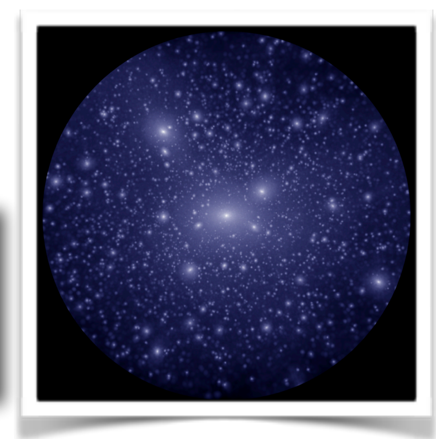
2. Same simulations predict a lot of lower mass substructures.
— Down to masses of about ~ 10^{10} M_{sun} halo mass these objects are consistent with hosting "classical dwarfs"



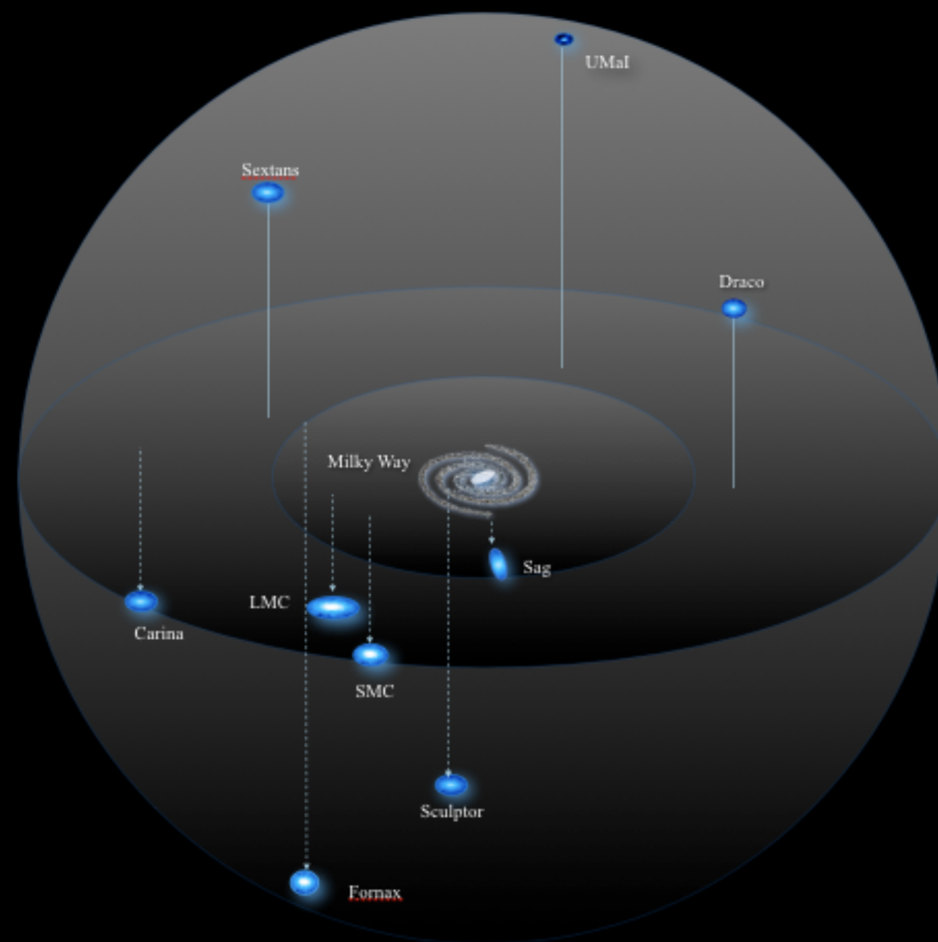
3. Ultra-faint dwarfs may inhabit smaller halos, down to ~10^9 M_{sun} (?) halo mass. Currently hard to say. New detections with future surveys (LSST) will test.

Big Q: Is there truly <u>dark</u> substructure?

The detection of abundant, baryon-free, low-mass dark matter halos would be an unambiguous validation of the particle dark matter paradigm



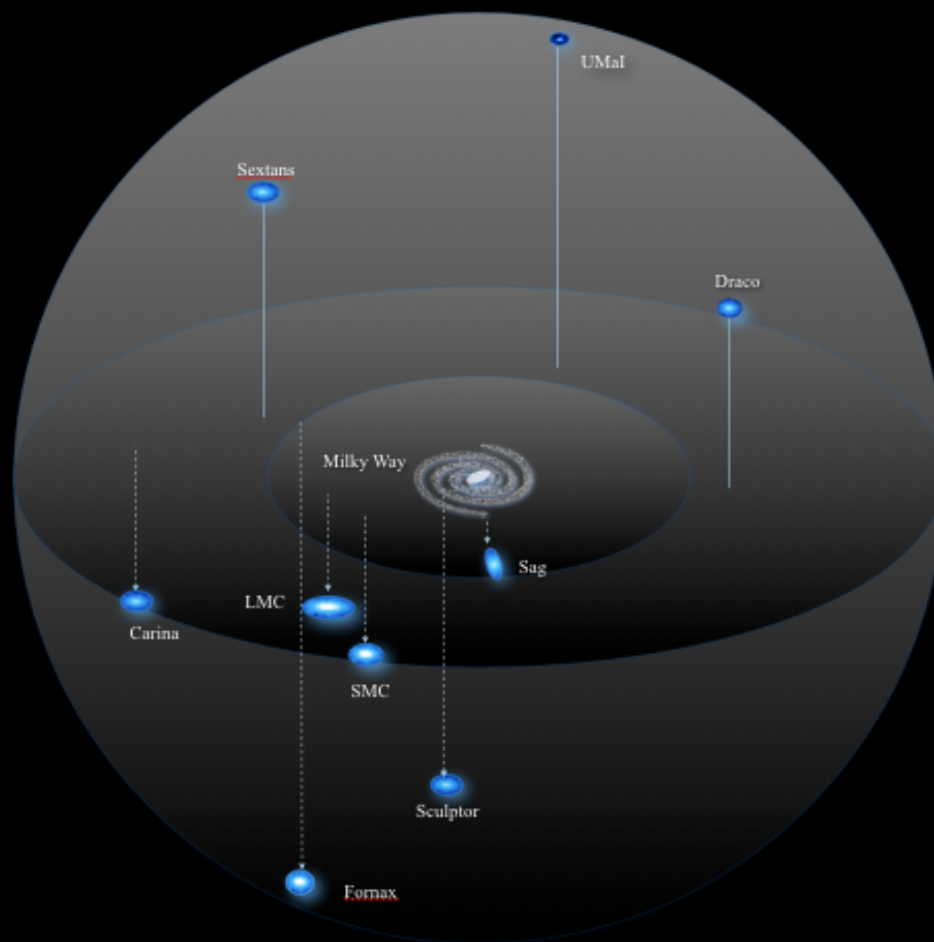
“NATURAL” ANSWER TO MISSING SATELLITES



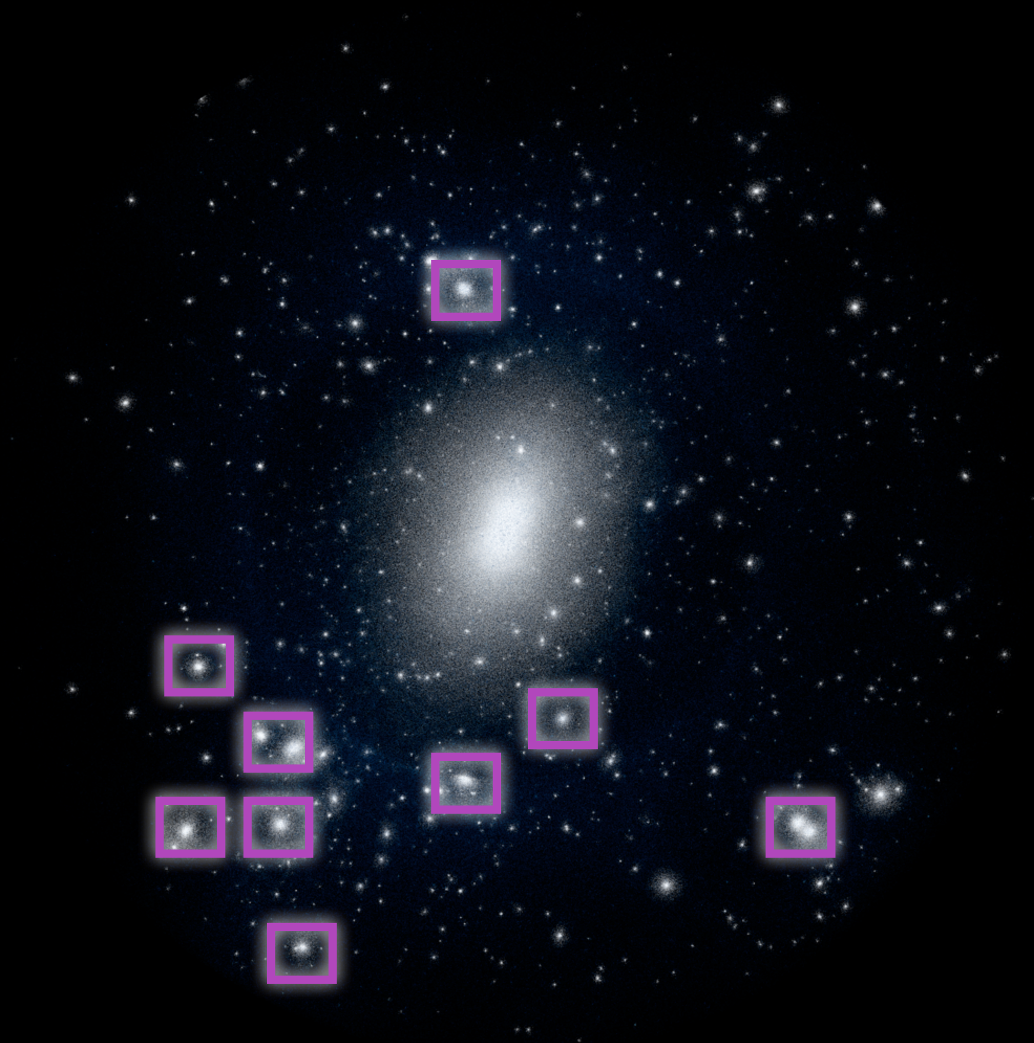
only the biggest clumps have enough stars to see?

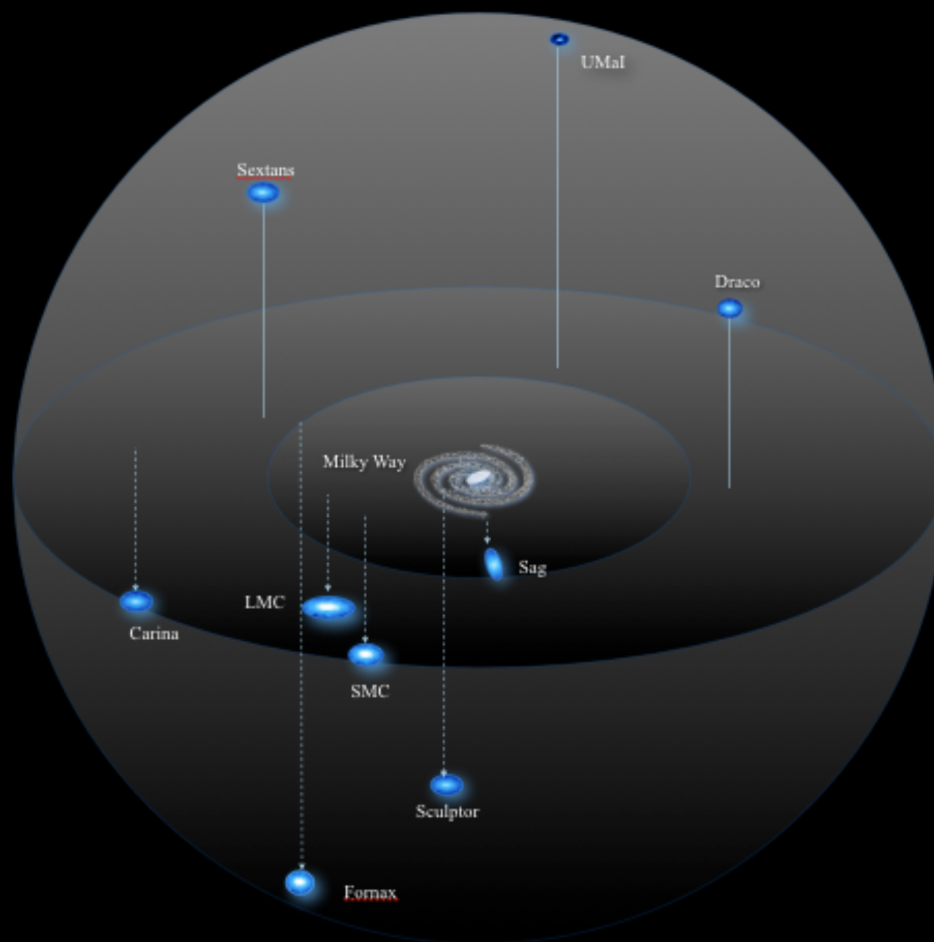
e.g. JSB, Kravtsov, & Weinberg 2000

“EASY” ANSWER


UMaI
Sextans
Draco
Milky Way
Sag
LMC
Carina
SMC
Sculptor
Fornax

“EASY” ANSWER




UMaI
Sextans
Draco
Milky Way
Sag
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Carina
SMC
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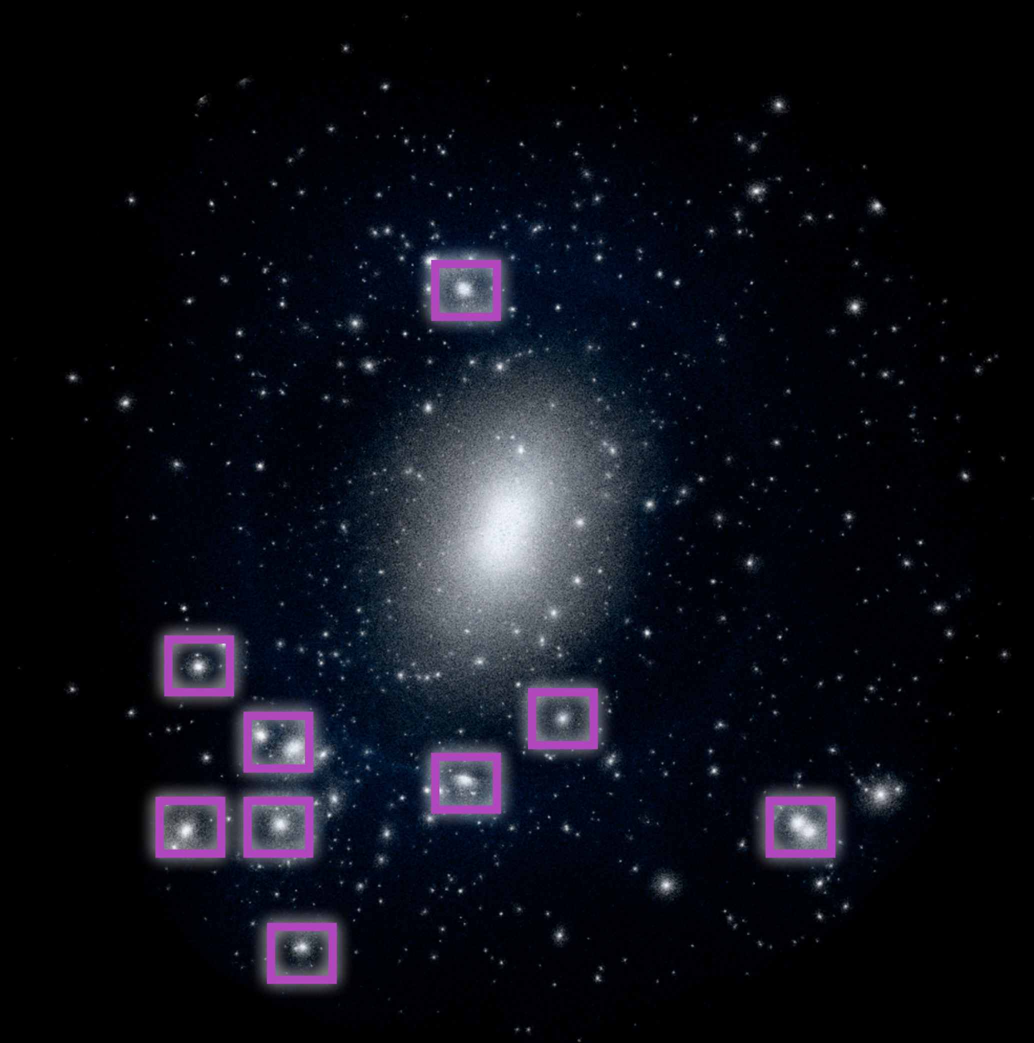
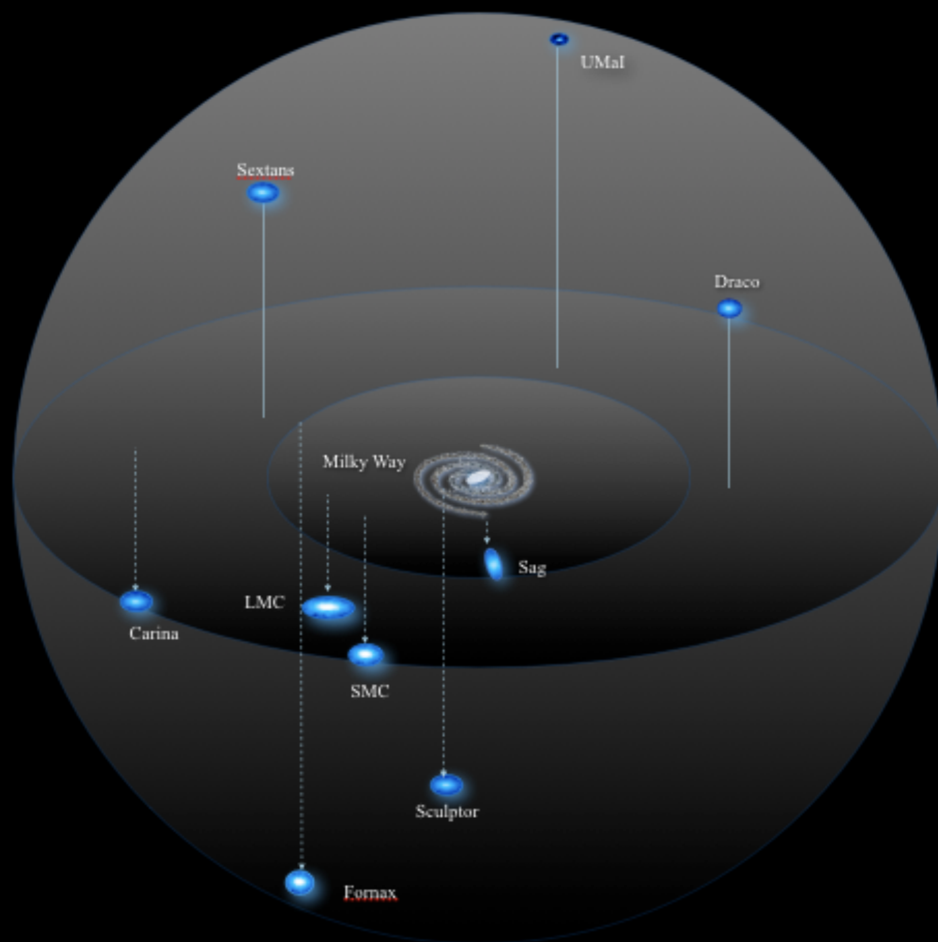
Fornax

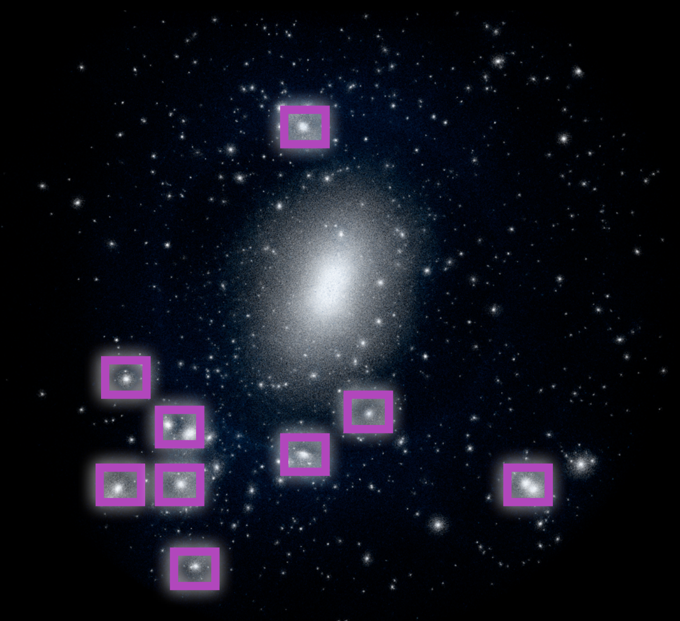
DOES THIS ACTUALLY WORK?

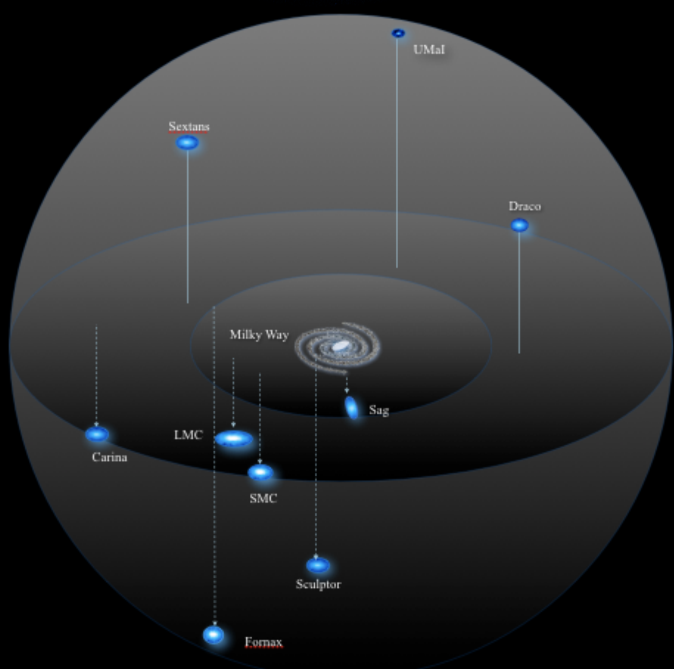


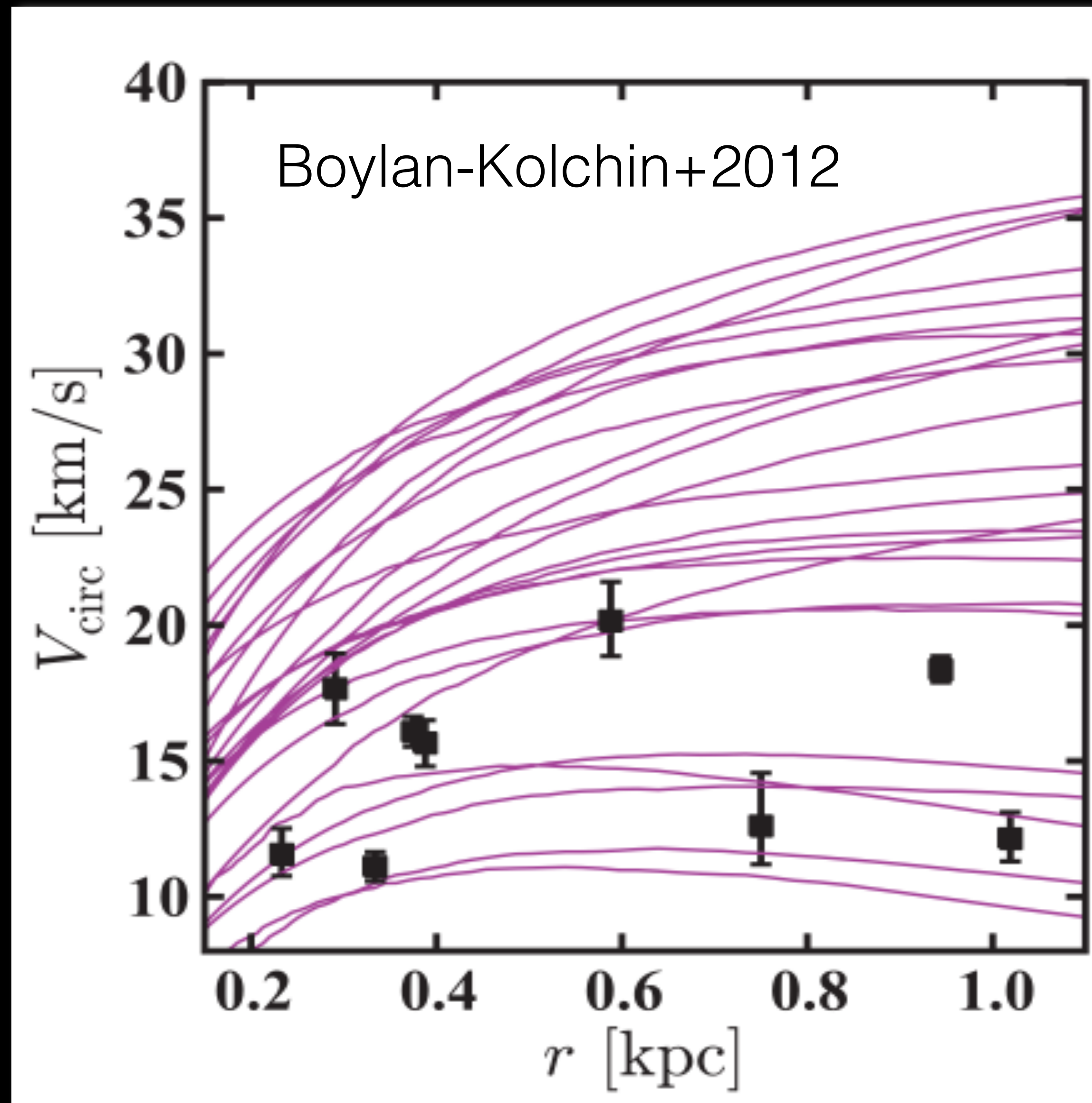


NOPE: “TOO BIG TO FAIL PROBLEM”

