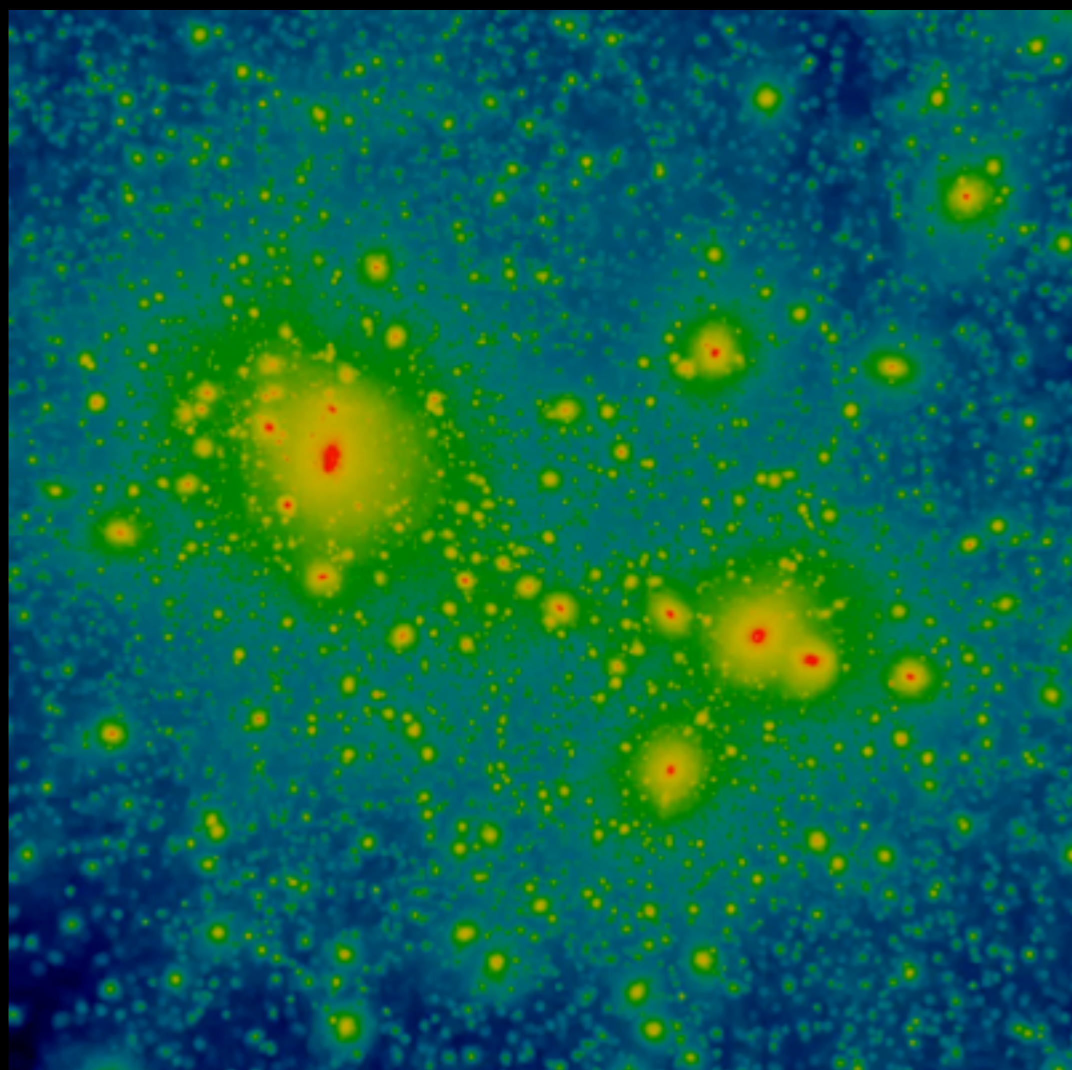
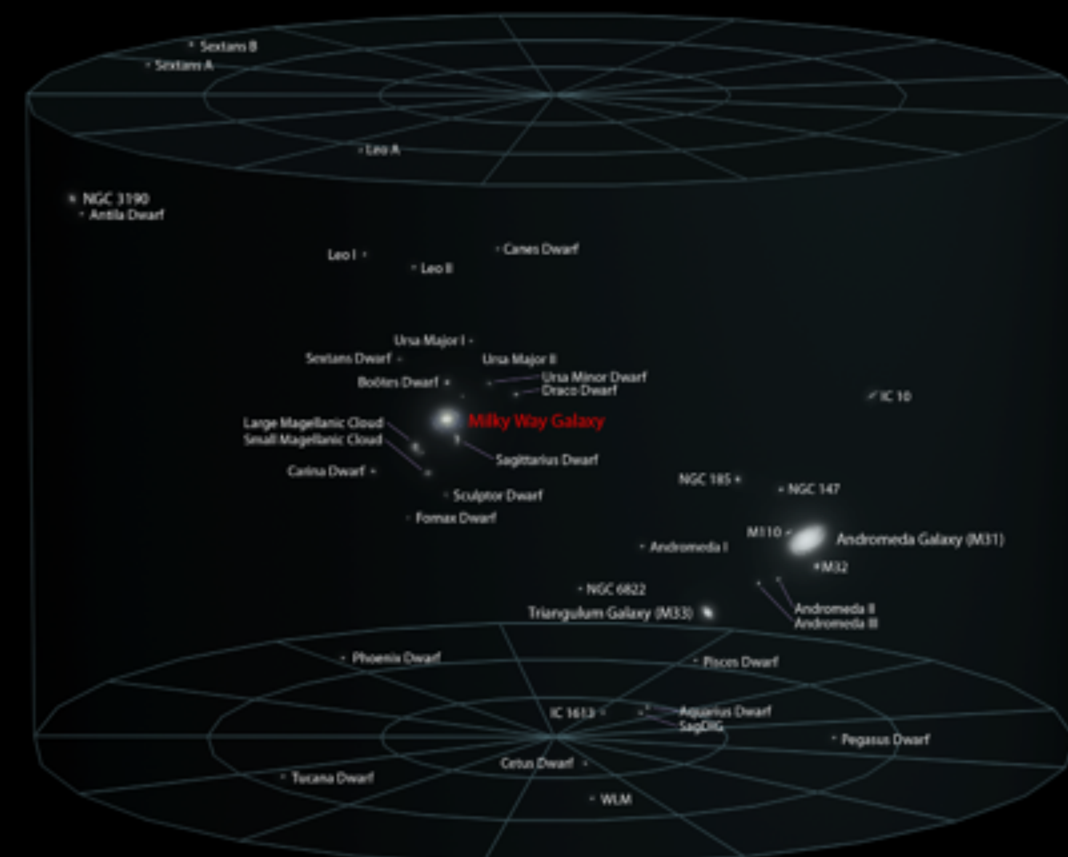
LESSONS IN NEAR-FIELD COSMOLOGY FROM SIMULATING THE LOCAL VOLUME