Massive subhalos are **too dense** to match data

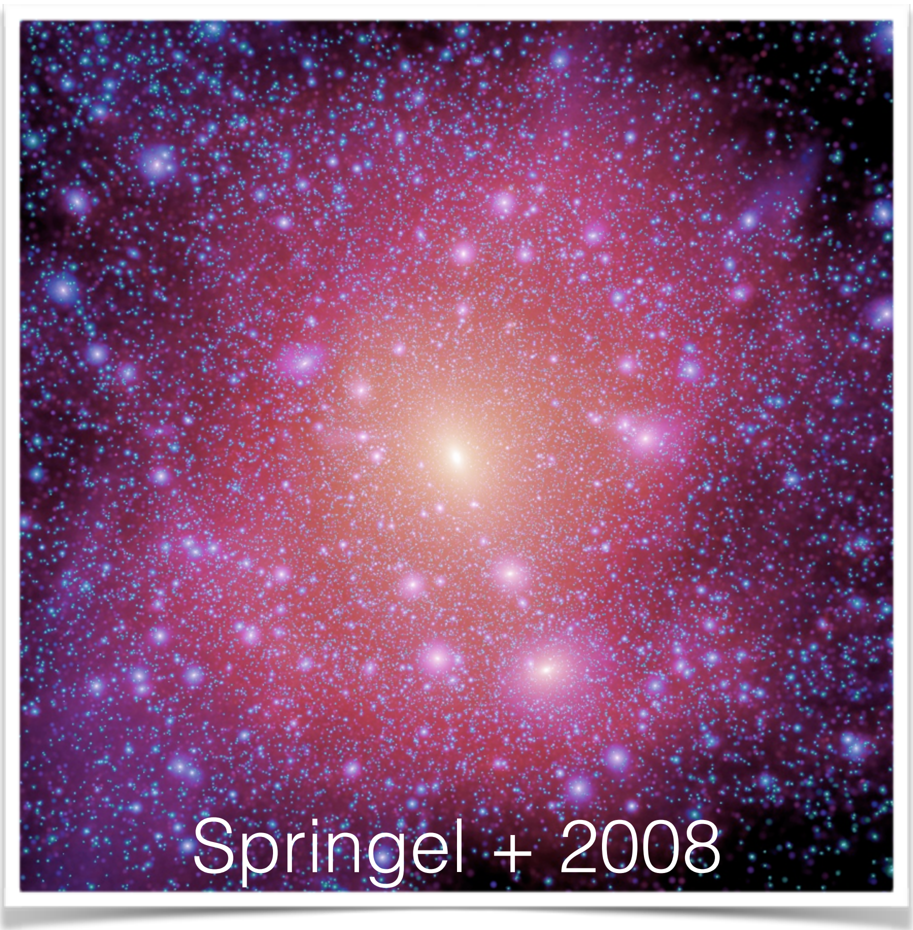


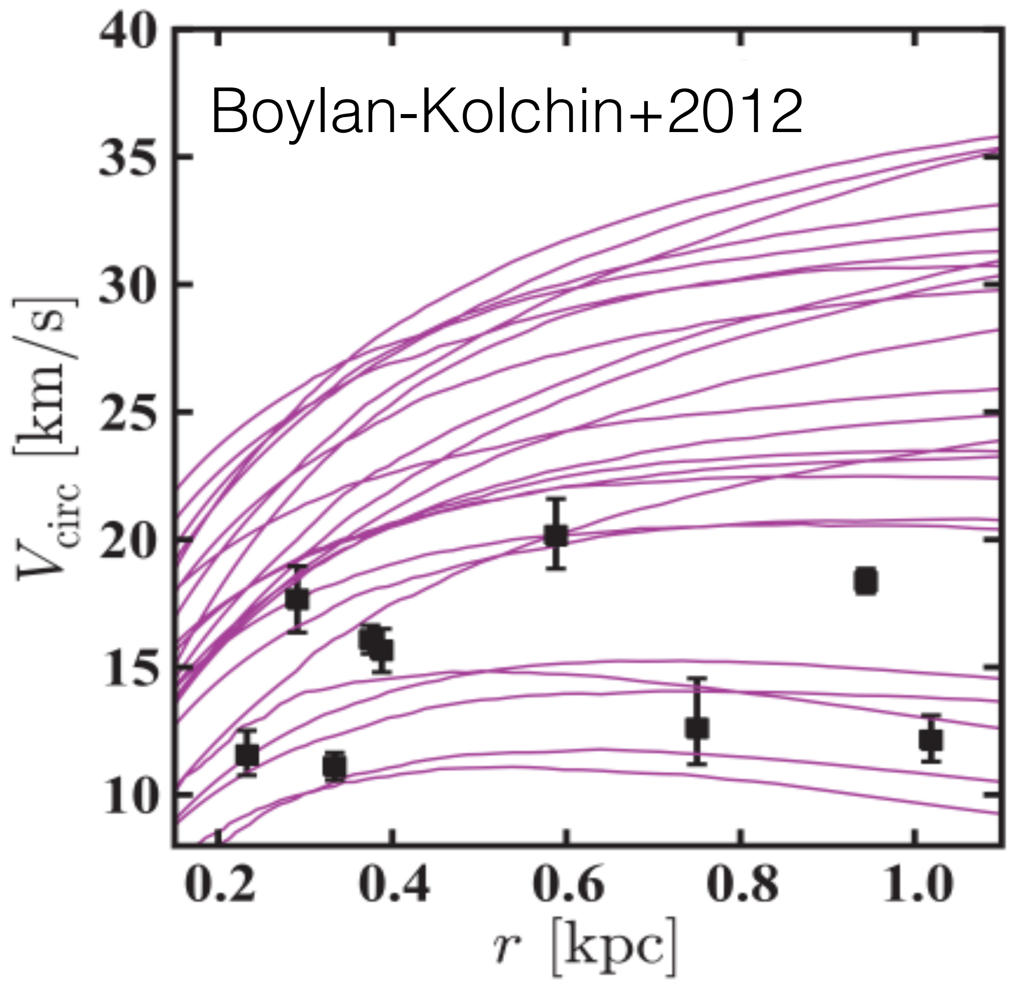




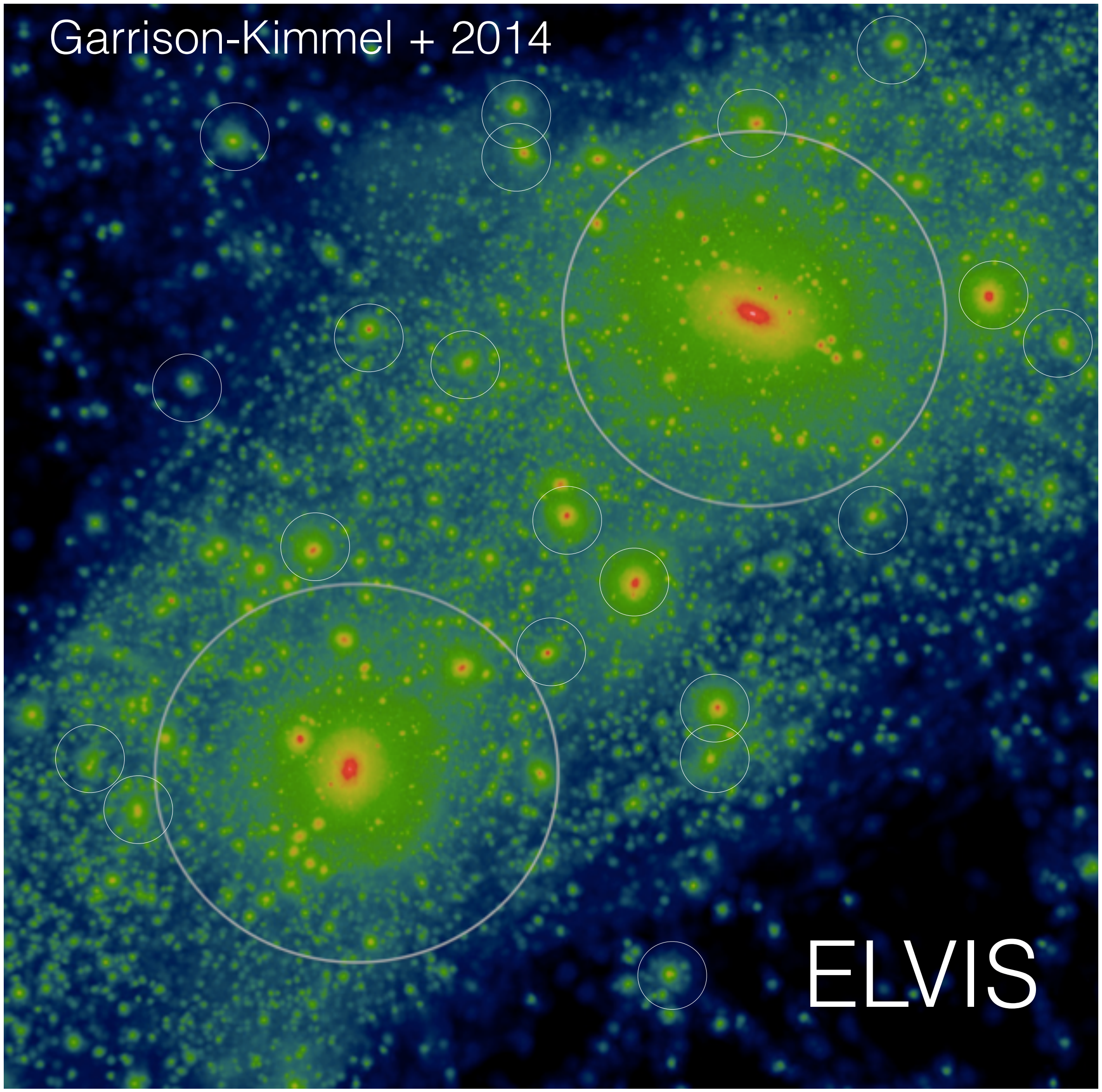
Boylan-Kolchin, JSB, & Kaplinghat (2011)

TOO BIG TO FAIL IN THE MILKY WAY

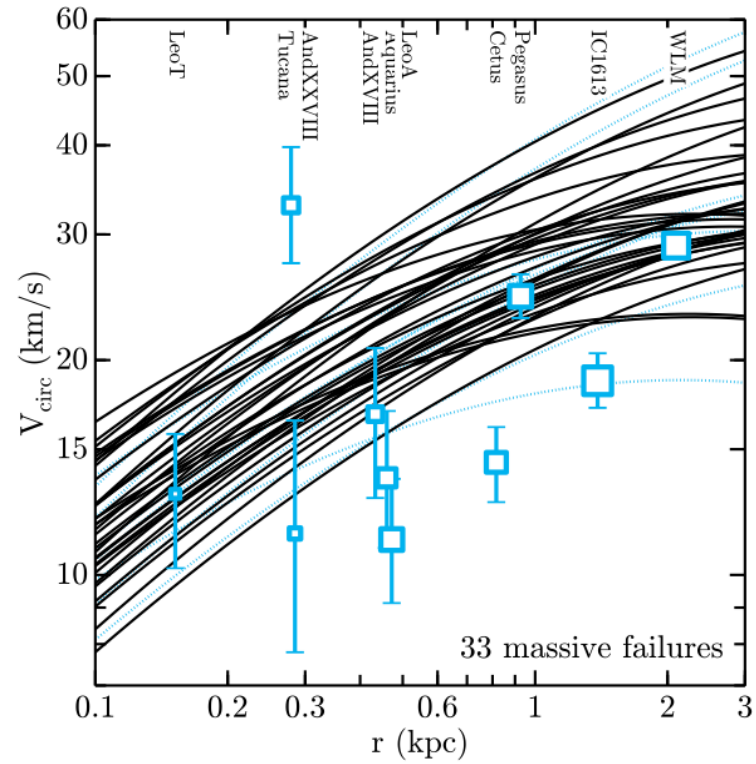




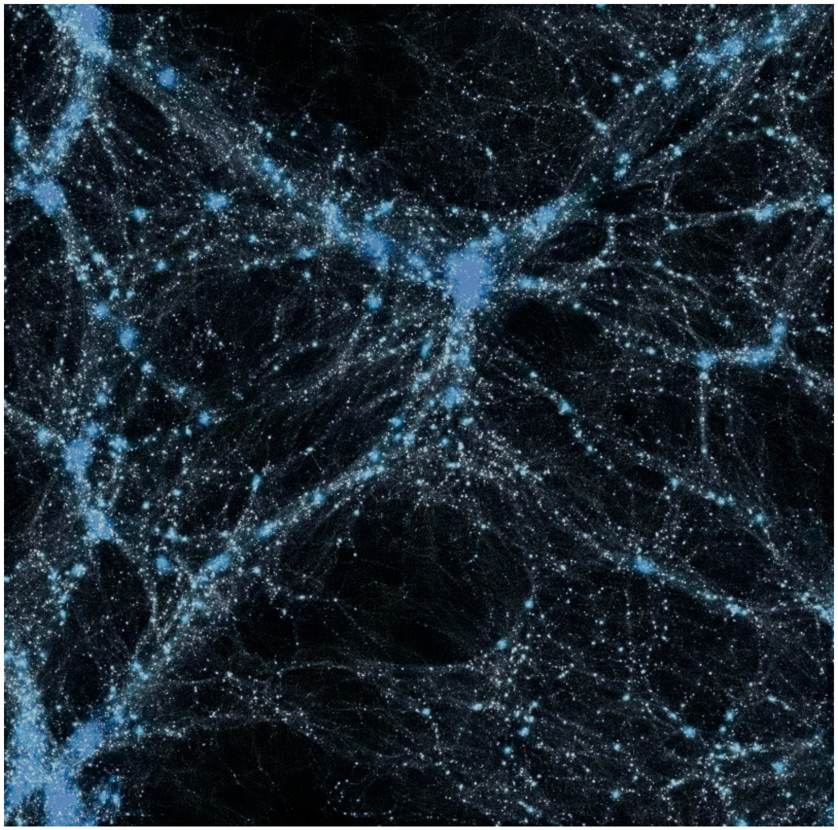
TOO BIG TO FAIL IN THE LOCAL GROUP

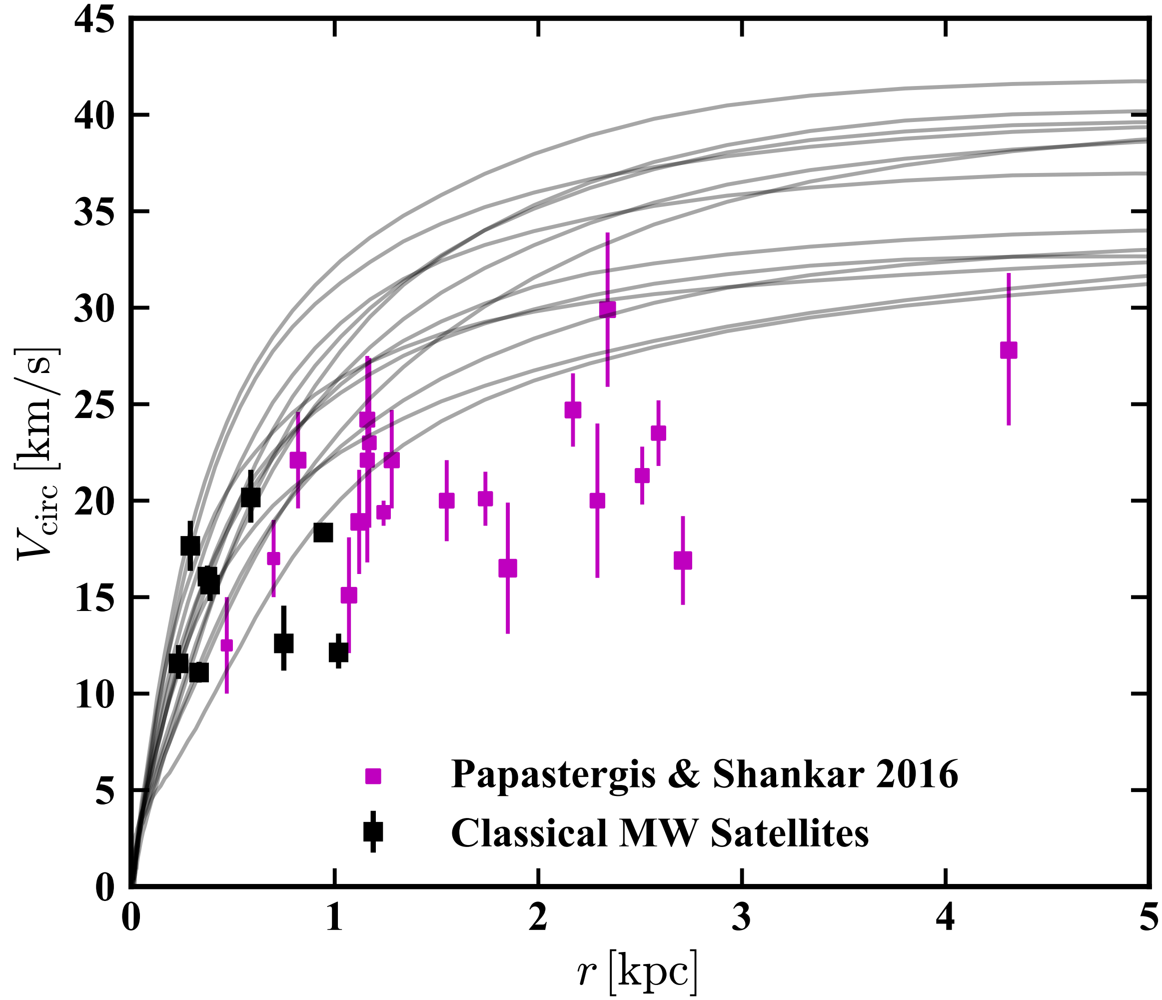


New kinematic masses for Local Group dwarfs by Kirby+2014



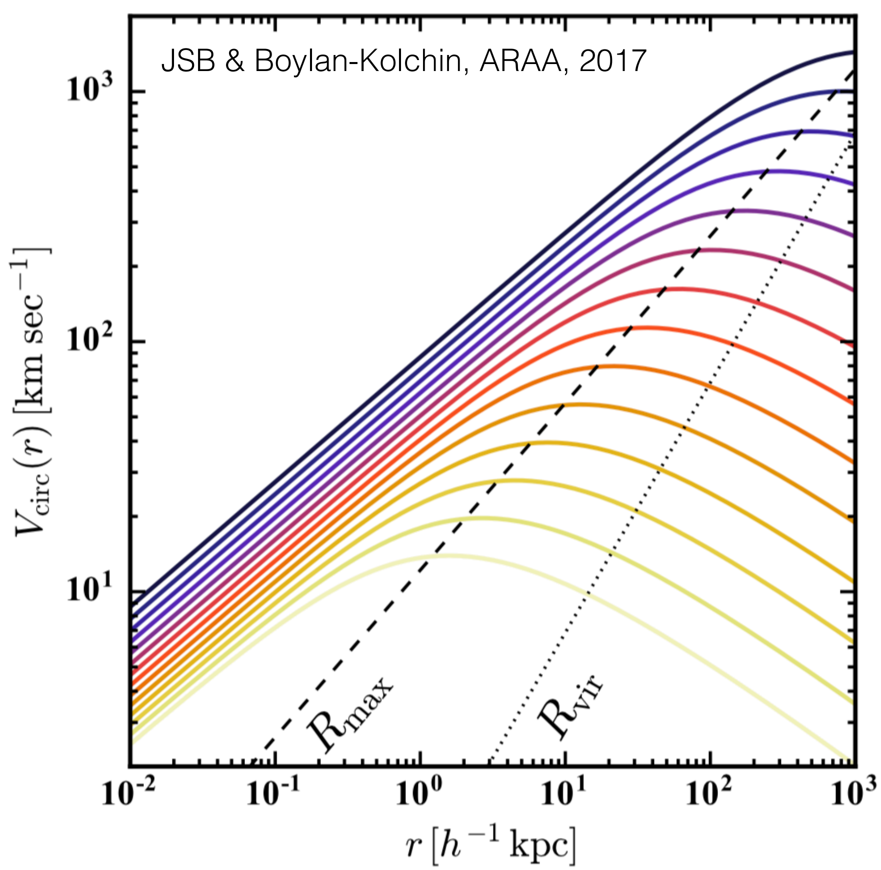
TOO BIG TO FAIL IN THE FIELD

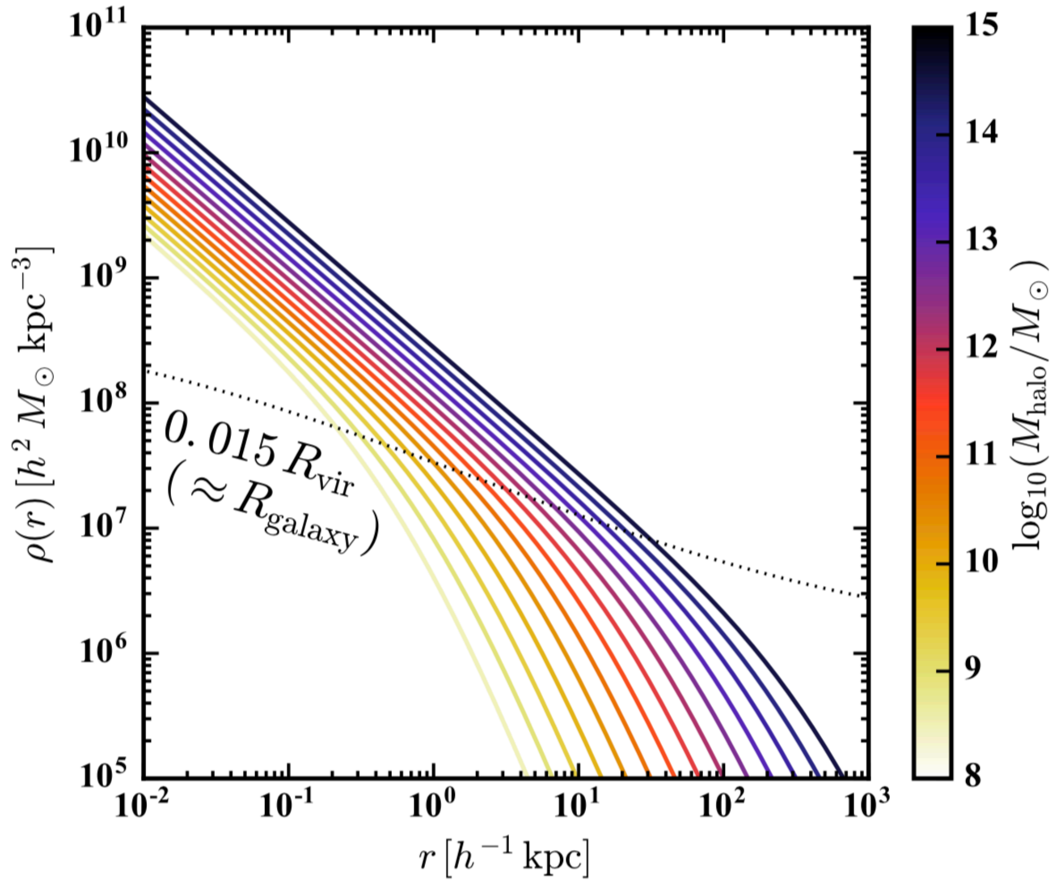




JSB & Boylan-Kolchin, ARAA, 2017

Density Structure of Dark Matter Halos





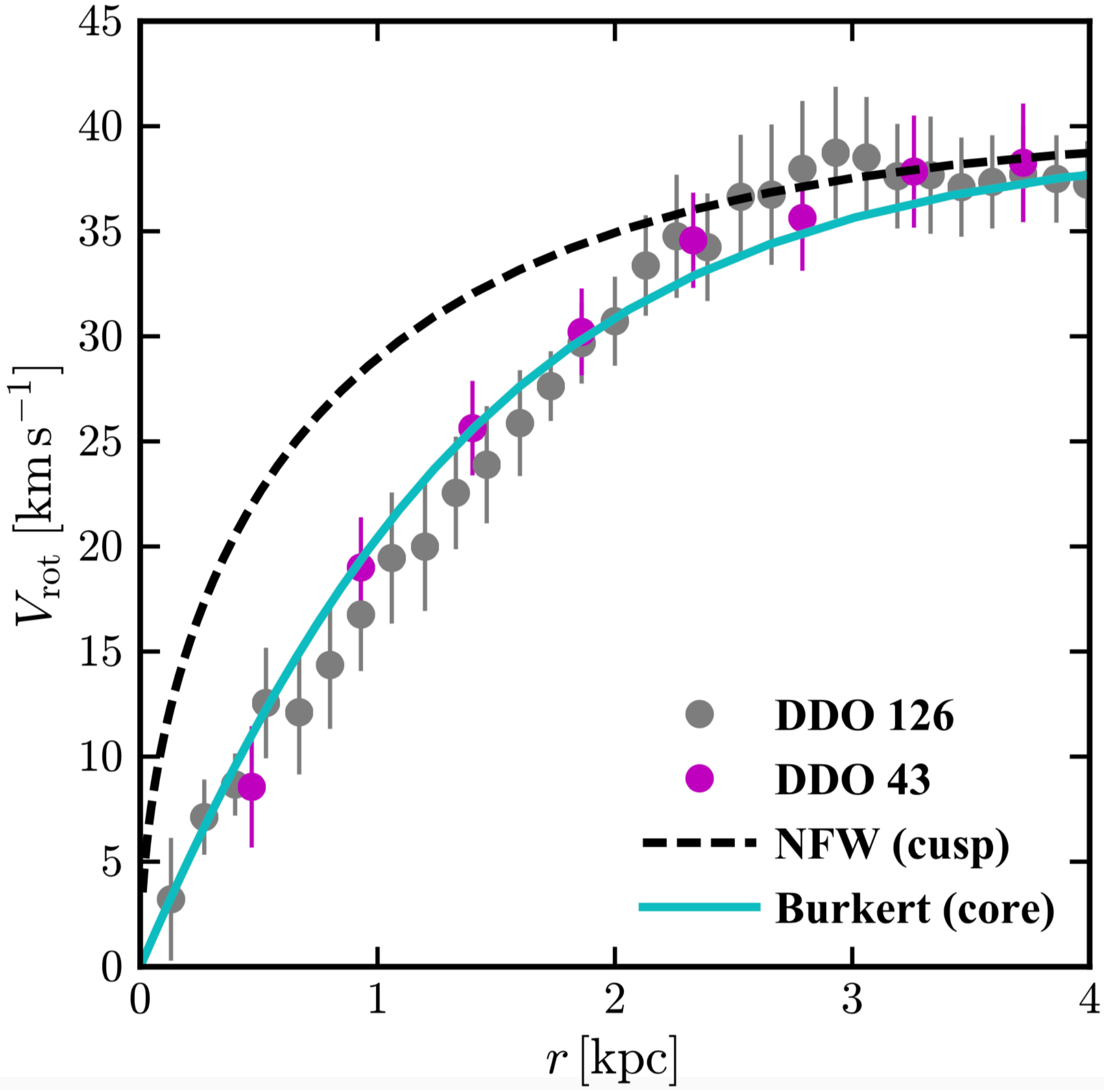
$$\rho(r) = \frac{4\rho_{-2}}{(r/r_{-2})(1+r/r_{-2})^2}.$$

$$\rho(r) \propto r^{-\gamma} \qquad \gamma \simeq 0.8 - 1.4$$

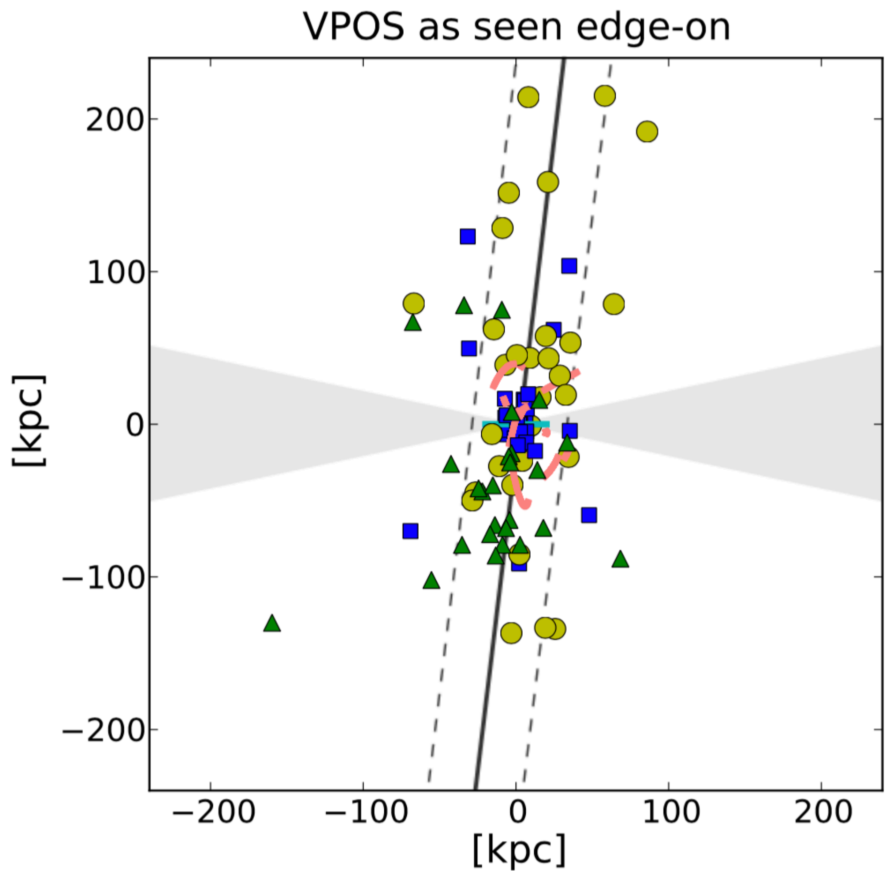
Navarro, Frenk, White (1996)

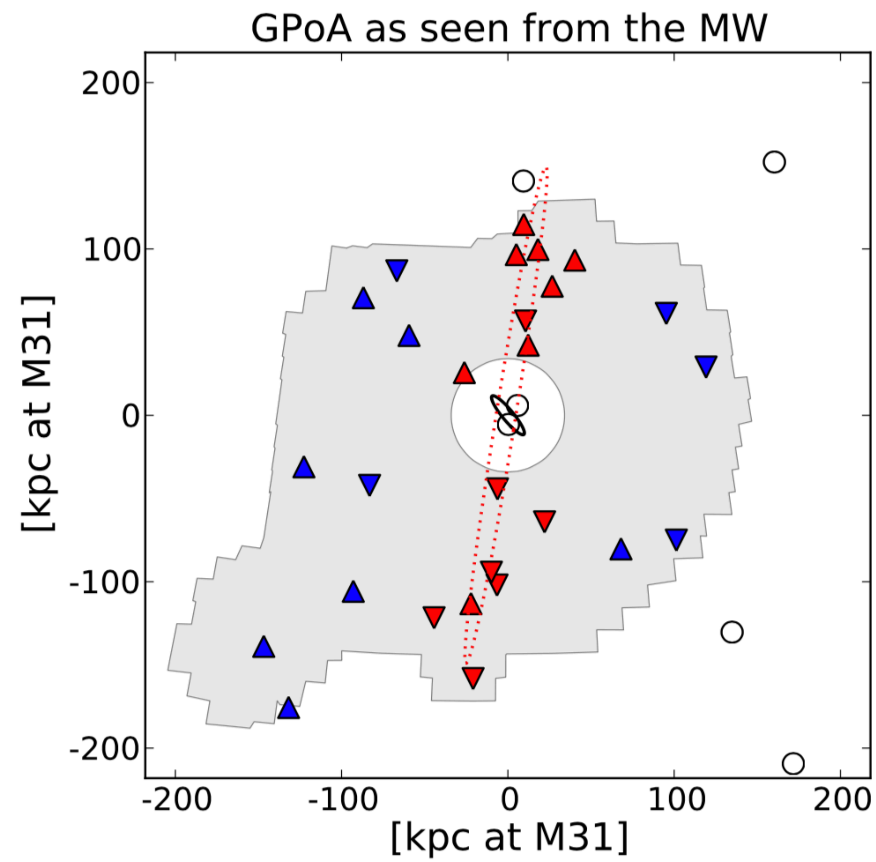
at radii of interest for small galaxies

Cusp/Core Problem



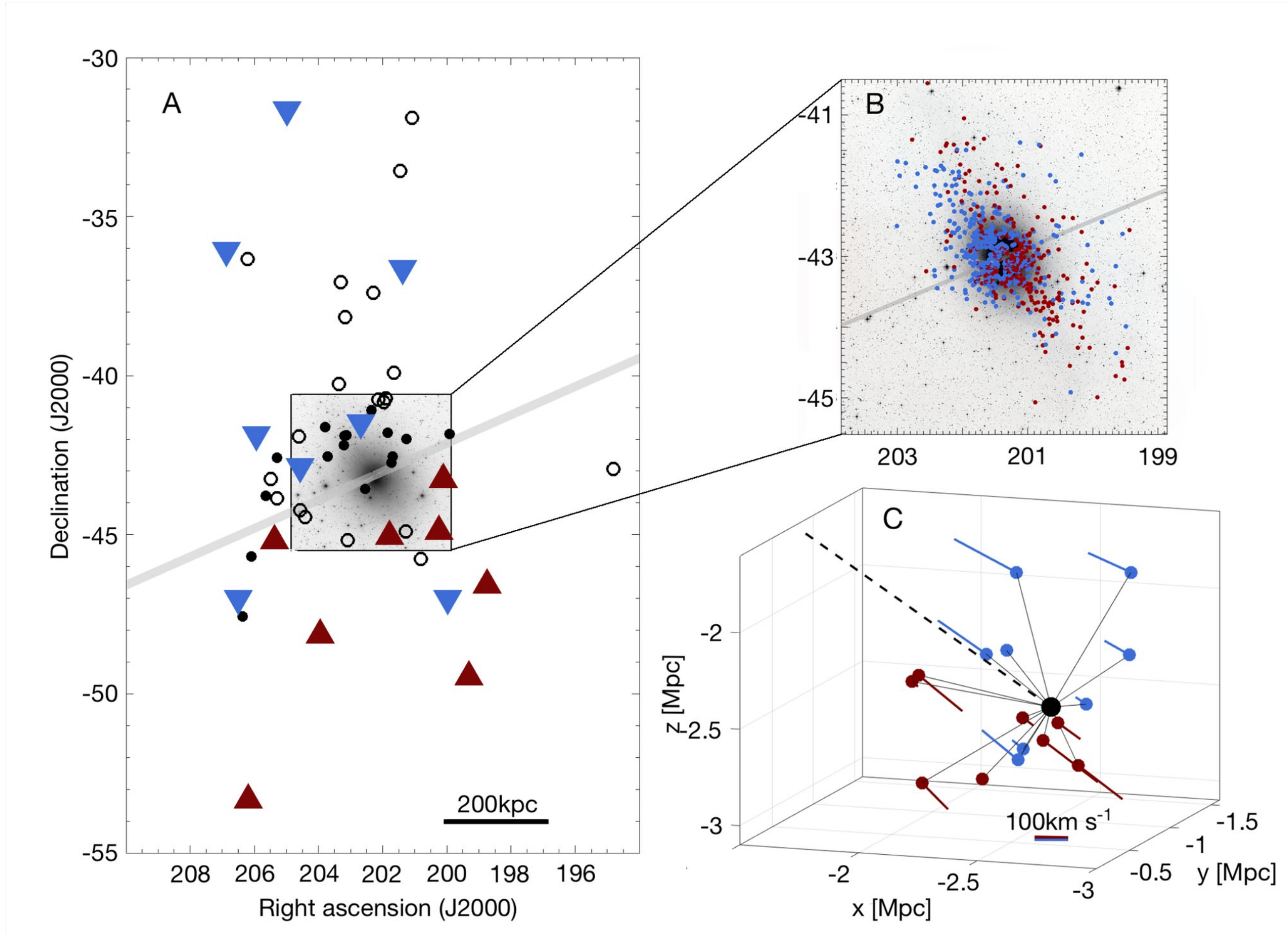
Rotating planes of satellites





satellite galaxies around the Centaurus A galaxy

Muller et al. 2018



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?

[redacted]

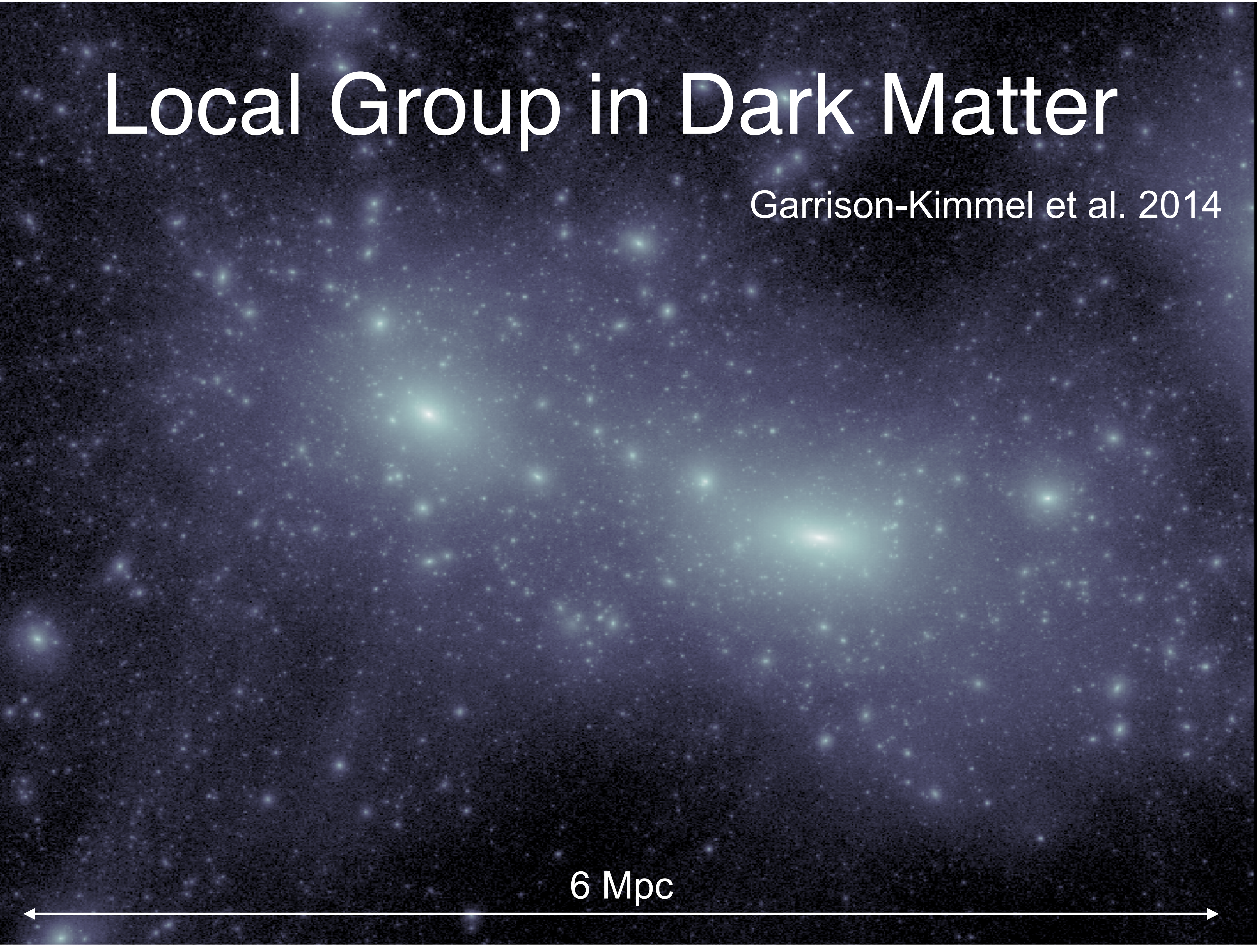
Dark Matter
Advanced Training Institute

Observations and simulations of structure formation in the Universe

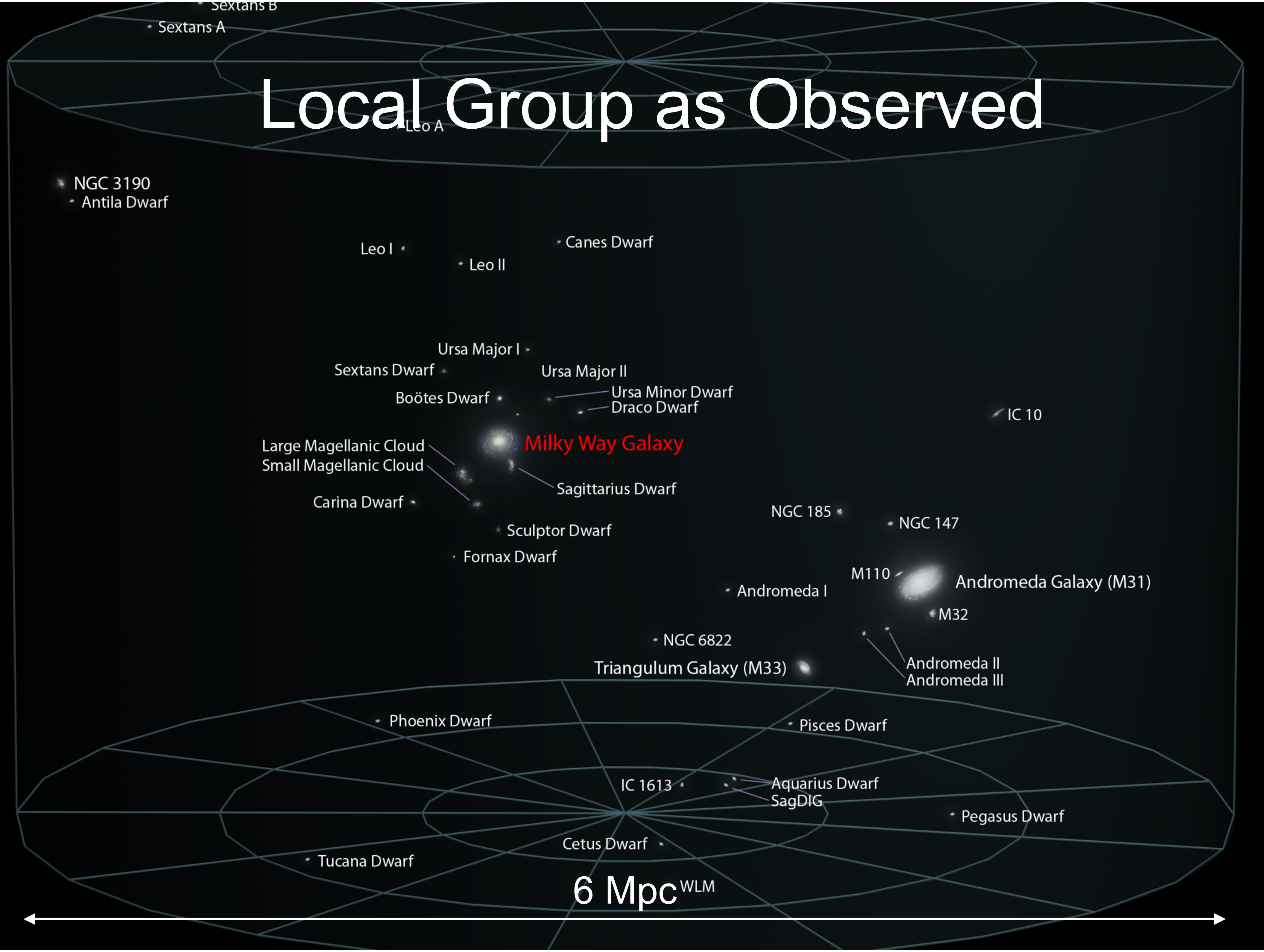
Lecture 2
Simulations with alternative DM & baryons

James Bullock
UC Irvine

Local Group in Dark Matter



Local Group as Observed



CDM+ FEEDBACK


Star formation + Radiation pressure


Stellar winds

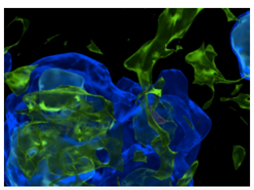
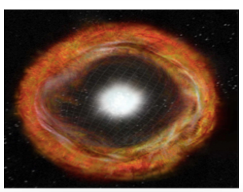


Photo-Ionization


Supernovae: Impart energy & momentum directly into local SPH particles, never turn off cooling.


Active Galactic Nuclei

<u>Numerical Methods</u>
- Smoothed Particle Hydrodynamics [Gadget]
- Fixed Mesh /Adaptive Mesh [Enzo/Art]
- Moving mesh [Arepo]
- Mesh-free [Gizmo]

<u>Size of simulations</u>
- Cosmological volumes (~100 Mpc box)
  - Con: Low resolution

- High-Resolution “Zoomed-in” runs
  - Con: Smaller samples

FIRE-2 Simulations: Physics versus Numerics in Galaxy Formation

Philip F. Hopkins*[1], Andrew Wetzel[1,2,3]†, Dušan Kereš[4], Claude-André Faucher-Giguère[5], Eliot Quataert[6], Michael Boylan-Kolchin[7], Norman Murray[8], Christopher C. Hayward[9], Shea Garrison-Kimmel[1], Cameron Hummels[1], Robert Feldmann[6,10], Paul Torrey[11], Xiangcheng Ma[1], Daniel Anglés-Alcázar[5], Kung-Yi Su[1], Matthew Orr[1], Denise Schmitz[1], Ivanna Escala[1], Robyn Sanderson[1], Michael Y. Grudić[1], Zachary Hafen[5], Ji-Hoon Kim[12], Alex Fitts[7], James S. Bullock[13], Coral Wheeler[1], T. K. Chan[4], Oliver D. Elbert[13], Desika Narayanan[14]

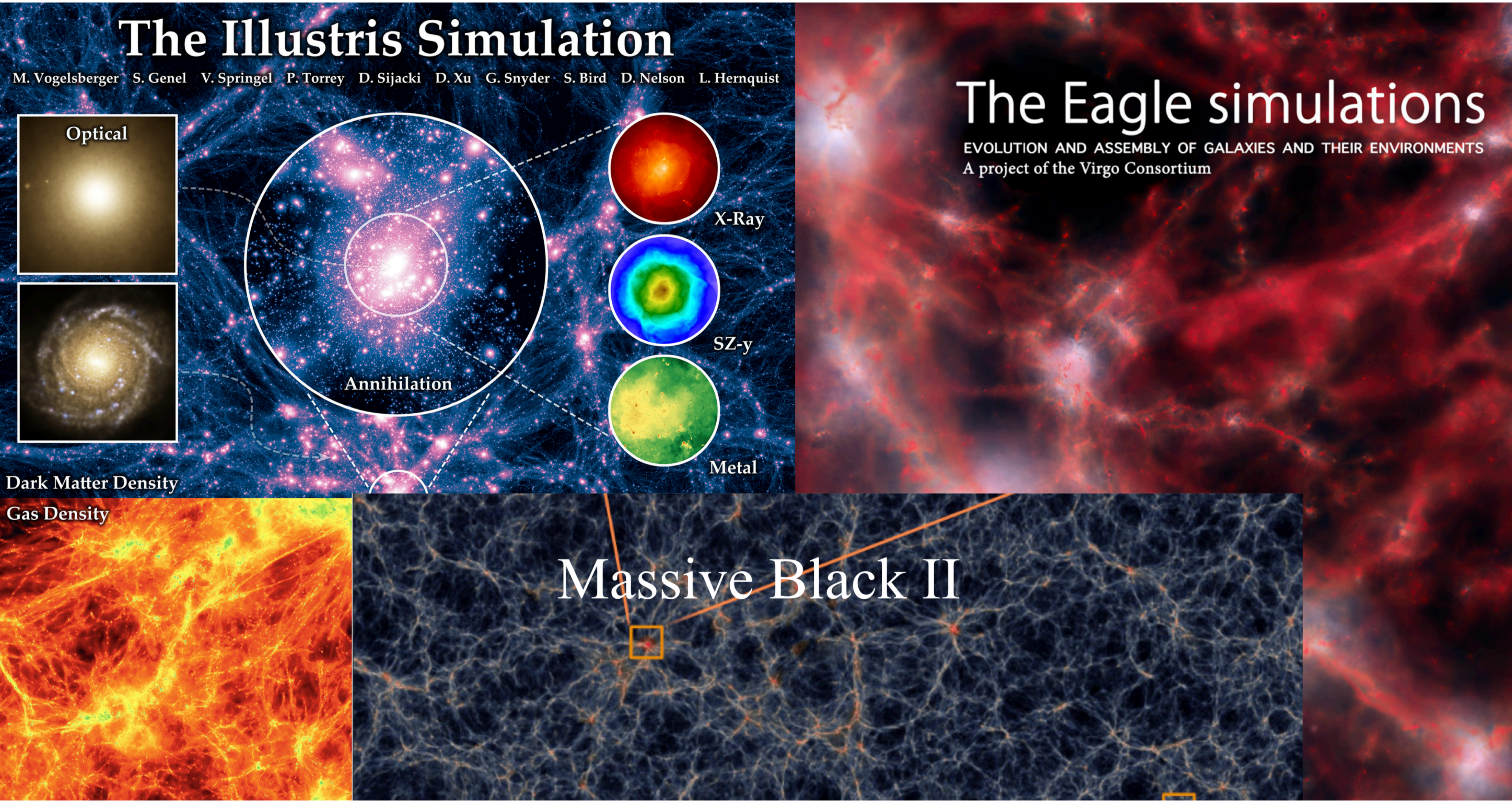
Hopkins et al. 2018

A lot going on "under the hood"

Table 2. Physics & Numerics Explored in This Paper (and Papers II & III)

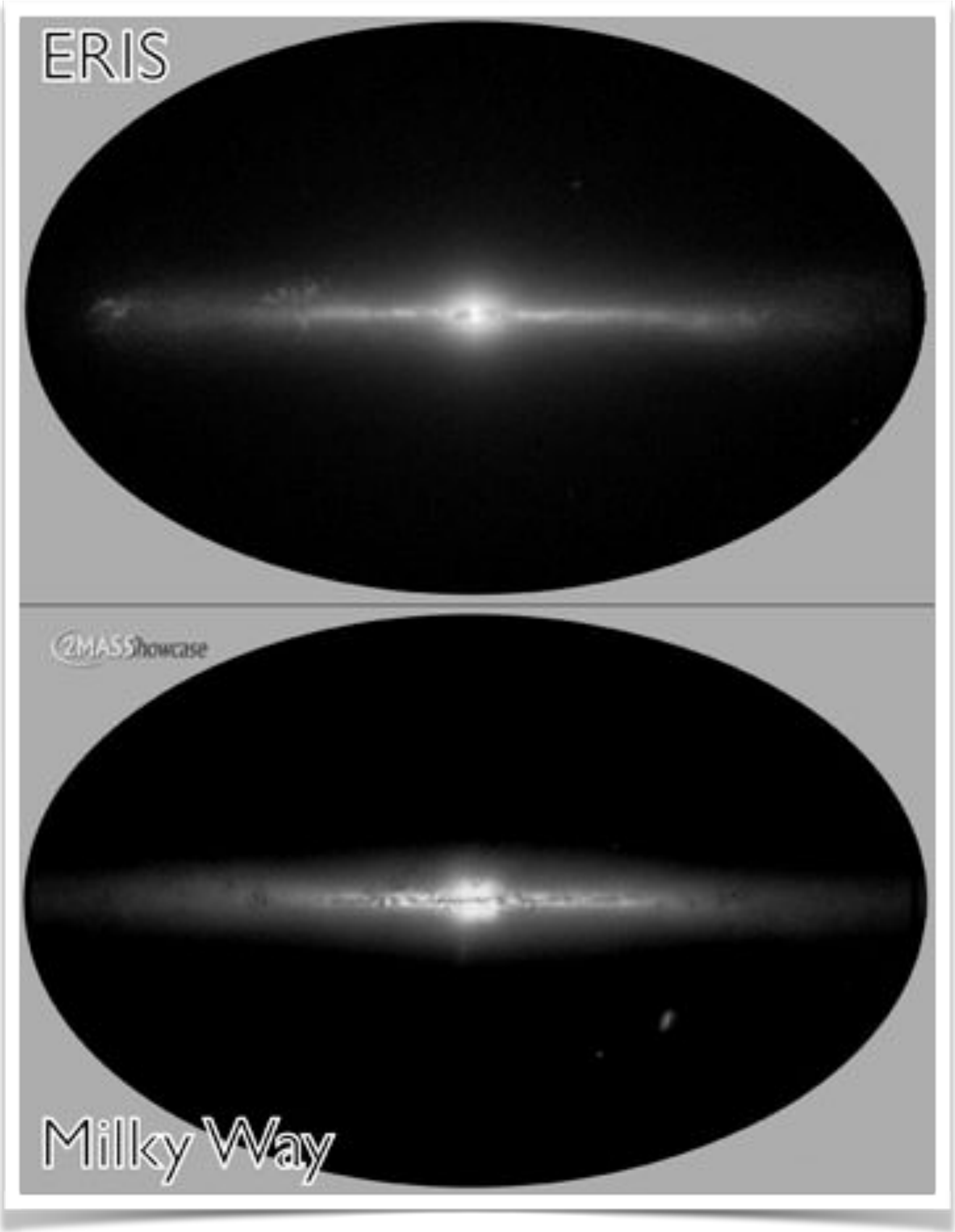
Physics/Numerics	§	Effects in FIRE-2 Simulations	Guidelines
		Resolution:	
Mass Resolution	4.1	Most results converge after resolving the Toomre scale, some (e.g. massive galaxy morphology) depend on resolved winds/hot gas	Convergence criteria in § 4.1.3 (Eq. 5-7)
Collisionless (DM/Stellar) Force Softening	4.2	Irrelevant unless *extremely* small or very large values used, adaptive collisionless softenings require additional timestep limiters	Optimal range of values in § 4.2.3
Gas Force Softening	4.2	Forcing fixed softening generally has no effect, unless too large, then fragmentation & SF are artificially suppressed	Fully-adaptive softenings (matching gas) should be used
Timestep Criteria	4.3	Provided that standard stability criteria are met, this has no effect. Additional limiters needed for stellar evolution & adaptive softening	Standard limiters + Stellar (Eq. 12) + Adaptive softening (Eq. 13)
		(Magneto)-Hydrodynamics:	
Hydro Method (MFM vs. SPH)	5	Irrelevant for dwarfs. Important for massive galaxies with hot halos. SPH suppresses cooling & artificially allows clumpy winds to vent	Newer methods recommended
Artificial Pressure "Floors"	6	Unimportant unless set too large, then prevents real fragmentation. Double-counts "sub-grid" treatment of fragmentation with SF model	Do not use with self-gravity based SF models
Magnetic Fields, Conduction, Viscosity	F	Weak effects on sub-galactic scales (dense gas, morphology, turbulent ISM) (Not studied here, but in Su et al. 2016; effects in CGM could be larger)	See Su et al. (2016)
Metal Diffusion (sub-resolution mixing)	7.2 & F	Small effects on galaxy properties & dynamics, but potentially important for abundance distributions of stars	Best practice depends on numerical hydro method
		Cooling:	
Molecular Chemistry/Cooling	7 & B	No effect on galaxy properties or star formation (just a tracer). Not important star formation criterion if fragmentation is resolved	May be relevant at $[Z/H] \ll -3$, can be important for observational tracers
Low-Temperature Cooling ($T \ll 10^4$ K)	7 & B	Details have no dynamical effects because $t_{\rm cool} \ll t_{\rm dyn}$ in cold gas to opacity limit ($\sim 0.01\,M_{\odot}$). Relevant for observables in cold phase	*Some* needed to form cold clouds, details dynamically irrelevant
Metal-Line Cooling ($T \gtrsim 10^4$ K)	7 & B	Dominates cooling in metal-rich centers of "hot halos" around massive galaxies, and of individual SNe blastwaves	Needed: important in super-bubbles & "hot halos"
Photo-Heating (Background)	7 & B	Significantly suppresses star formation in small ($M_{\rm halo} \lesssim 10^{10}\,M_{\odot}$) dwarfs	Needed: dwarfs & CGM/IGM
		Star Formation:	
Self-Gravity (Virial) Criterion	8 & C	Negligible effect on galaxy properties (SF is feedback-regulated). More accurately identifies collapsing regions in high-dynamic range situations	Recommended see Appendix C for implementation
Density Threshold	8 & C	Negligible effect on galaxy properties (SF is feedback-regulated) Can be arbitrarily high with adaptive gas softenings	Should exceed galactic mean density; ideally, highest resolved densities
Jeans-Instability Criterion	8 & C	Negligible effect on galaxy properties (SF is feedback-regulated). Automatically satisfied in high-density, self-gravitating gas	Not necessary
Self-shielding/Molecular Criterion	8 & C	Negligible effect on galaxy properties (SF is feedback-regulated). Automatically satisfied in high-density, self-gravitating gas	Not necessary
"Efficiency" (Rate) at Resolution Limit	8 & C	Negligible effect on galaxy properties (SF is feedback-regulated). If artificially lowered, more dense gas "piles up" until same SFR achieved	$\sim 100\%$ per free-fall in *locally-self-gravitating* gas
		Stellar Feedback:	
Continuous Mass-Loss (OB & AGB)	9 & A	Primarily important as a late-time fuel source for SF Relatively weak "primary" feedback effects on galactic scales	Should couple as Appendix D Rates given in § A
Supernovae (Ia & II) ("How to Couple")	A & D Paper II	Type-II: Dominant FB mechanism on cosmological scales. Need to account for *PdV* work if Sedov phase un-resolved. Subgrid models should reproduce exact solutions, conserve mass, energy, & momentum, and converge	Should couple as § D Validation & convergence tests & criteria in Paper II
Radiative Feedback (Photo-Heating & Radiation Pressure)	A & E Paper III	"Smooths" SF in dwarfs (less bursty) & suppresses SF in dense gas. UV background dominates in dwarfs. Photo-electric heating unimportant. IR multiple-scattering effects weak, except in massive galaxy nuclei.	Need photo-heating & single-scattering rad. pressure (Paper III) Rad.-hydro algorithm sub-dominant

Large Cosmological Volumes.
3 example simulations.



Able to match many (not all) global observations
- stellar mass functions, cosmic star formation histories, etc. look good

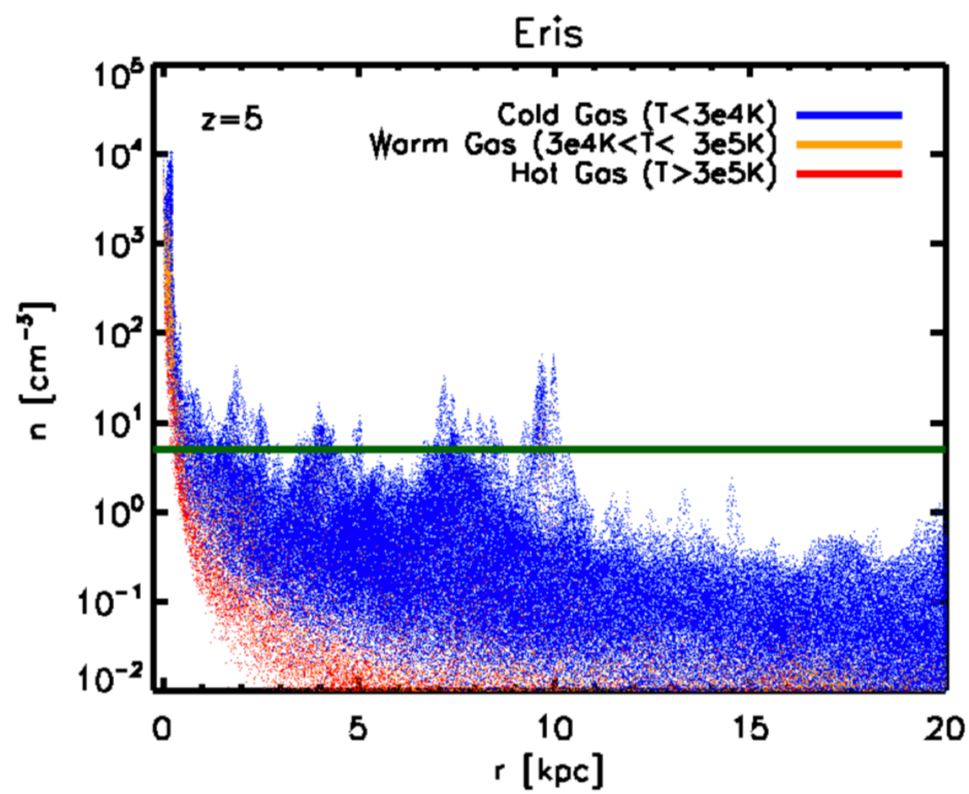
"Zoom Simulations"



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**

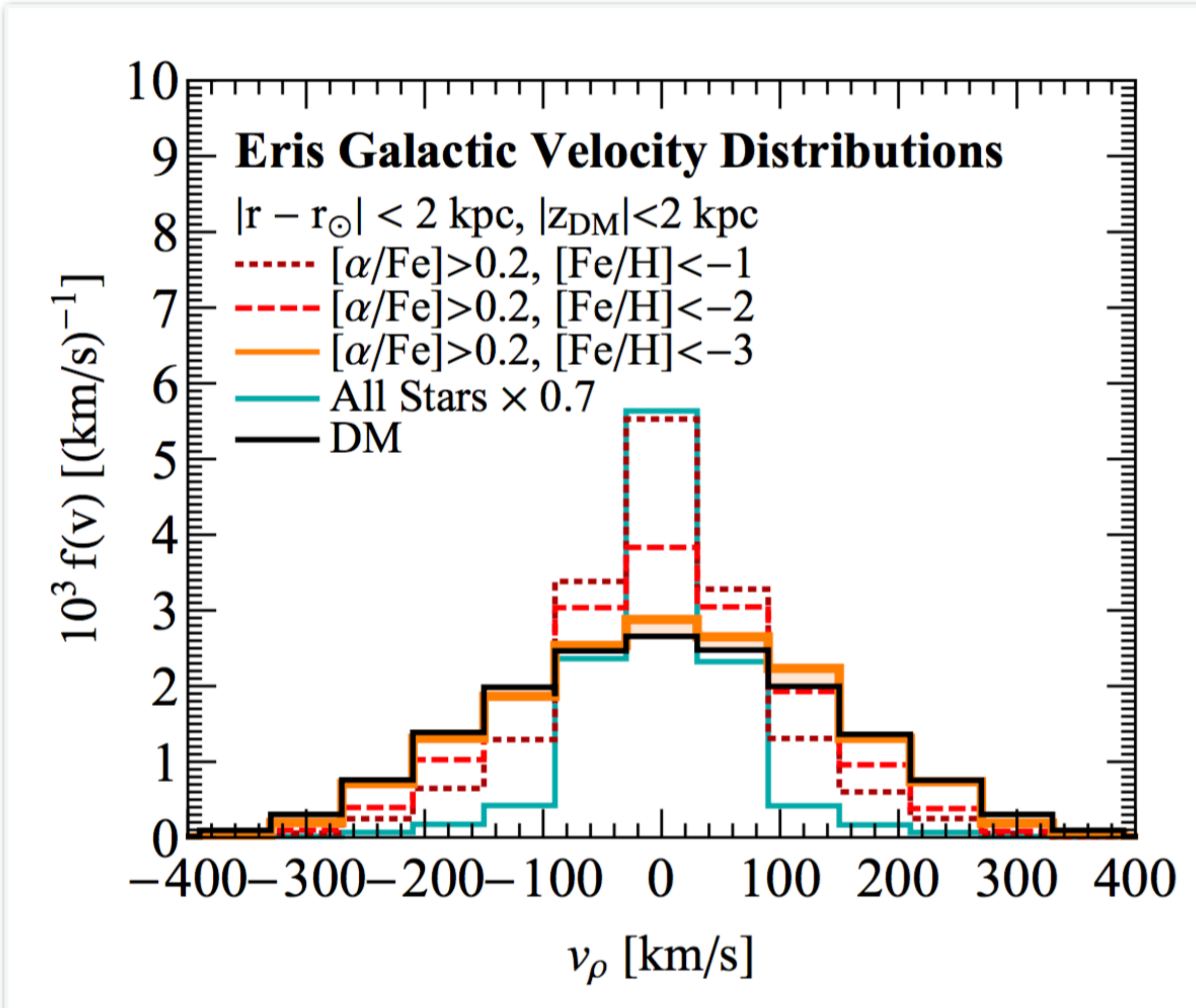


Empirical Determination of Dark Matter Velocities using Metal-Poor Stars

Jonah Herzog-Arbeitman,[1,*] Mariangela Lisanti,[1,†] Piero Madau,[2,3,‡] and Lina Necib[4,§]

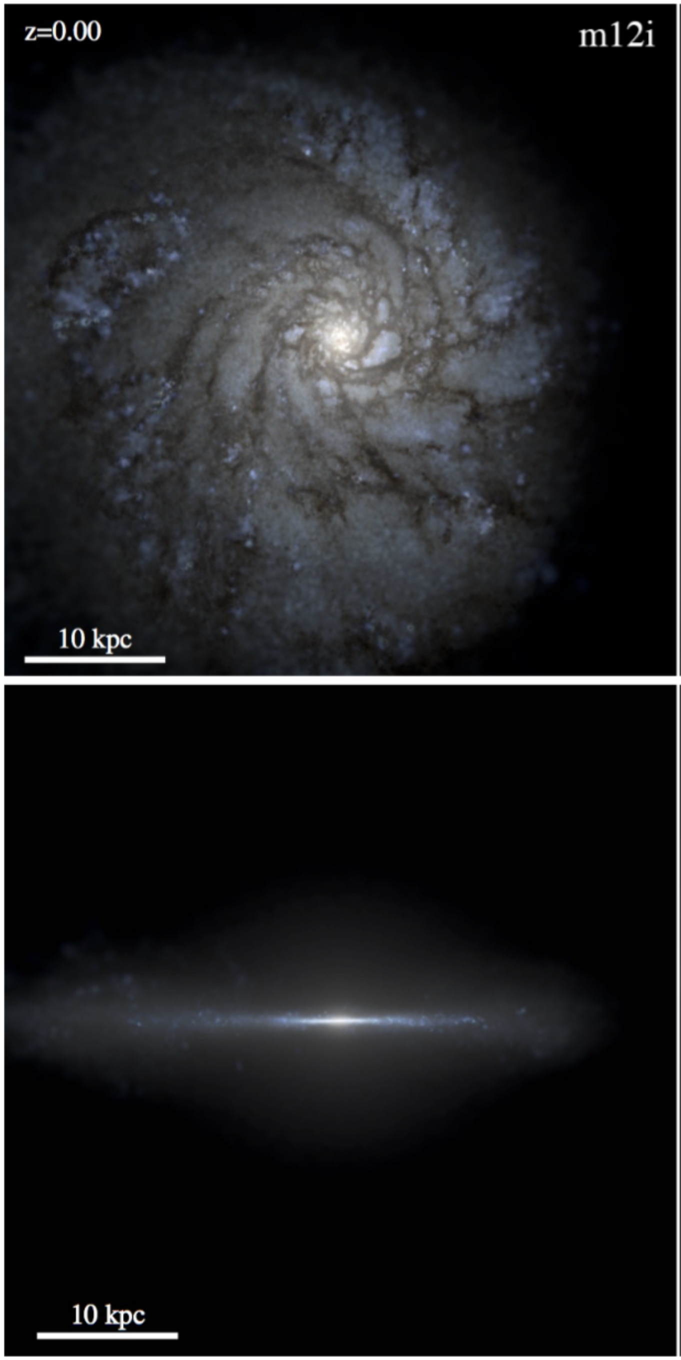
[1] *Department of Physics, Princeton University, Princeton, NJ 08544, USA*
[2] *Department of Astronomy & Astrophysics, University of California, Santa Cruz, CA 95064, USA*
[3] *Institut d'Astrophysique de Paris, Sorbonne Universités, 75014 Paris, France*
[4] *Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA*

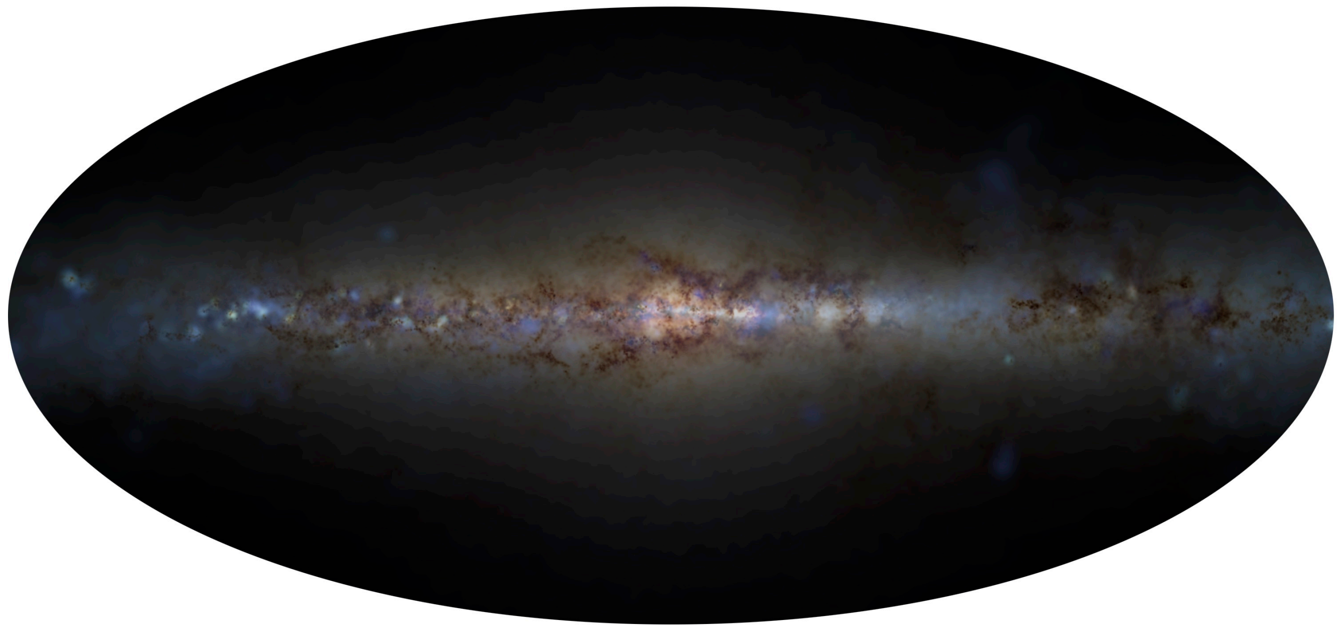
Old, metal-poor stars trace DM velocities?



arXiv:1704.04499v2 [astro-ph.GA] 12 Dec 2017

“Zoom Simulations”





Hopkins+2018 [FIRE]

See also: Wang et al. 2015 [NIHAO]

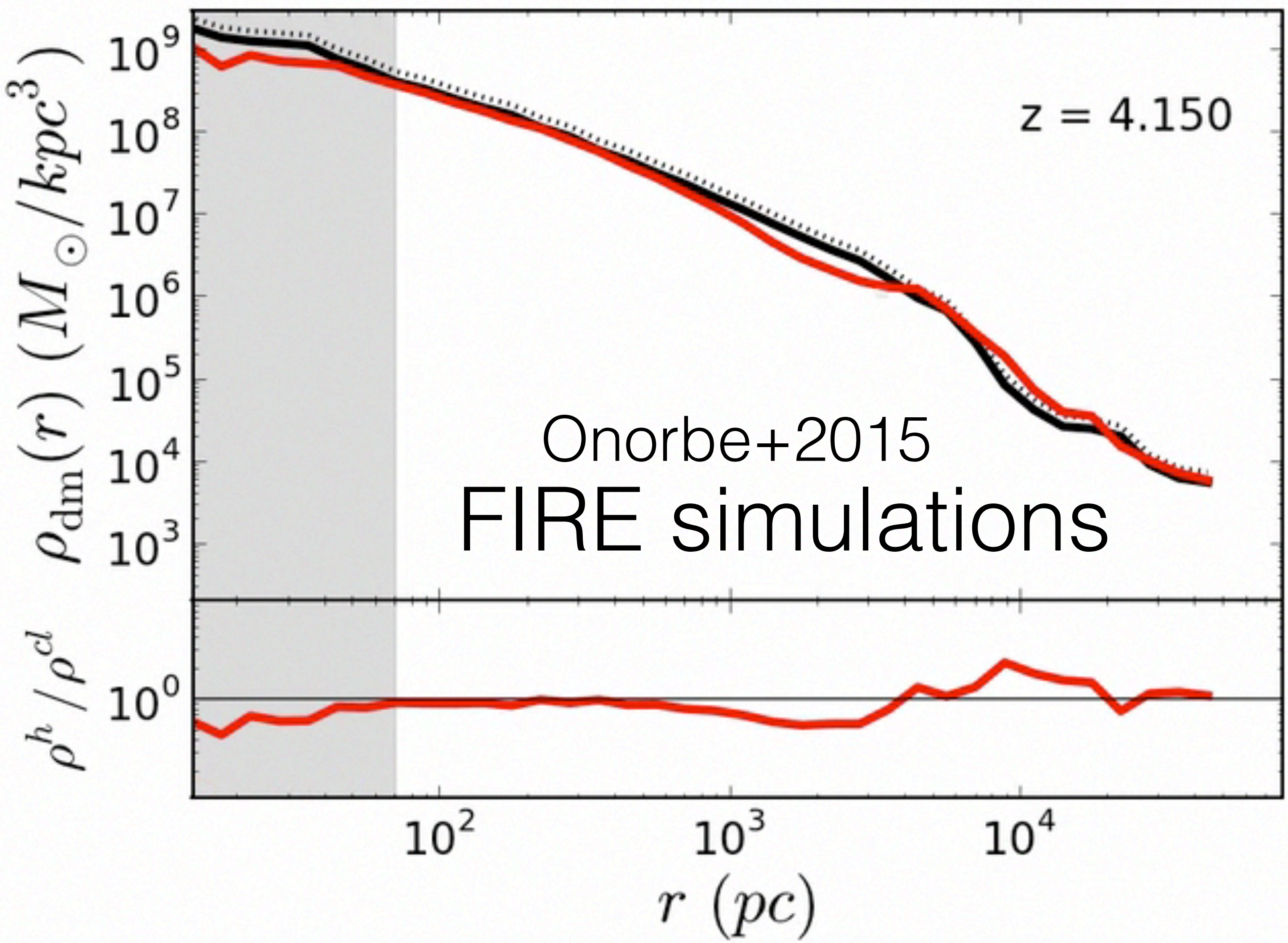
FIRE Simulation of "Milky Way"

Gas

Stars

Garrison-Kimmel et al. 2018

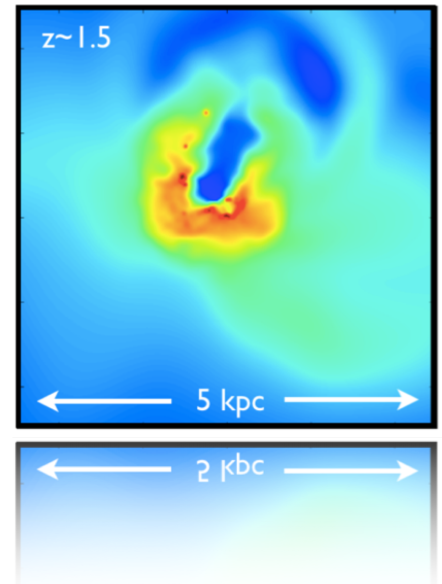
FEEDBACK CAN ALTER DM STRUCTURE



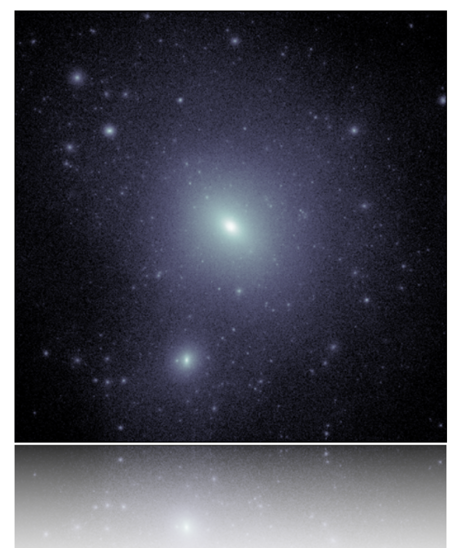
Onorbe+2015

FIRE simulations

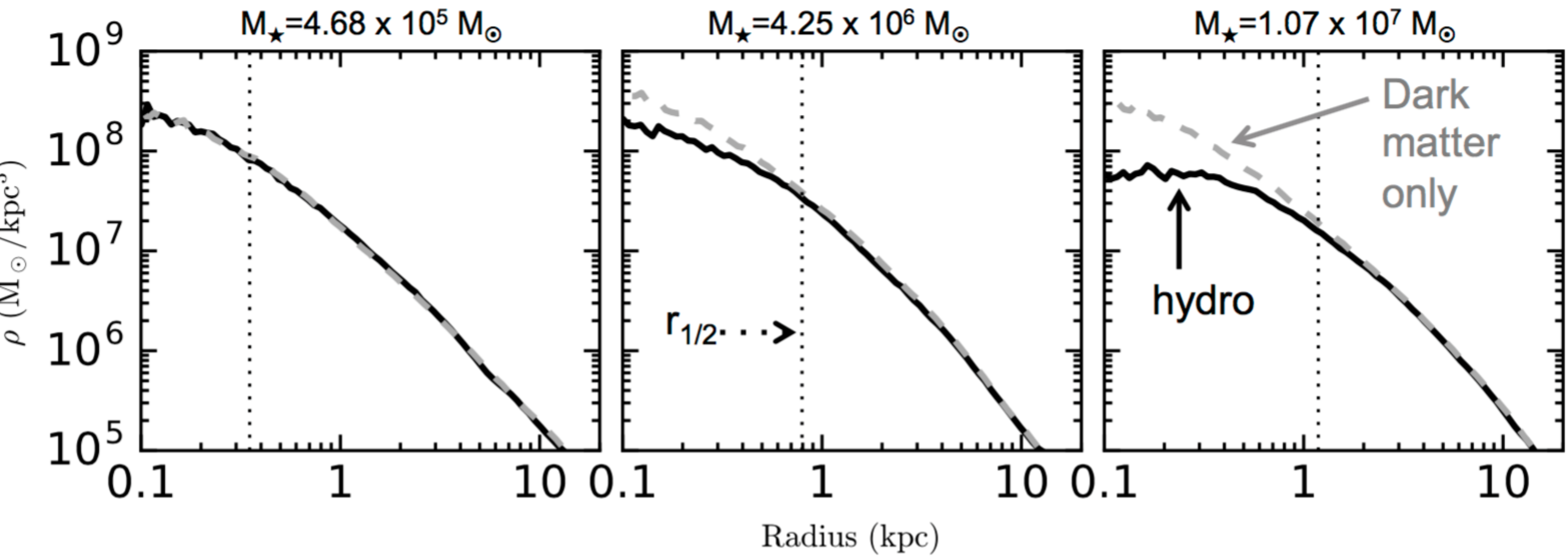
Red = Hydro



Black = only DM

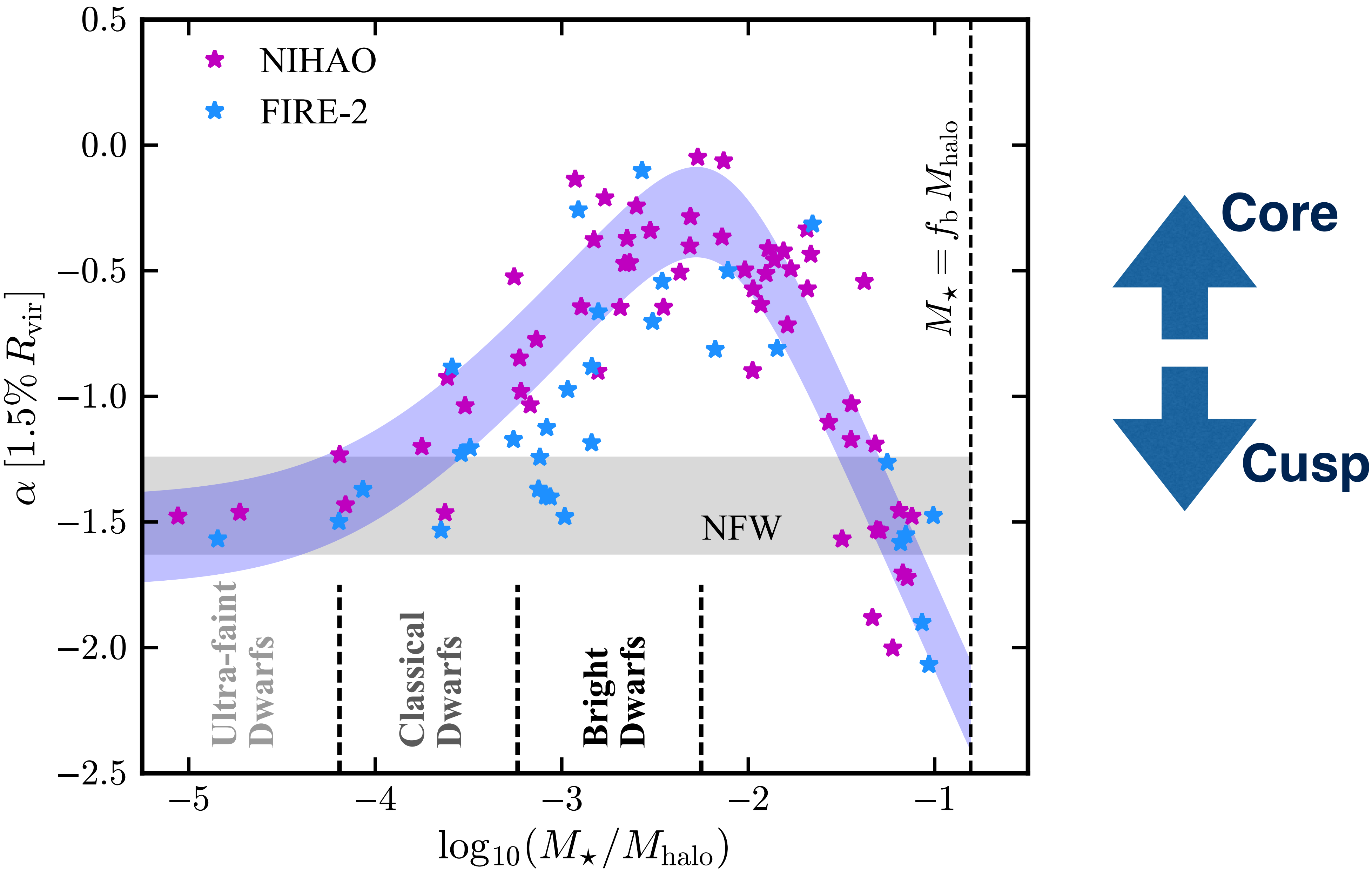


Need >3.e6M_{sun} stars to affect DM density profile



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?

Self Interacting Dark Matter

Spergel & Steinhardt (2000)

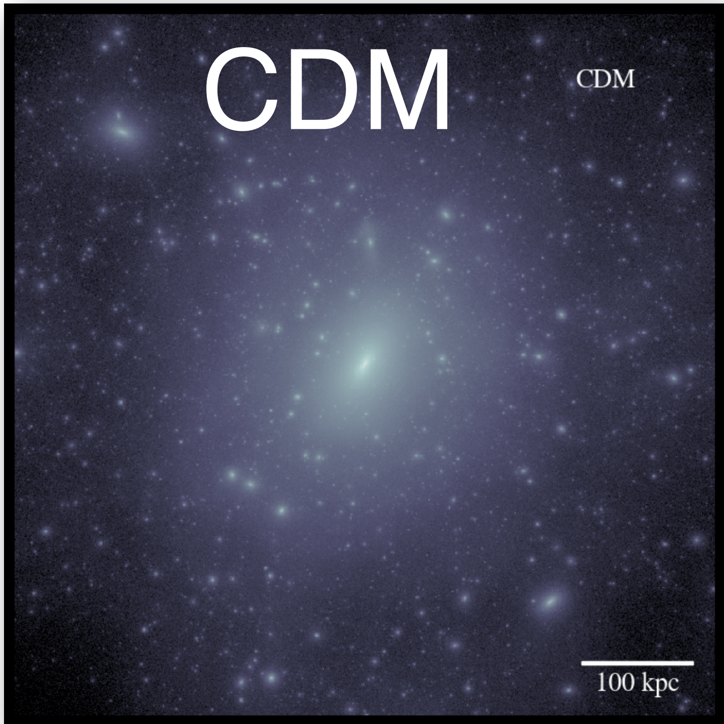
$$\Gamma = \rho_{\rm dm} \left(\frac{\sigma}{m}\right) v_{\rm rms}$$

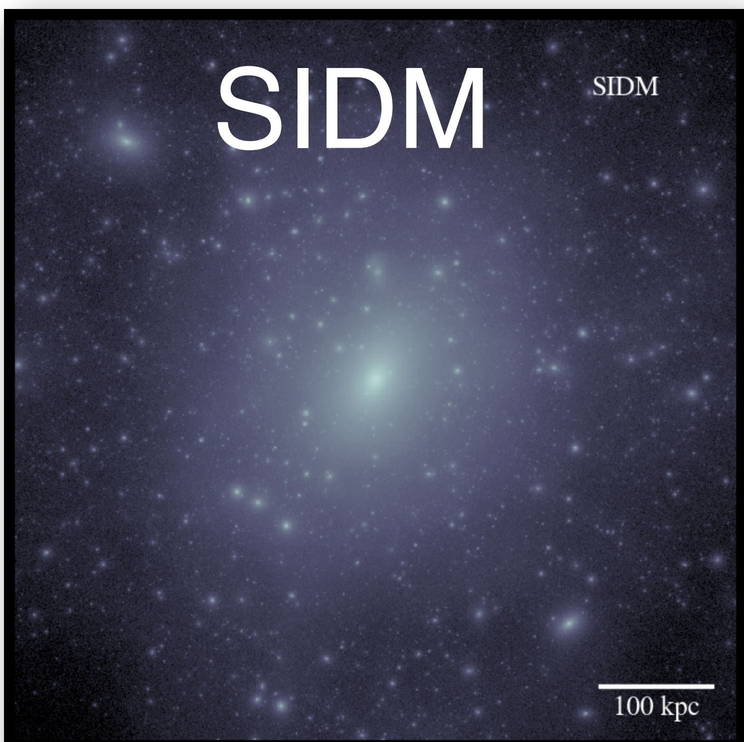
→ if rate is > 1 / $T_{\rm Hubble}$ interesting things happen

→ $$\frac{\sigma}{m} \sim 1\,{\rm cm}^2/g$$

most models have velocity-dependent cross sections

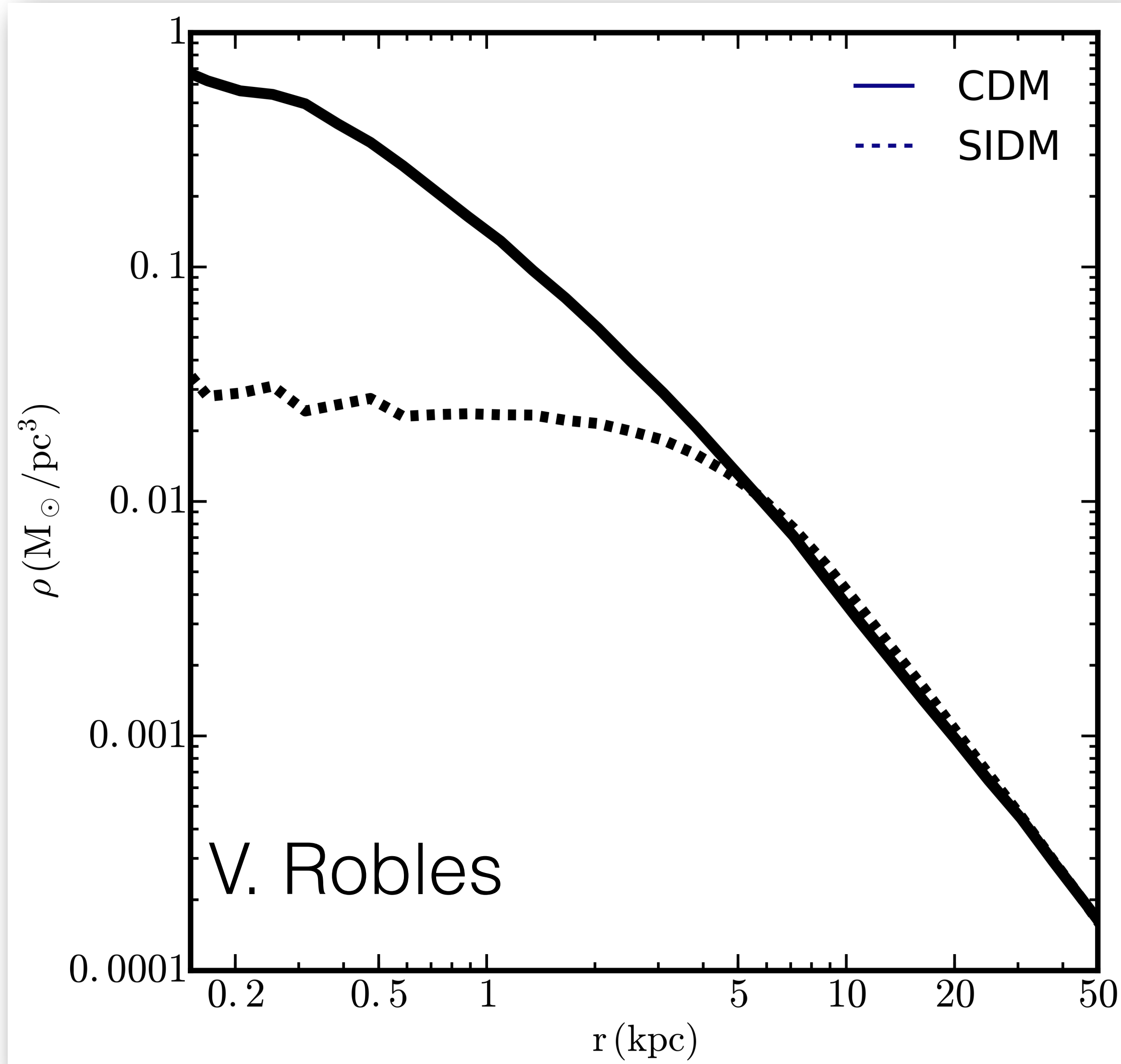
(Wittman+17; Kim+16; Elbert+16; Massey+16; Elbert+15; Peter+13; Rocha+13;Vogelsberger+12; Dawson+12).





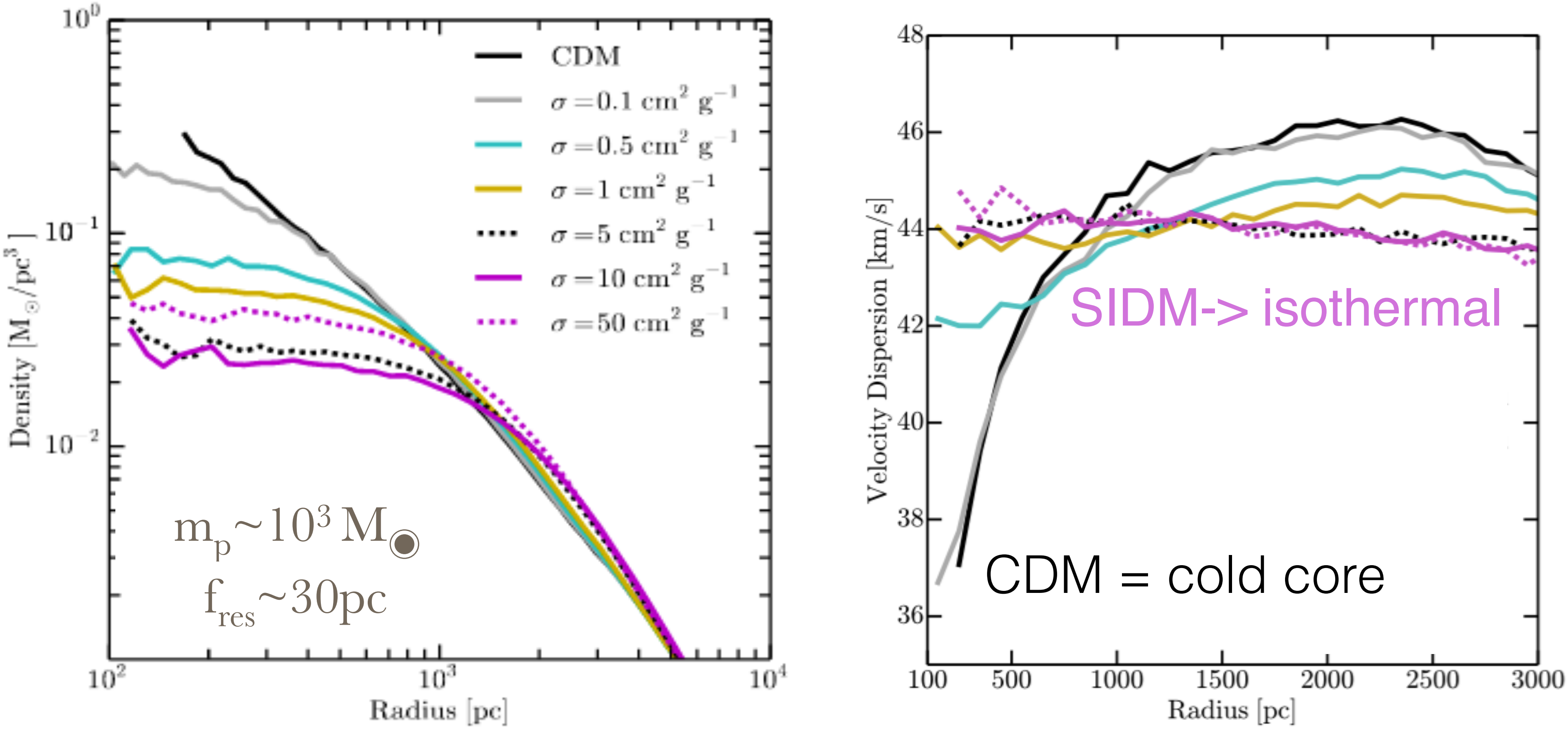
SIDM

similar substructure
- cored density profiles



SIDM: cored halos, alleviates cusp/core & TBTF problems

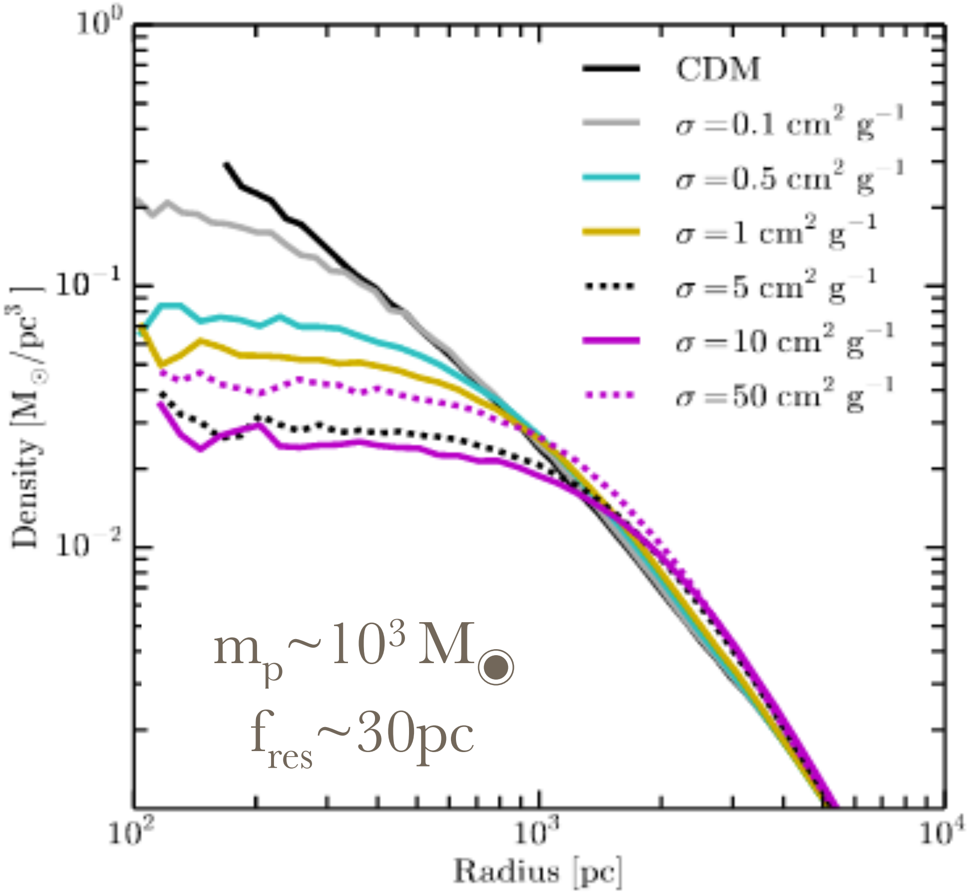
σ/m = 0.5-5 cm² /g



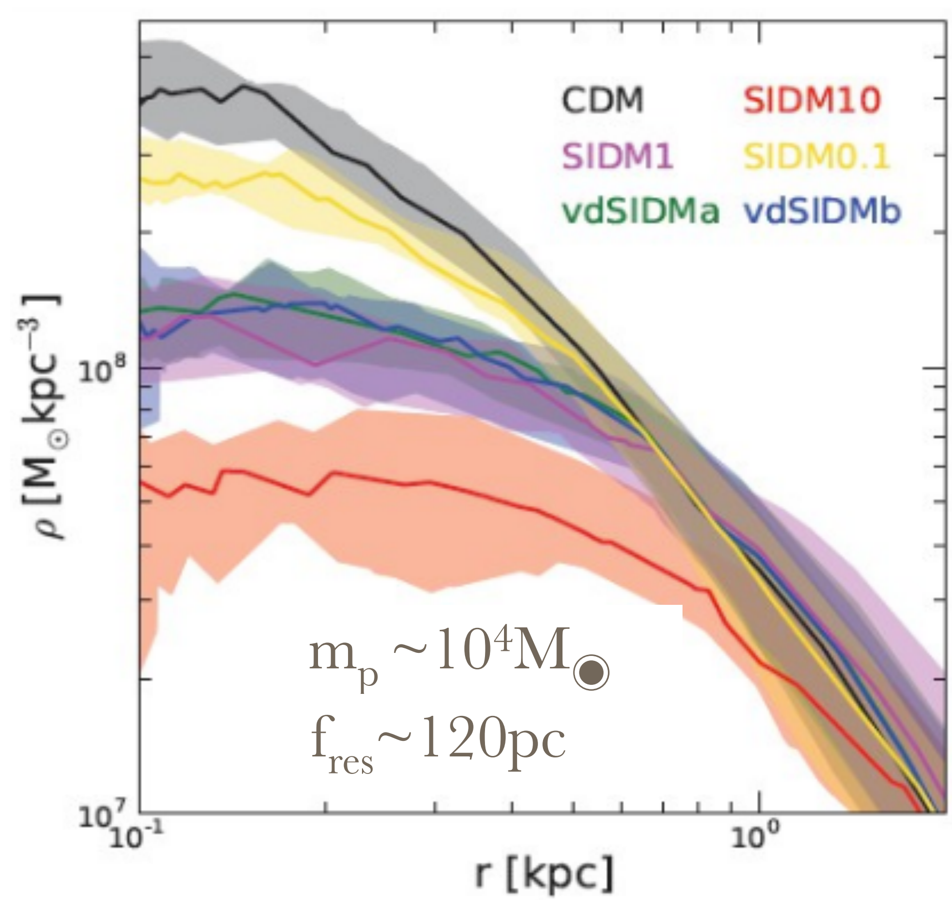
Elbert + 2015

SIDM: cored halos, alleviates cusp/core & TBTF problems

σ/m = 0.5-5 cm² /g

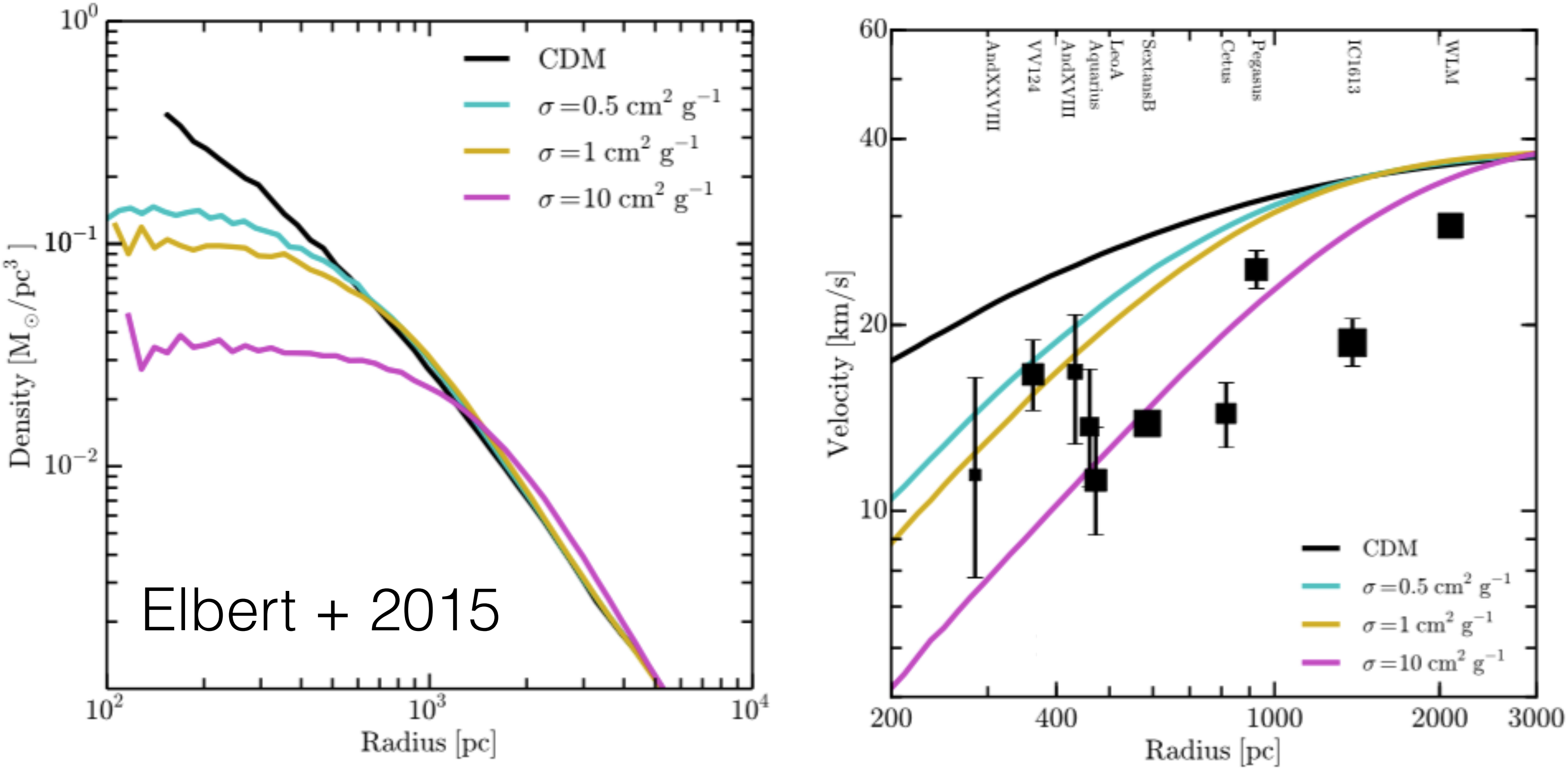


Elbert + 2015



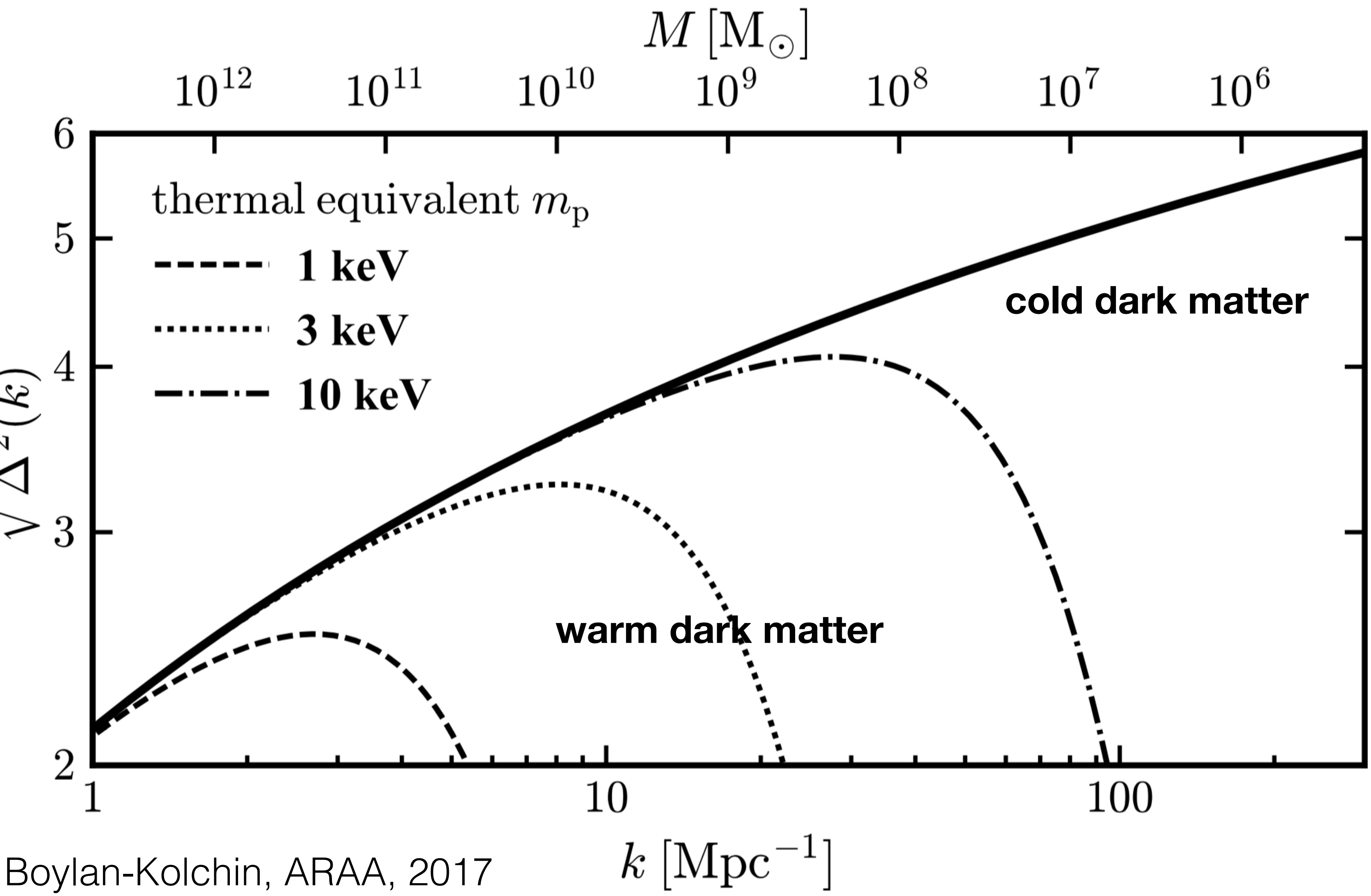
Vogelsberger+12,14; Zavala+14,

SIDM: Solves TBTF w/ cored halos



Spergel & Steinhardt (00); Vogelsberger+12; Rocha+13;Zavala+13

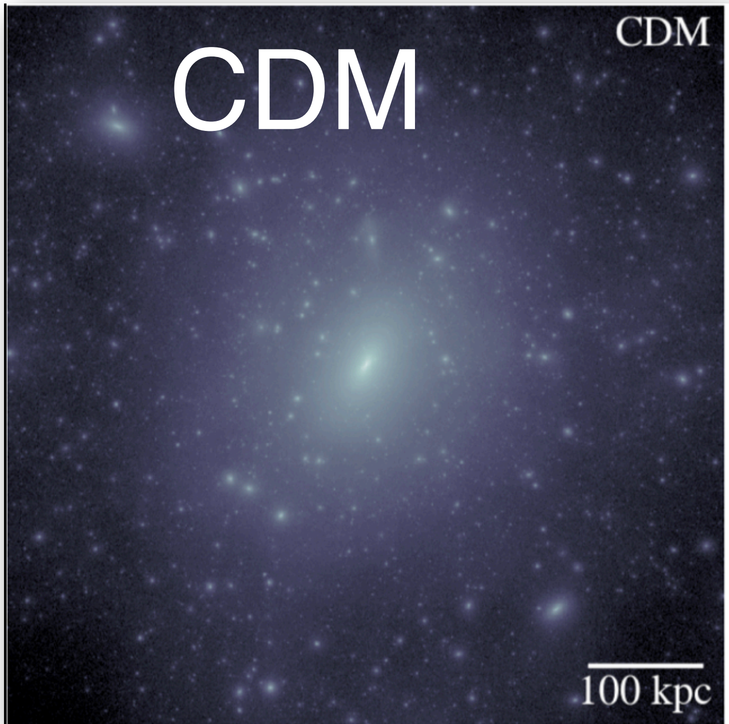
Warm Dark Matter

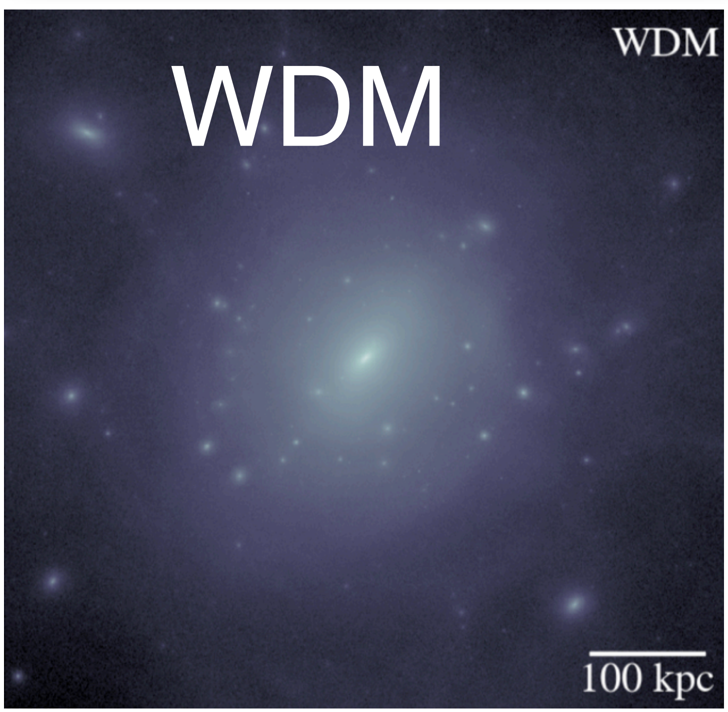


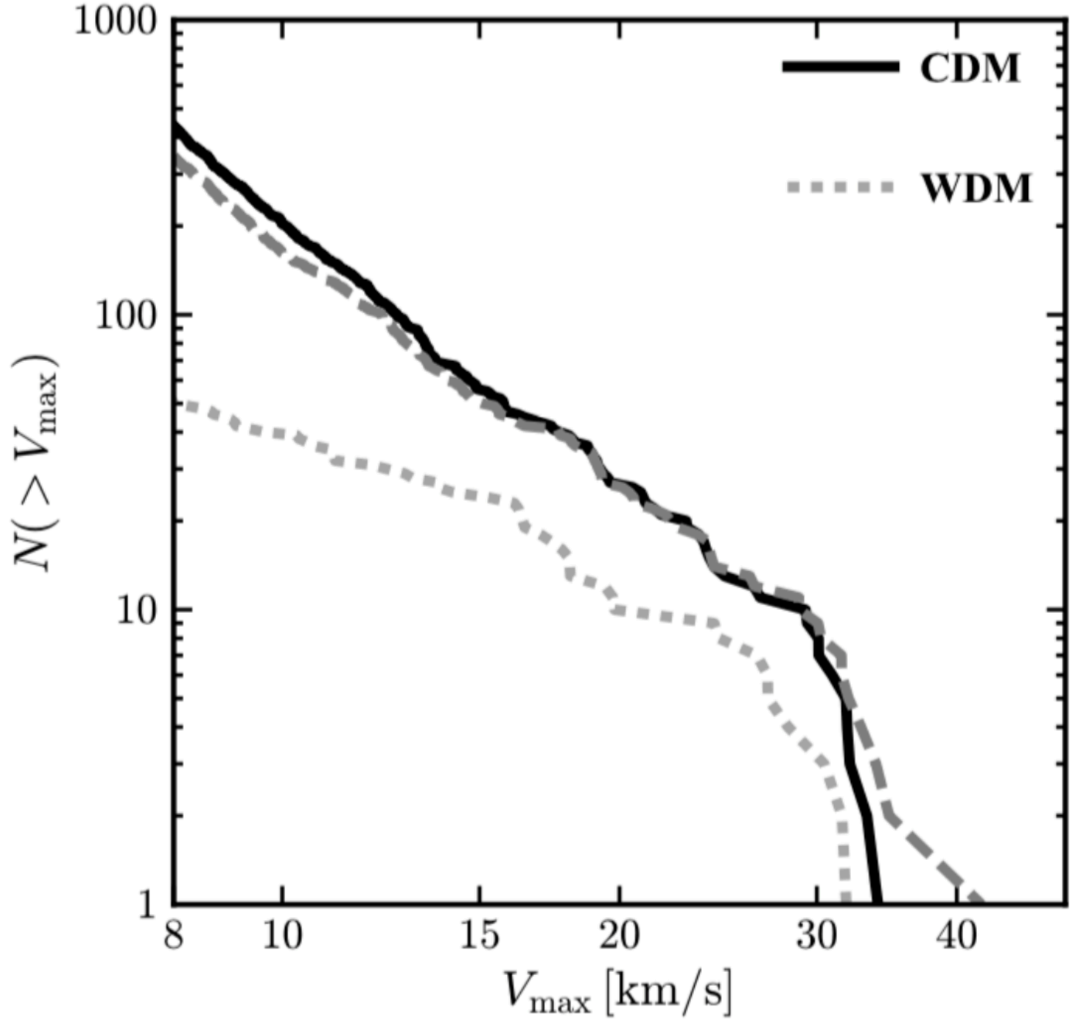
JSB & Boylan-Kolchin, ARAA, 2017

WDM

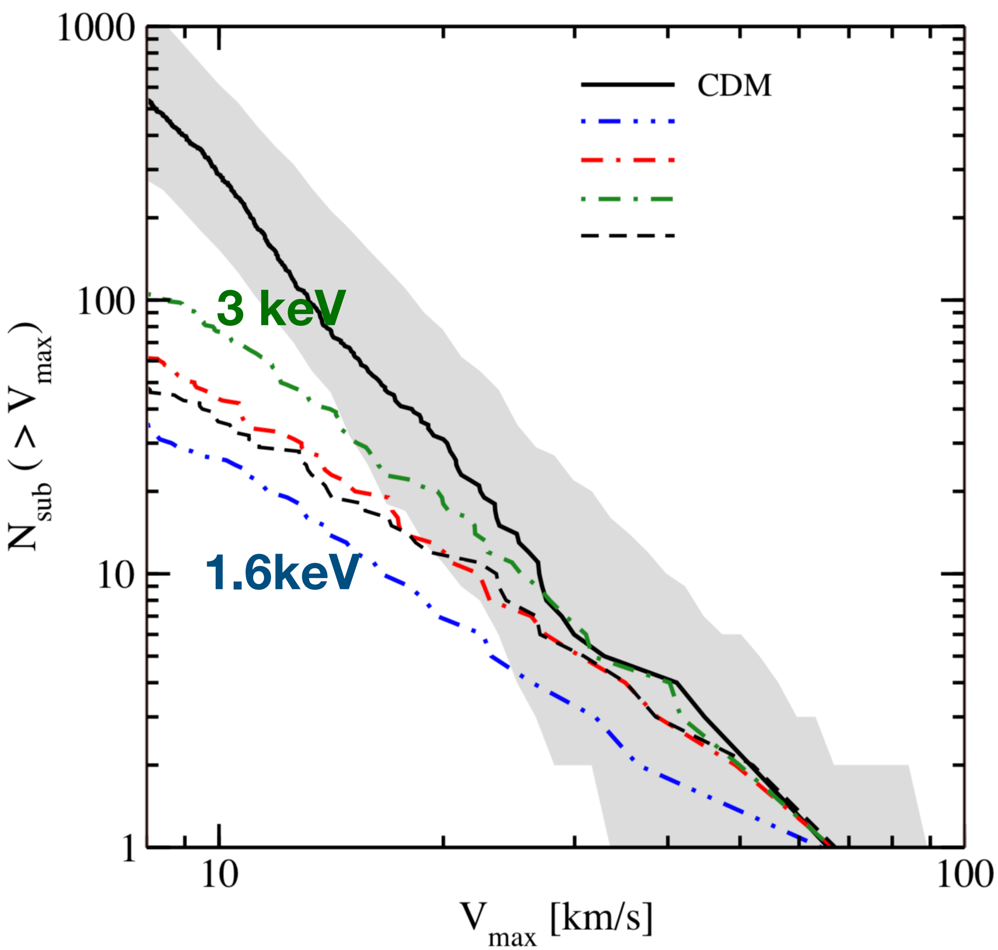
less substructure
- similar density profiles



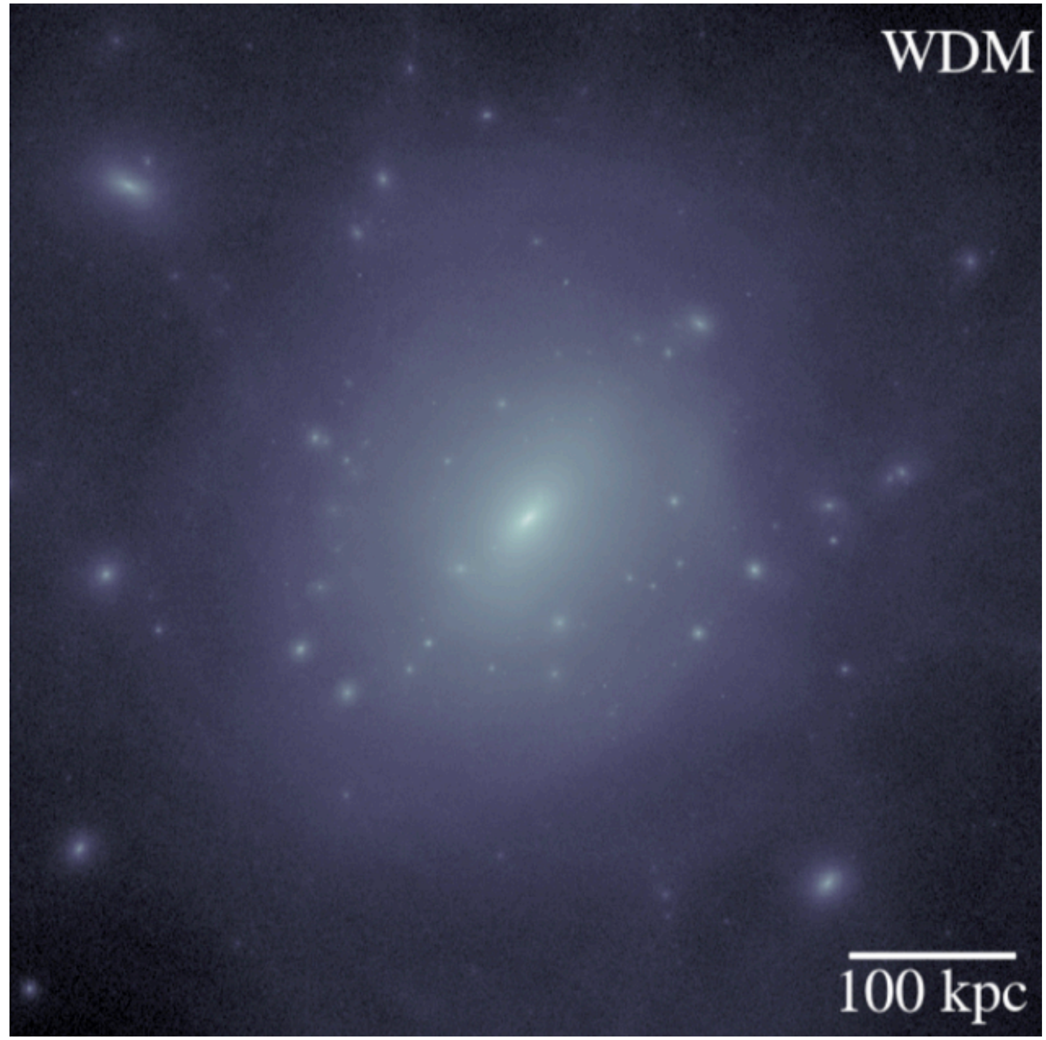




WDM => Less Substructure



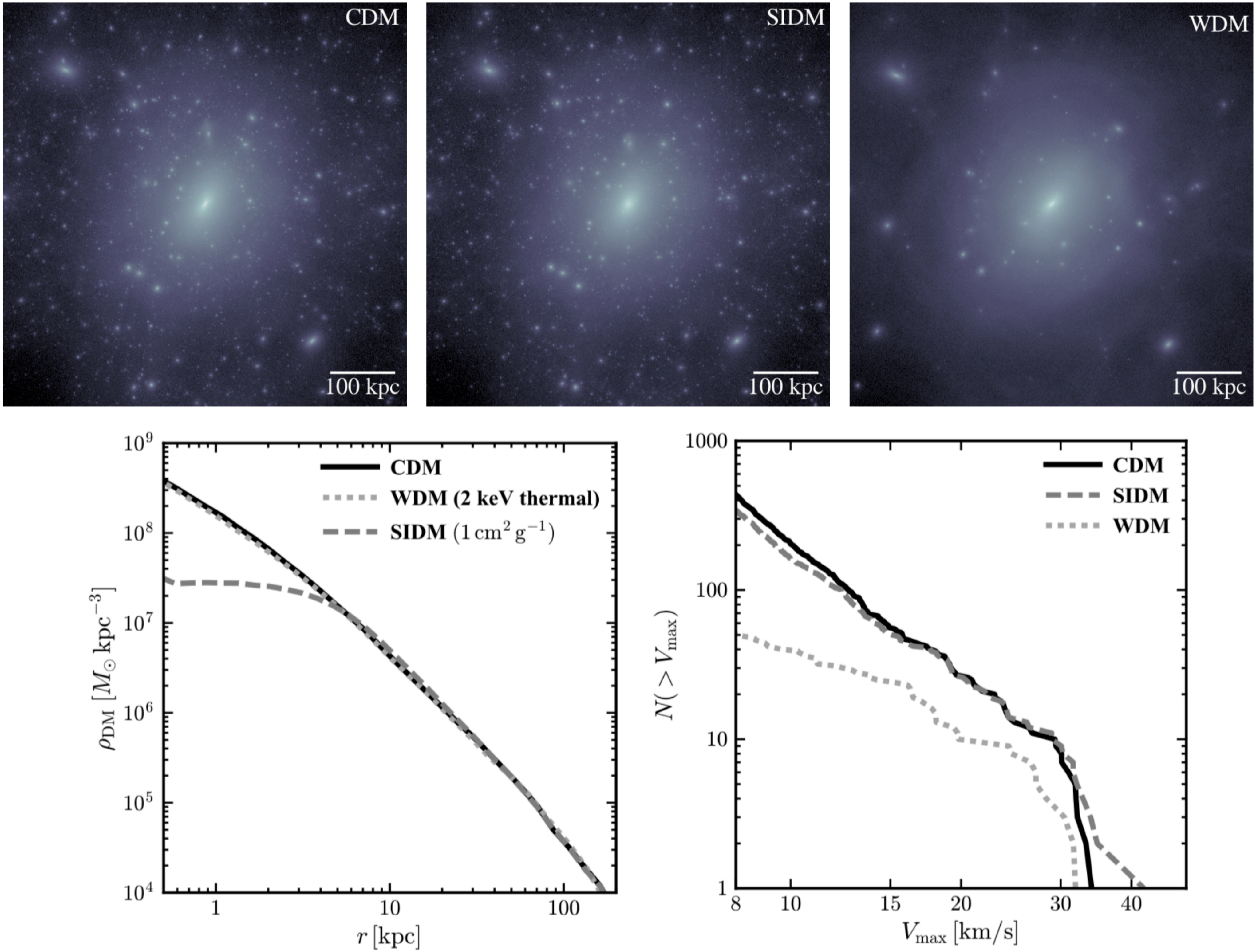
Horiuchi et al. 2015



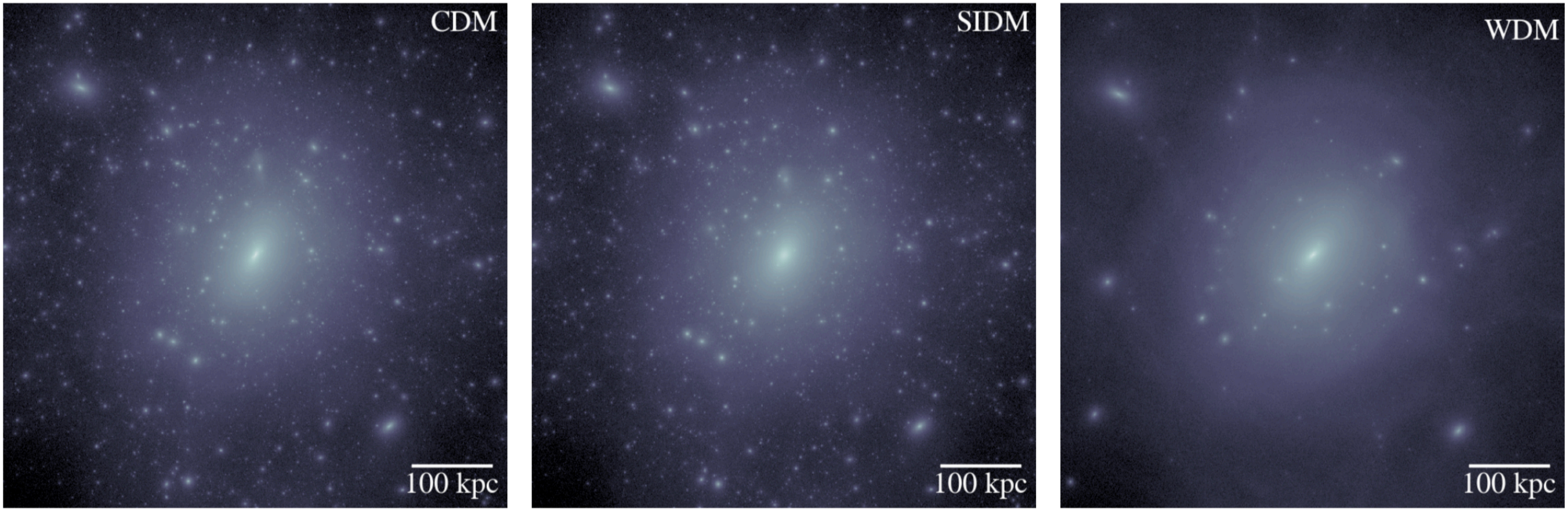
Shi-Fuller resonant model with a thermal equivalent mass of 2 keV

** This model is likely ruled out by the Ly-alpha forest (e.g. Irsic et al. 2017), who quote > 3.5 keV as conservative.

** Ly-alpha forest limit depends on assumed evolution of IGM temperature



CDM
SIDM
WDM
100 kpc
100 kpc
100 kpc
CDM
WDM (2 keV thermal)
SIDM $(1\,\mathrm{cm}^2\,\mathrm{g}^{-1})$
$\rho_{\mathrm{DM}}\,[M_\odot\,\mathrm{kpc}^{-3}]$
$r\,[\mathrm{kpc}]$
CDM
SIDM
WDM
$N(>V_{\mathrm{max}})$
$V_{\mathrm{max}}\,[\mathrm{km/s}]$



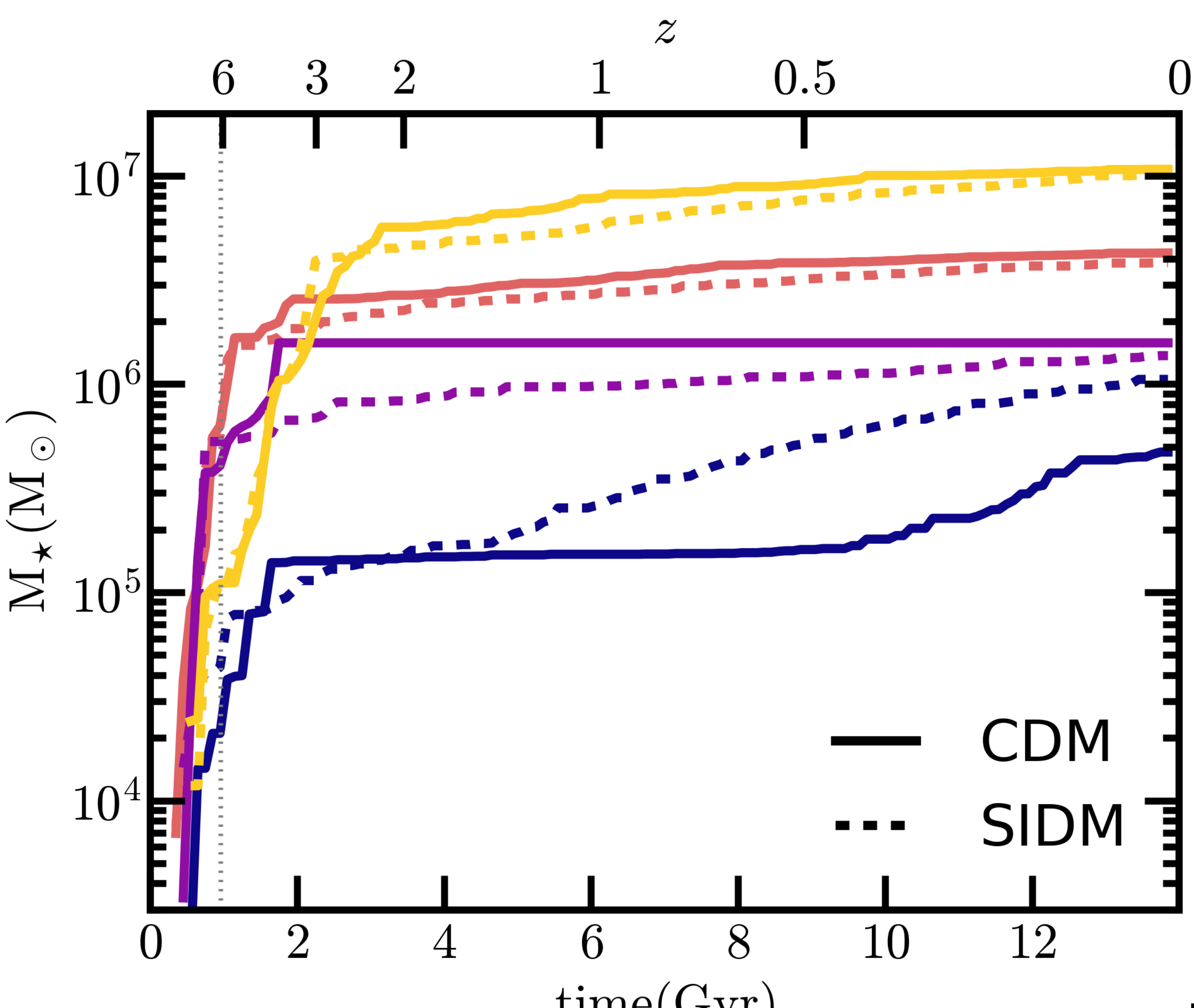
WDM

less substructure
- similar density profiles

SIDM

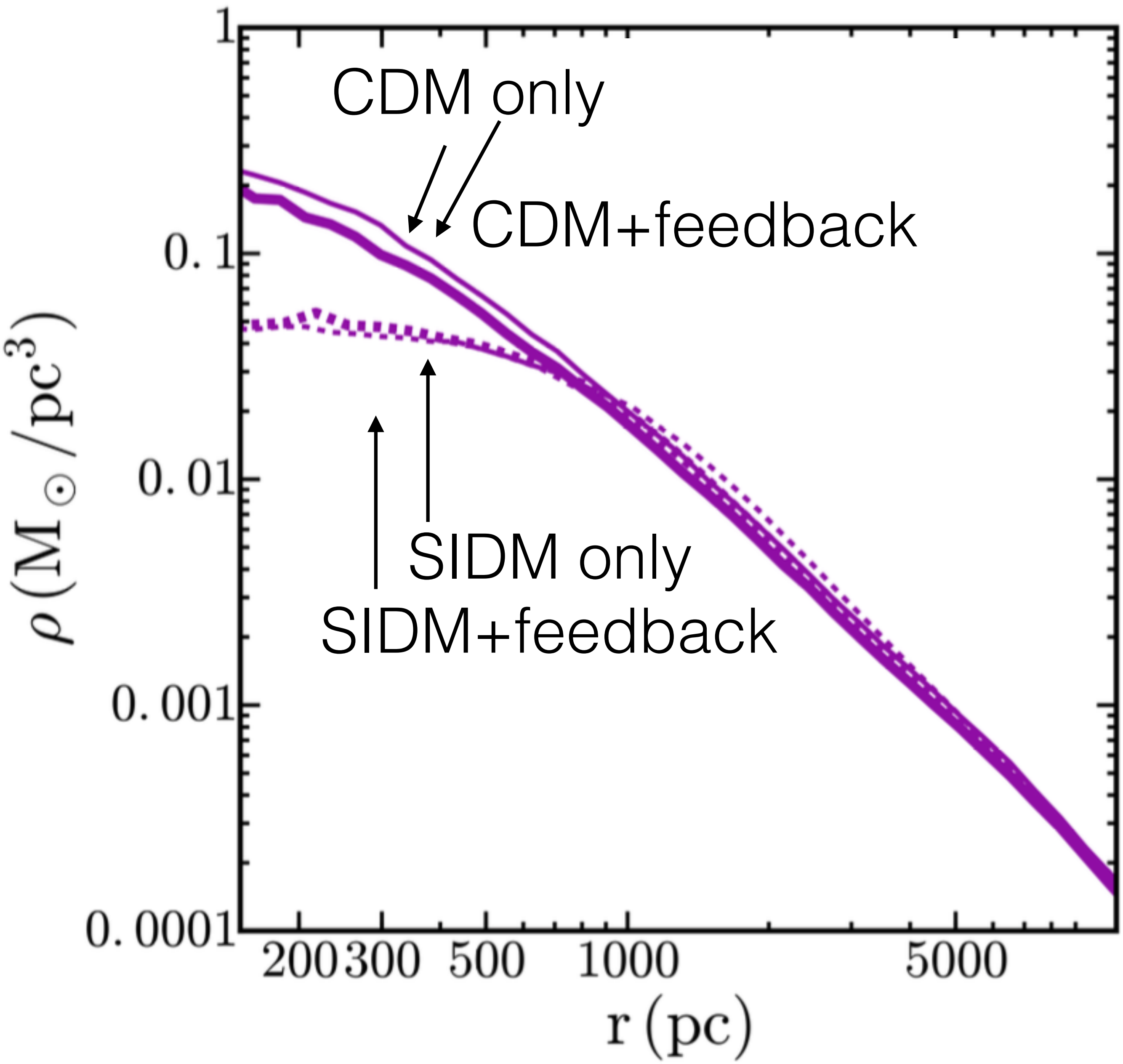
similar substructure
- cored density profiles

SIDM vs. CDM: Full FIRE physics



Robles+17

Falsifiable Prediction for SIDM



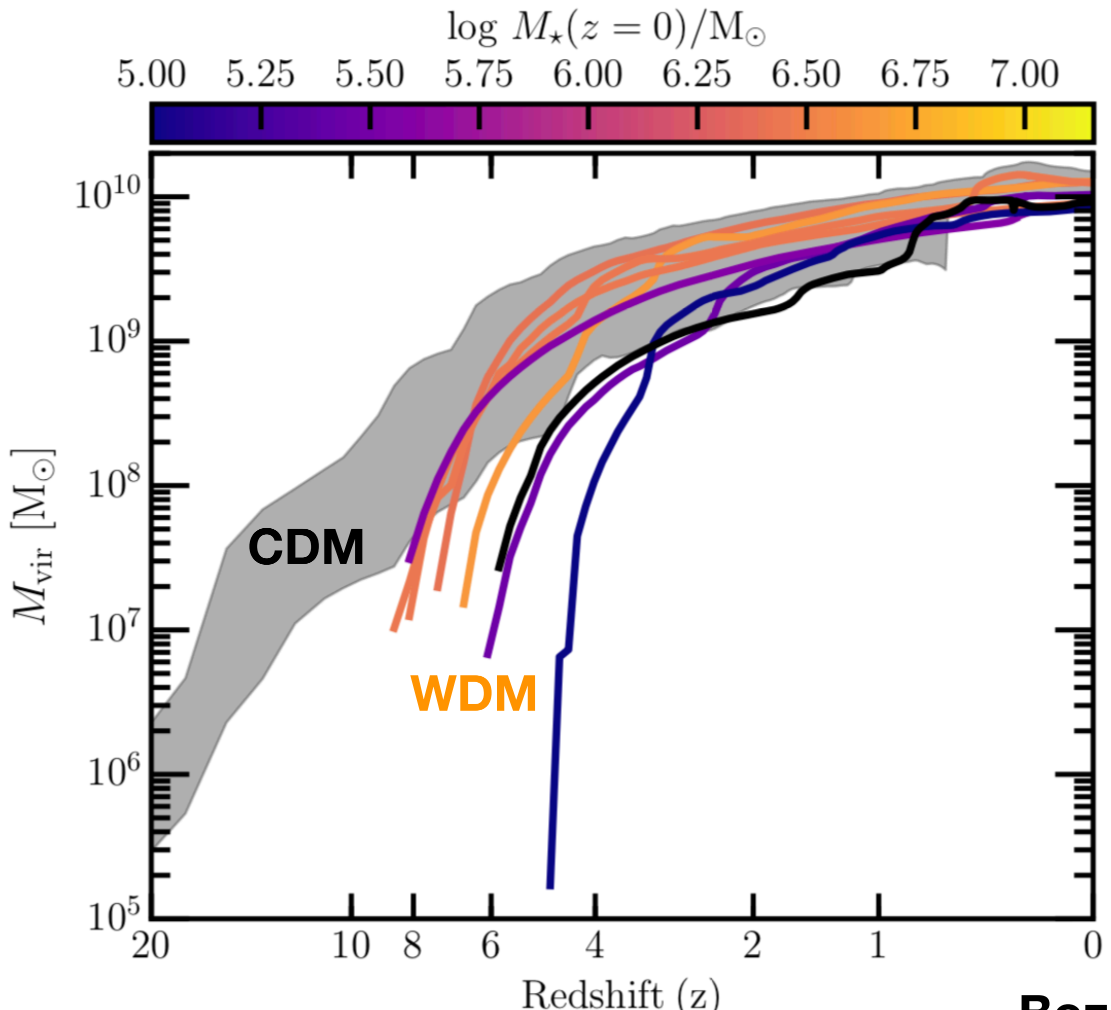
$M_* = 1.e6\ M_{sun}$

<u>Falsifiable prediction</u>:

Smallest galaxies should have constant-density cores in SIDM.

Robles+17

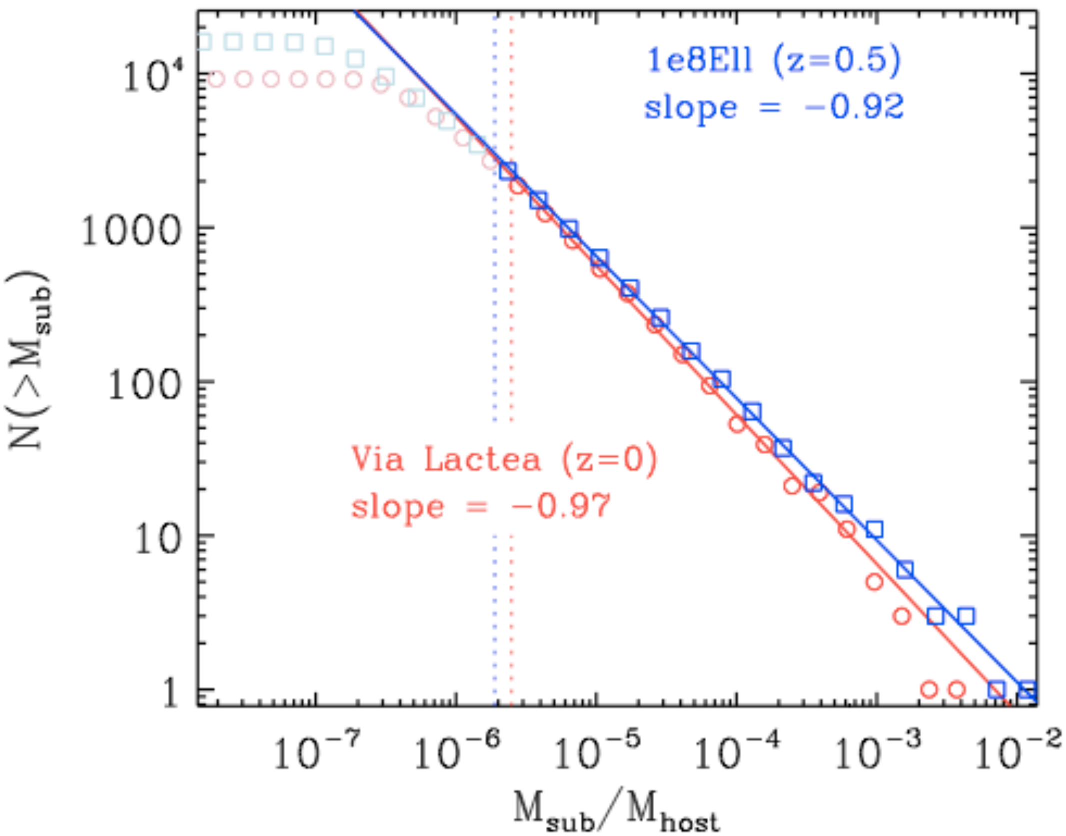
WDM + FULL FIRE Physics



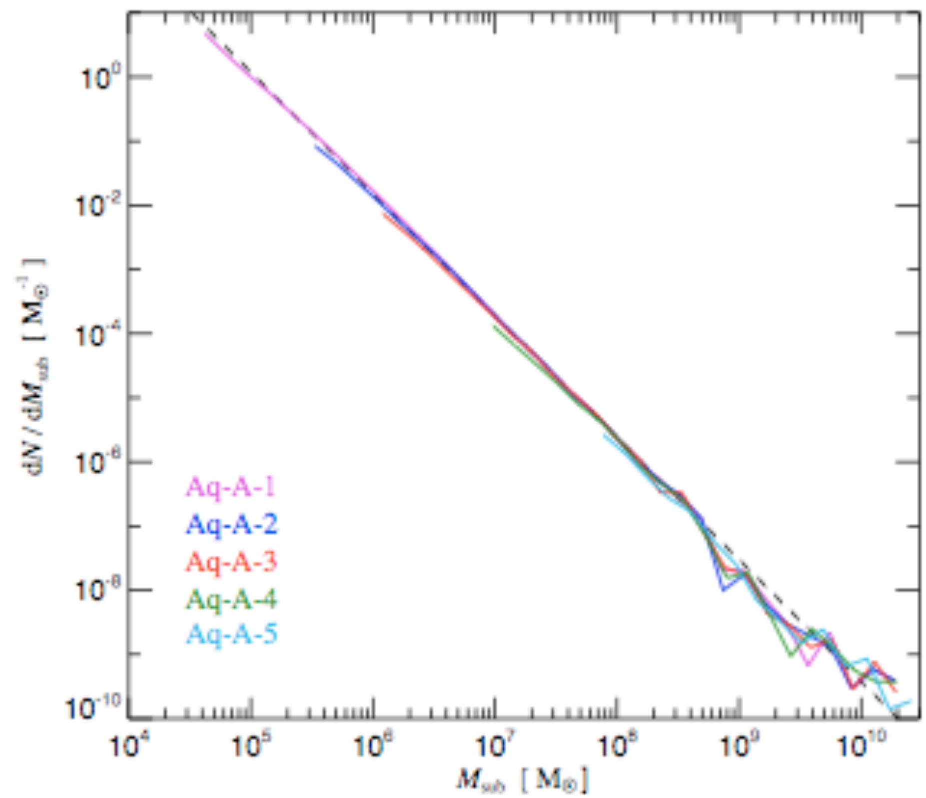
Bozek + 2018

The discovery of young ultra-faint dwarf galaxies with no ancient (reionization era) star formation – which do not form in CDM simulations – would therefore provide evidence in support of WDM.

Let's find those dark subhalos



Madau, Diemand, Kuhlen 08



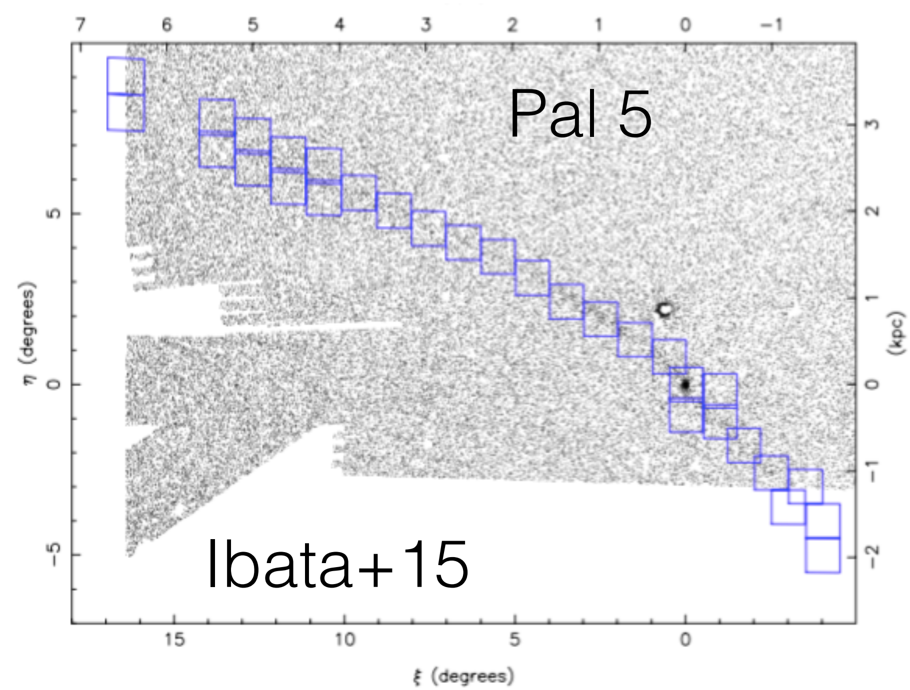
Springel et al. 08

LCDM: MW has ~10,000 w/ $M > \sim 10^6\ M_{sun}$

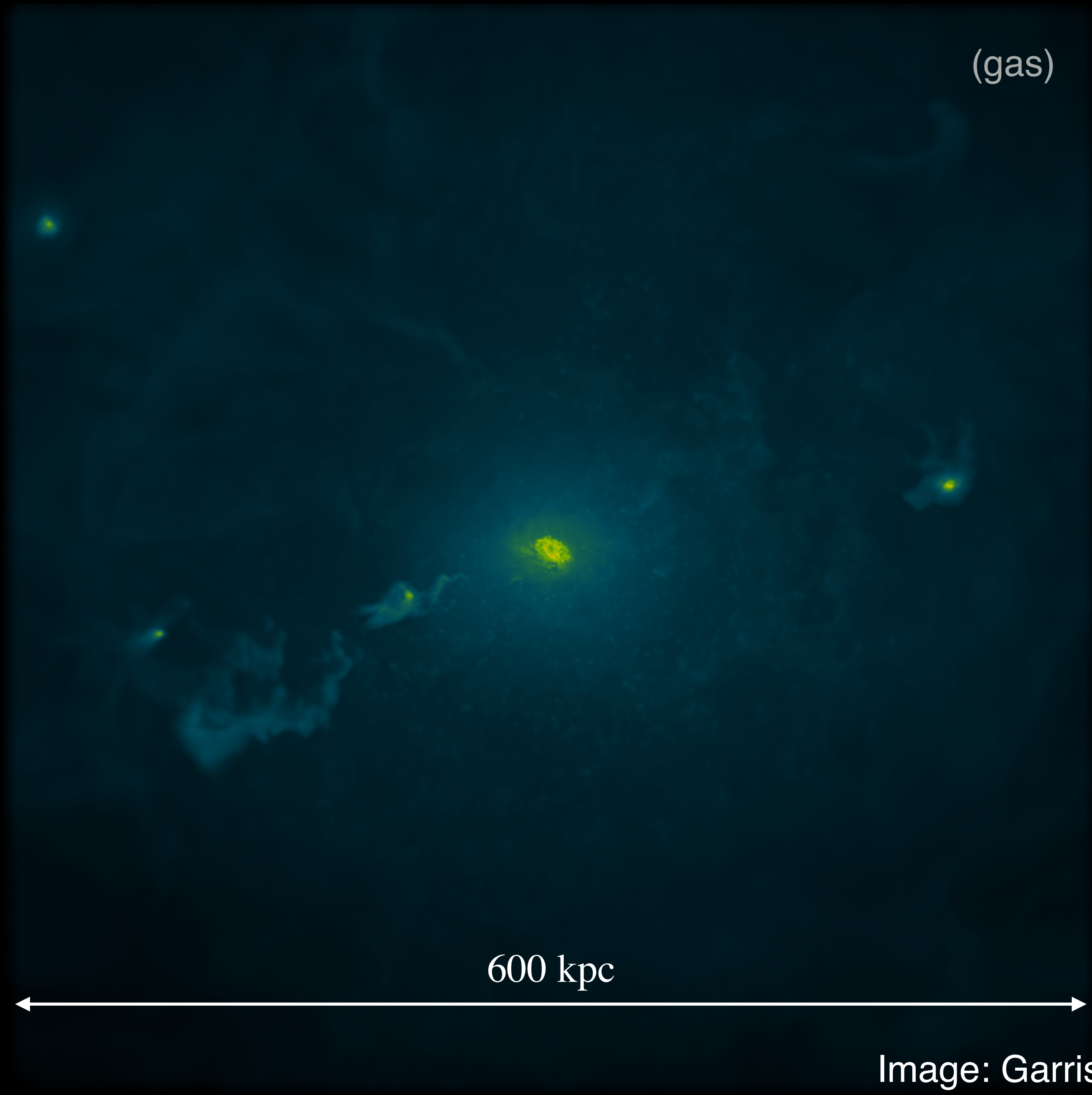
Towards finding **dark** substructure

- 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



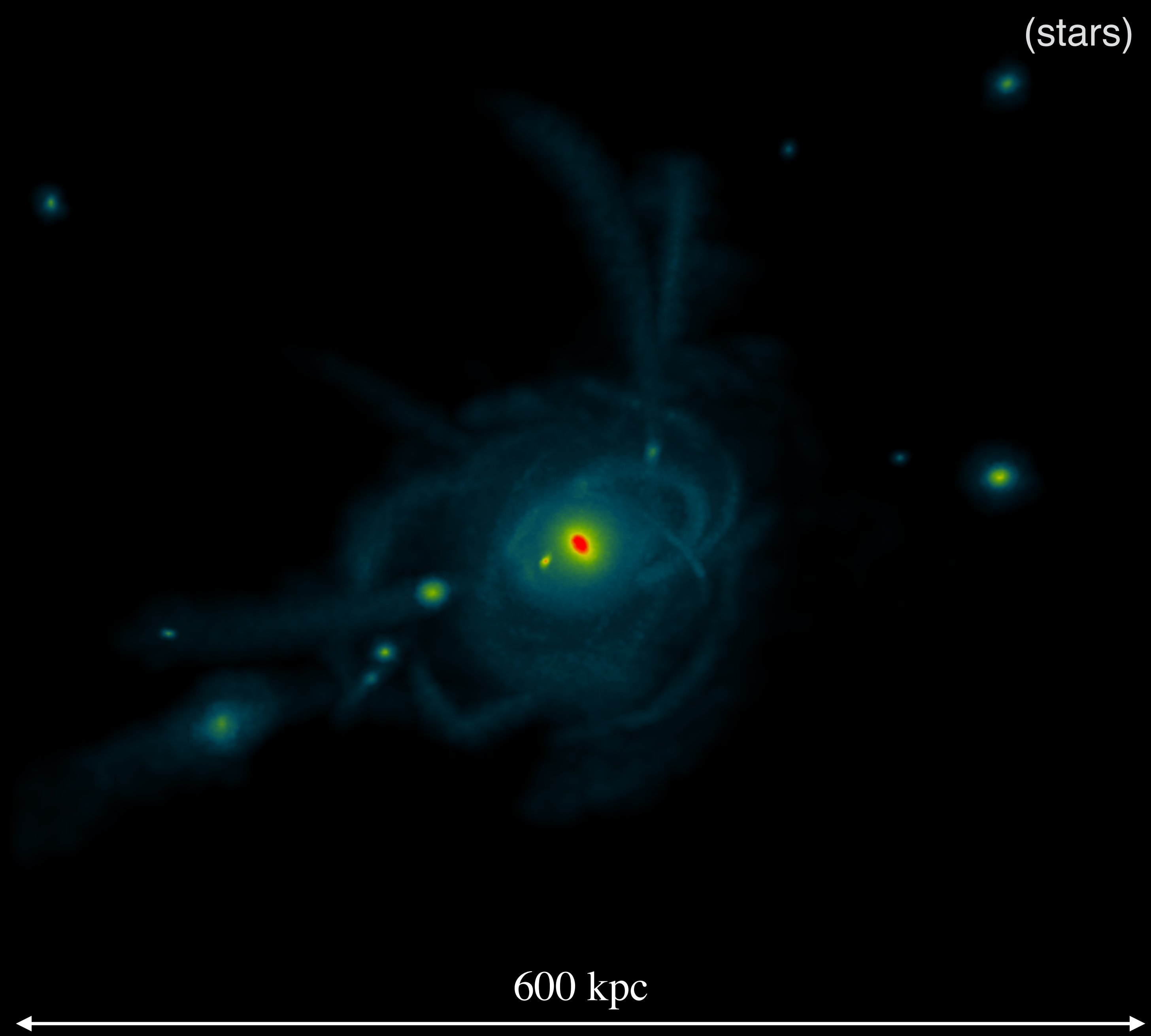
Latte Project: the Milky Way on FIRE (Feedback in Realistic Environments)



Wetzel+2016

Image: Garrison-Kimmel

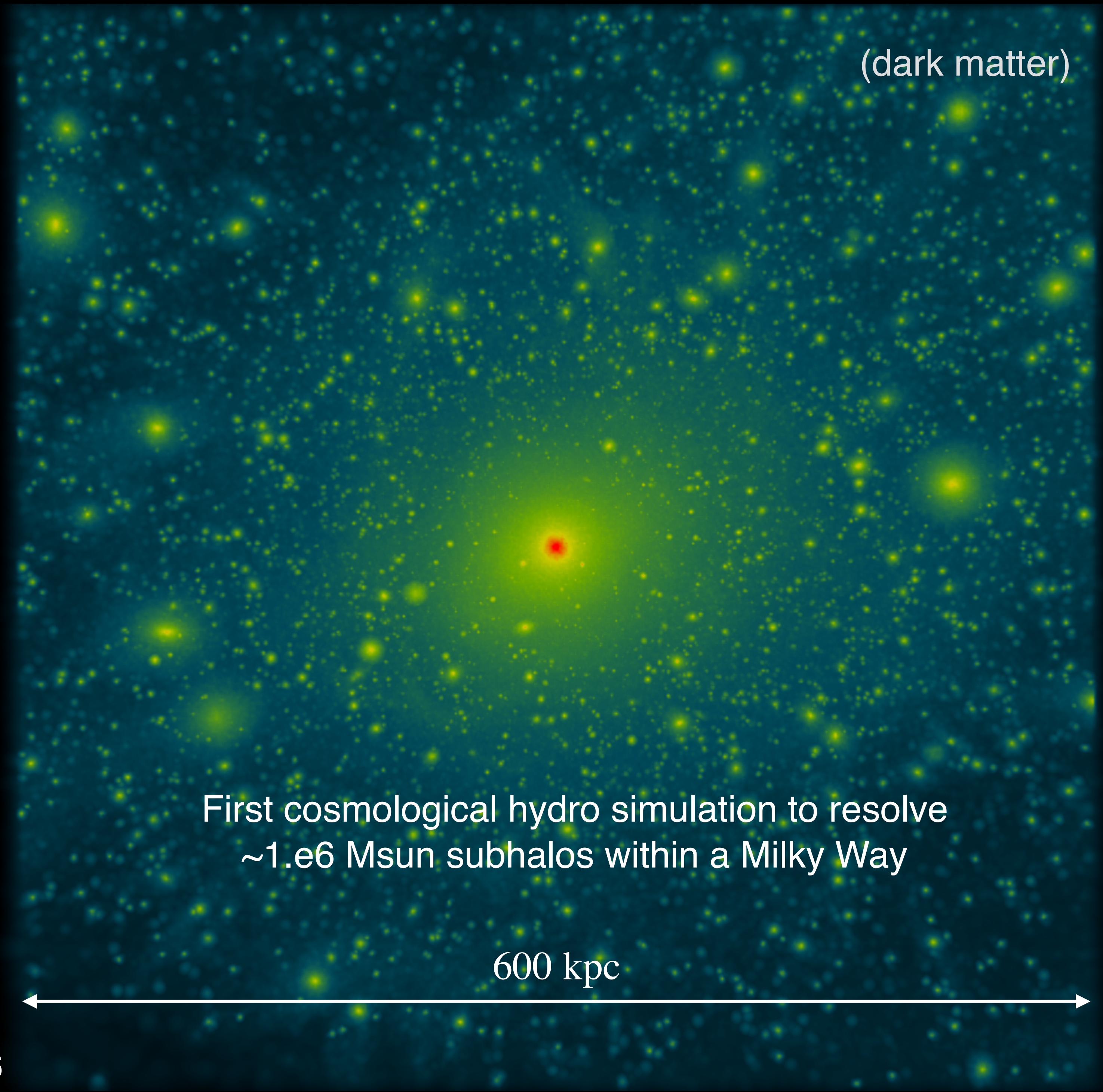
Latte Project: the Milky Way on FIRE (Feedback in Realistic Environments)



Wetzel+2016

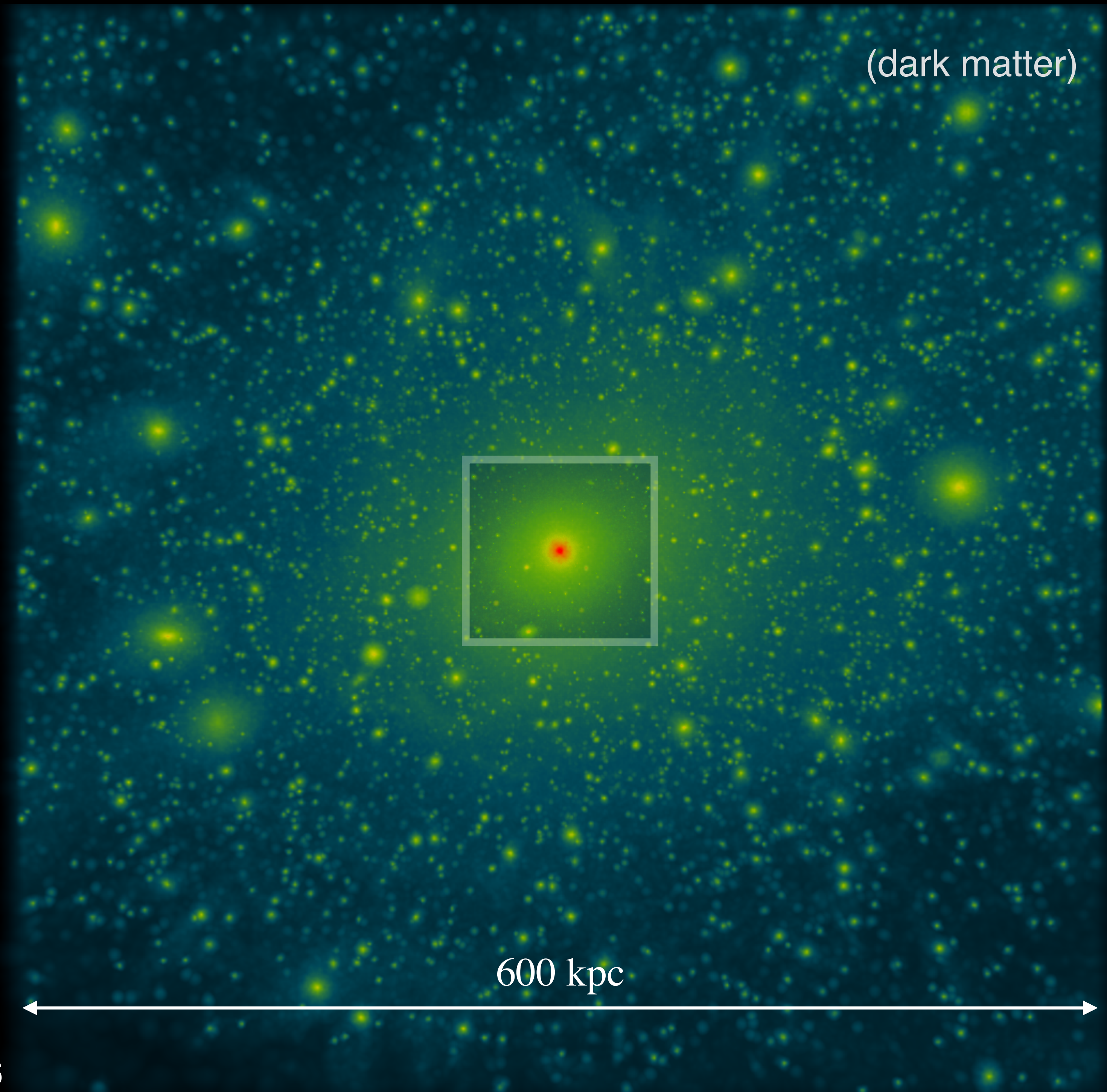
Image: Garrison-Kimmel

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



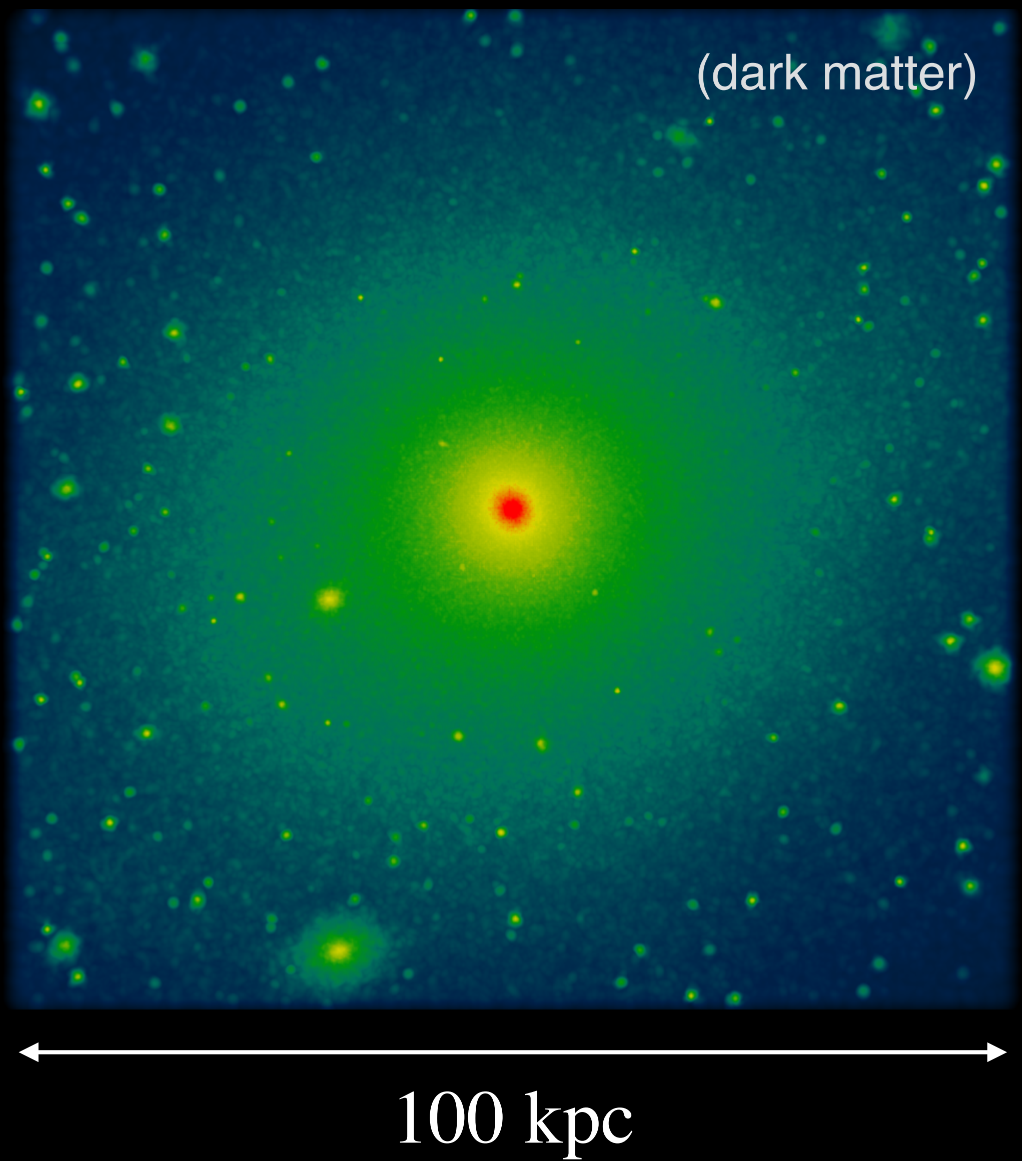
Wetzel+2016

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



Wetzel+2016

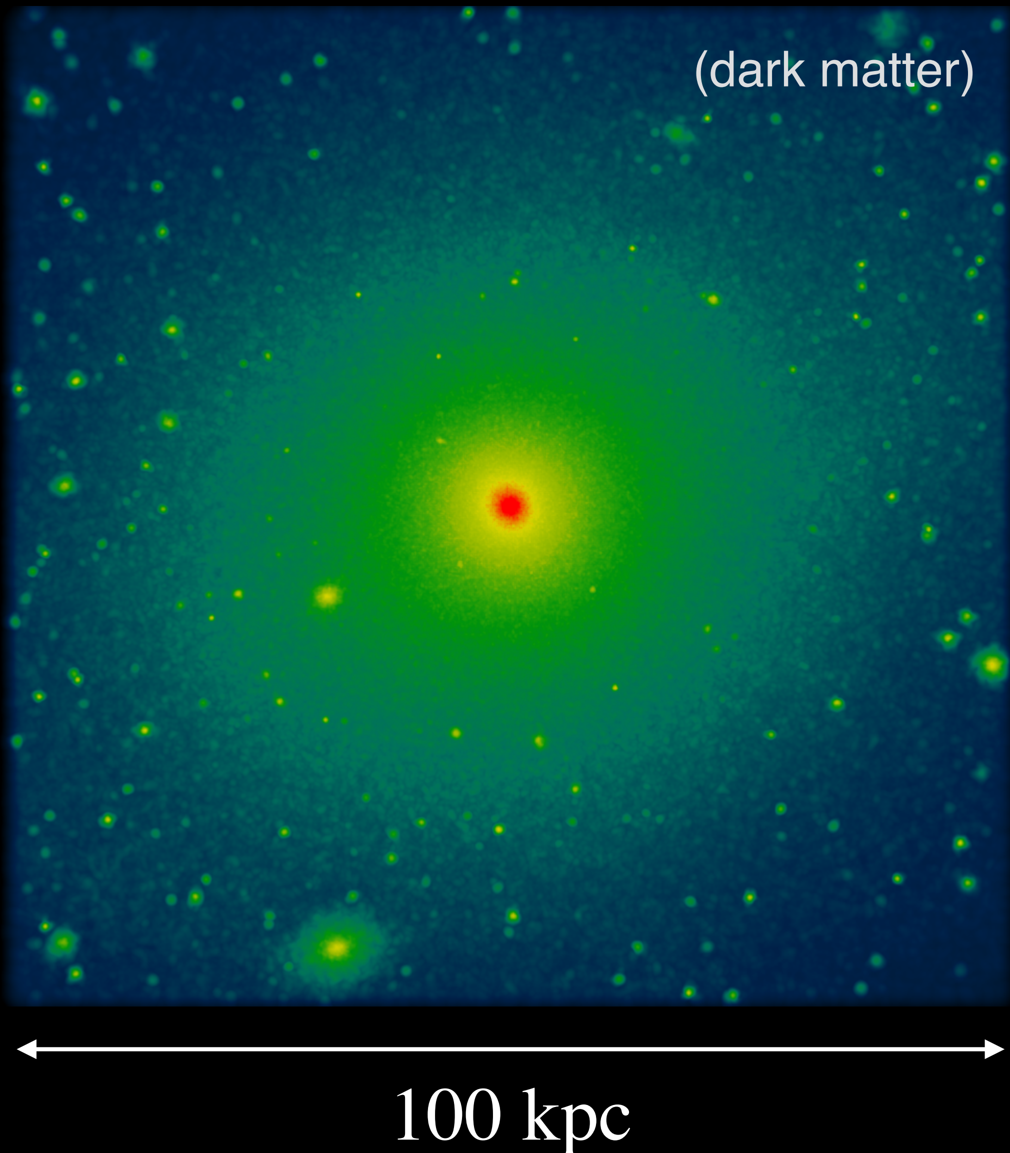
FIRE Hydrodynamics



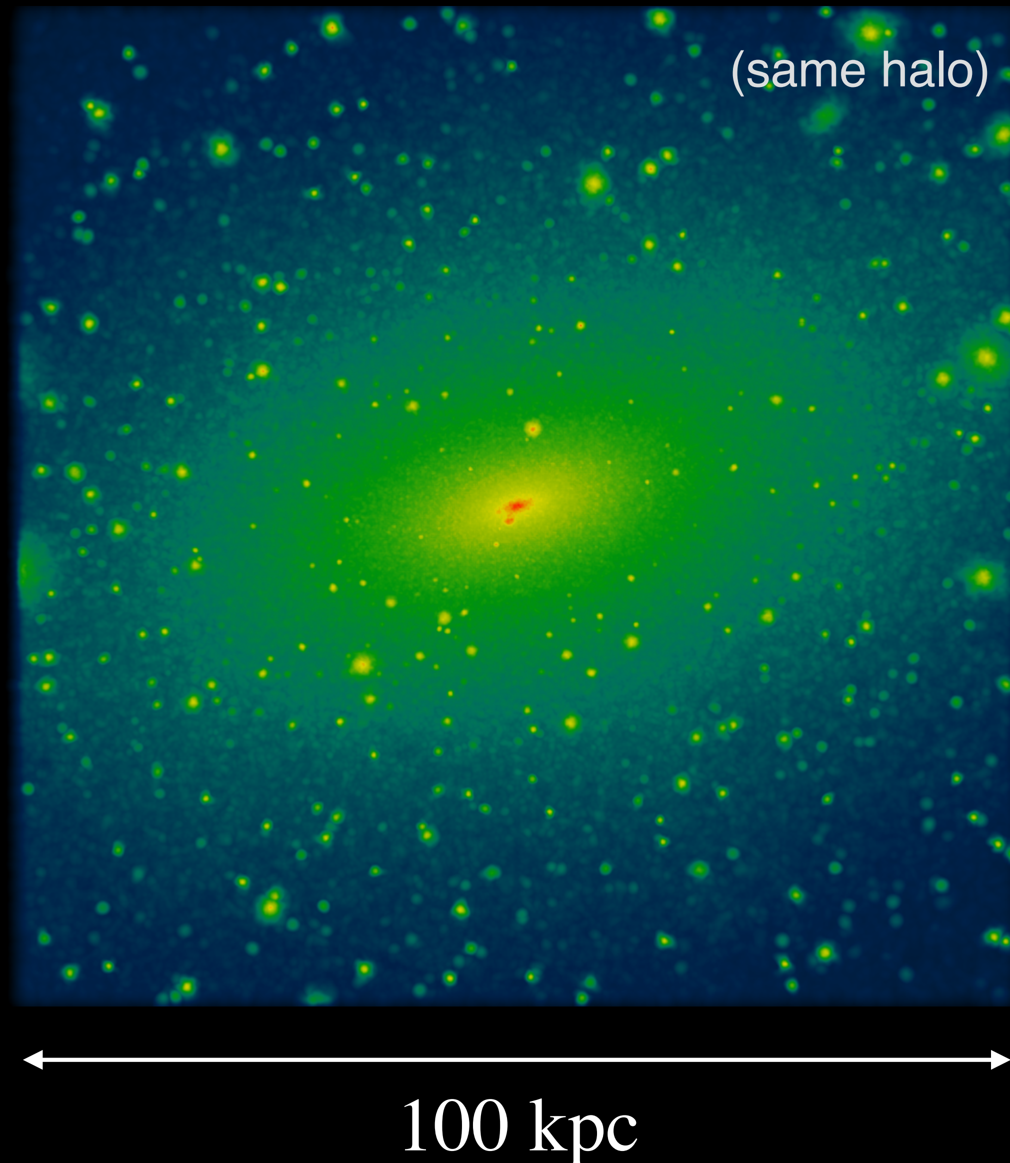
Garrison-Kimmel+2016

Baryons Matter (A Lot!)

FIRE Hydrodynamics

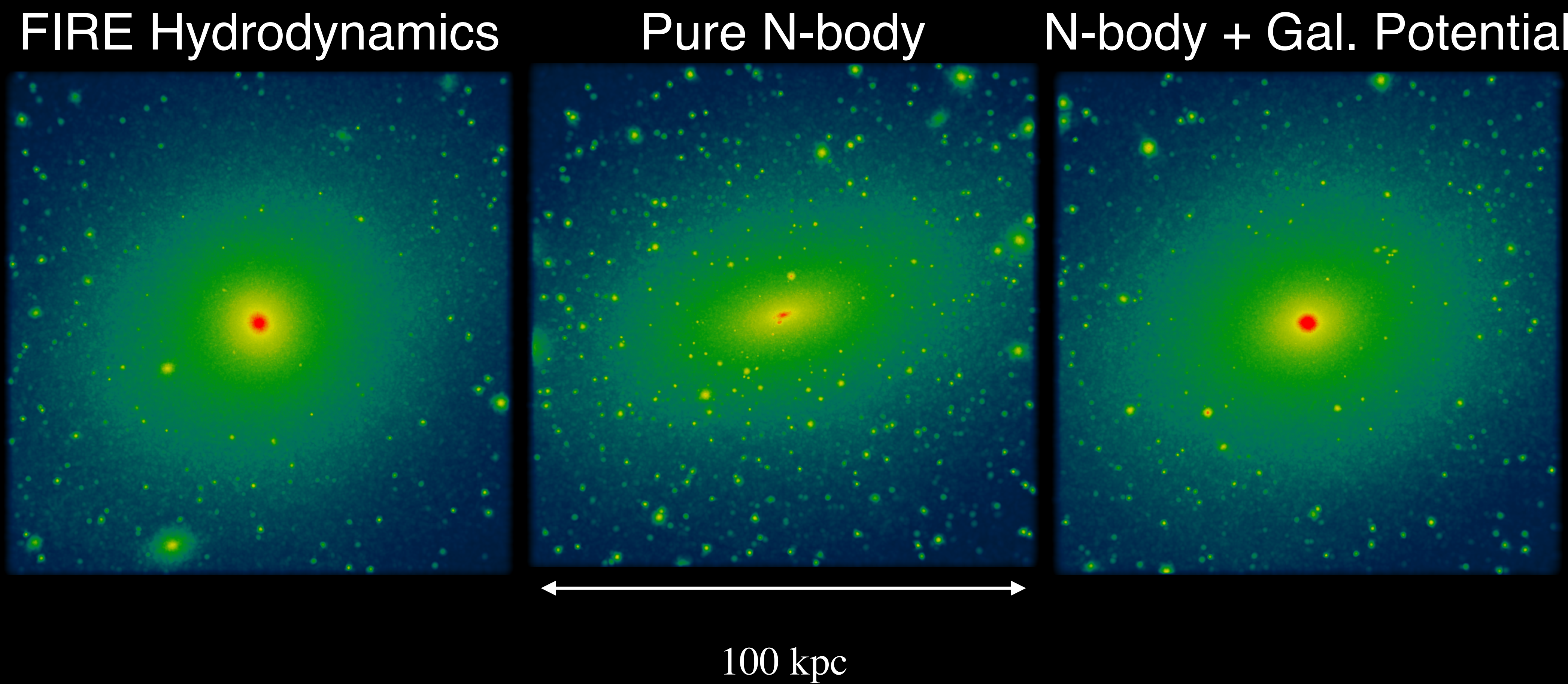


Pure N-Body



Garrison-Kimmel+2016

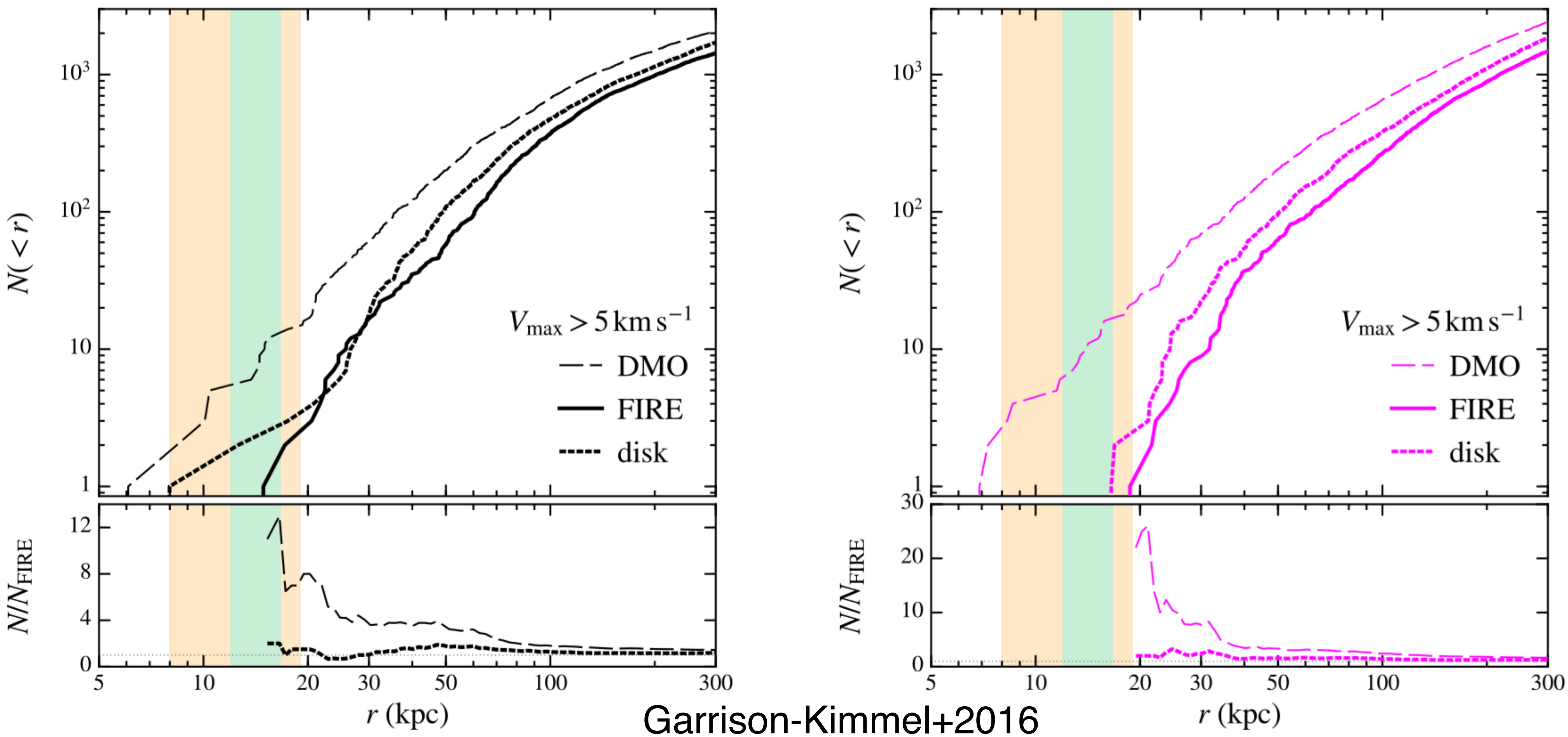
Most important Factor is Central Galaxy Potential



Garrison-Kimmel+2016

Baryons matter for substructure predictions

2 simulations at high resolution

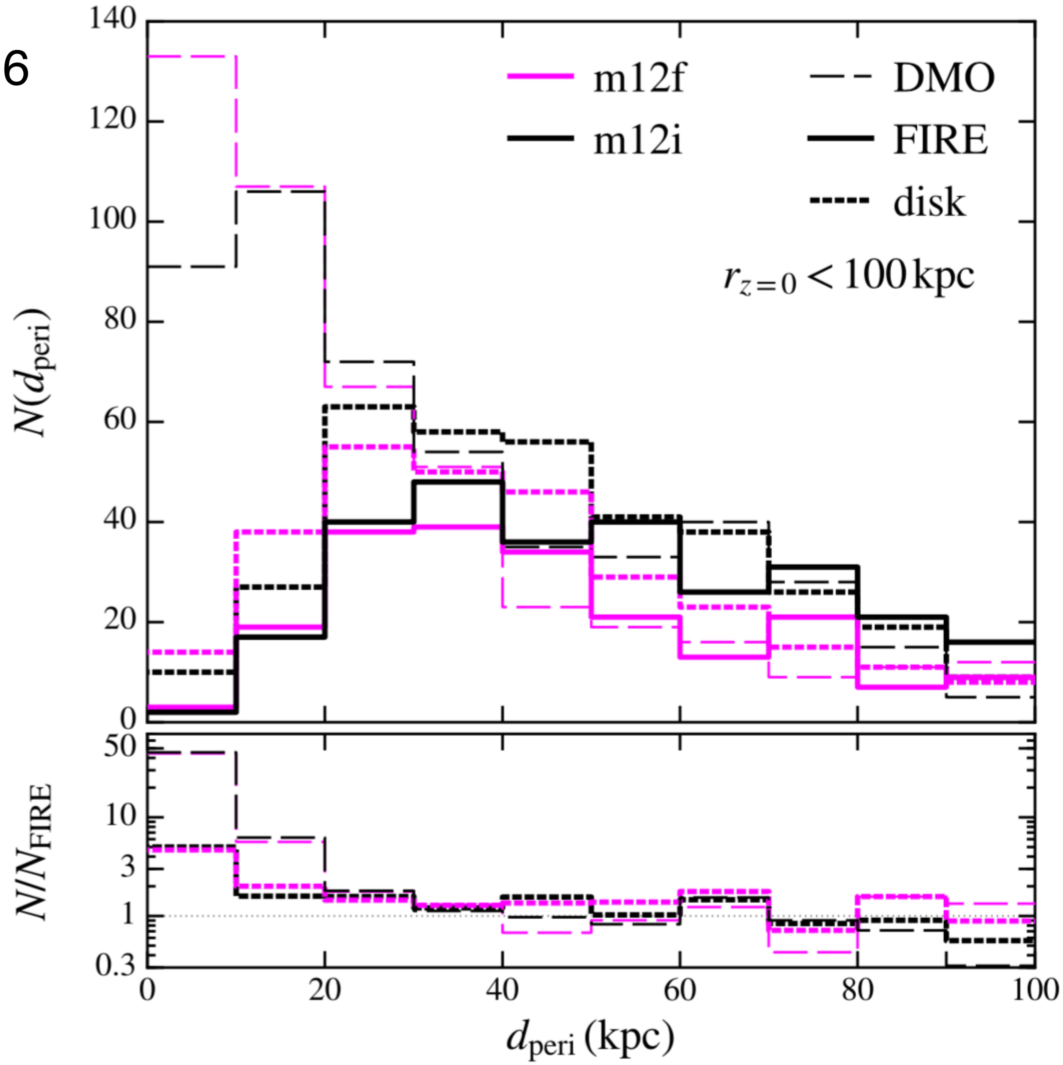


Garrison-Kimmel+2016

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