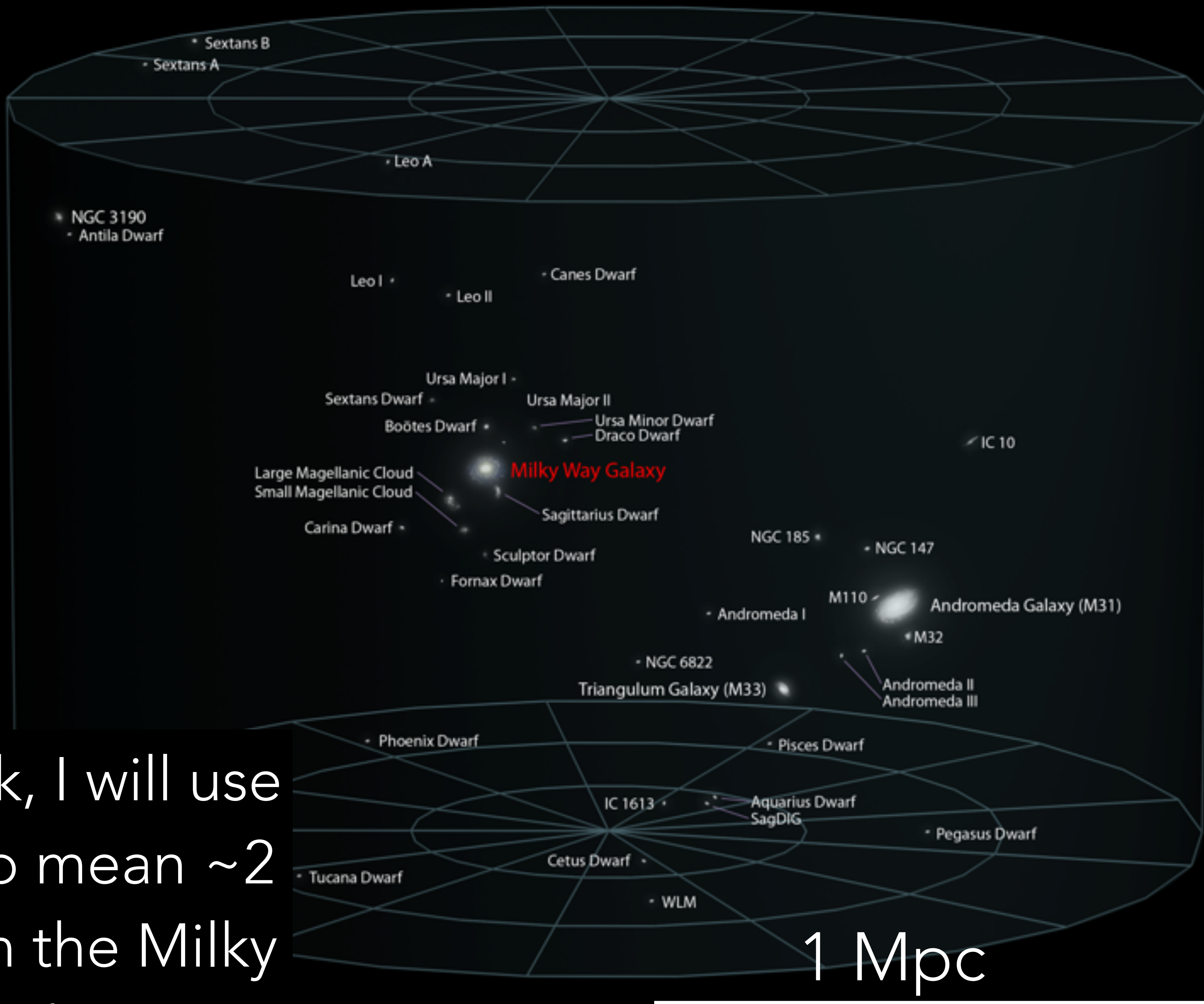




SHEA GARRISON-KIMMEL
UNIVERSITY OF CALIFORNIA, IRVINE

James Bullock, Mike Boylan-Kolchin, Evan Kirby, Jose Oñorbe,
Shunsaku Horiuchi, Kevork Abazajian, Manoj Kaplinghat, and Oliver Elbert

THE "LOCAL VOLUME"



In this talk, I will use "local" to mean ~2 Mpc from the Milky Way, including M31

OUTLINE

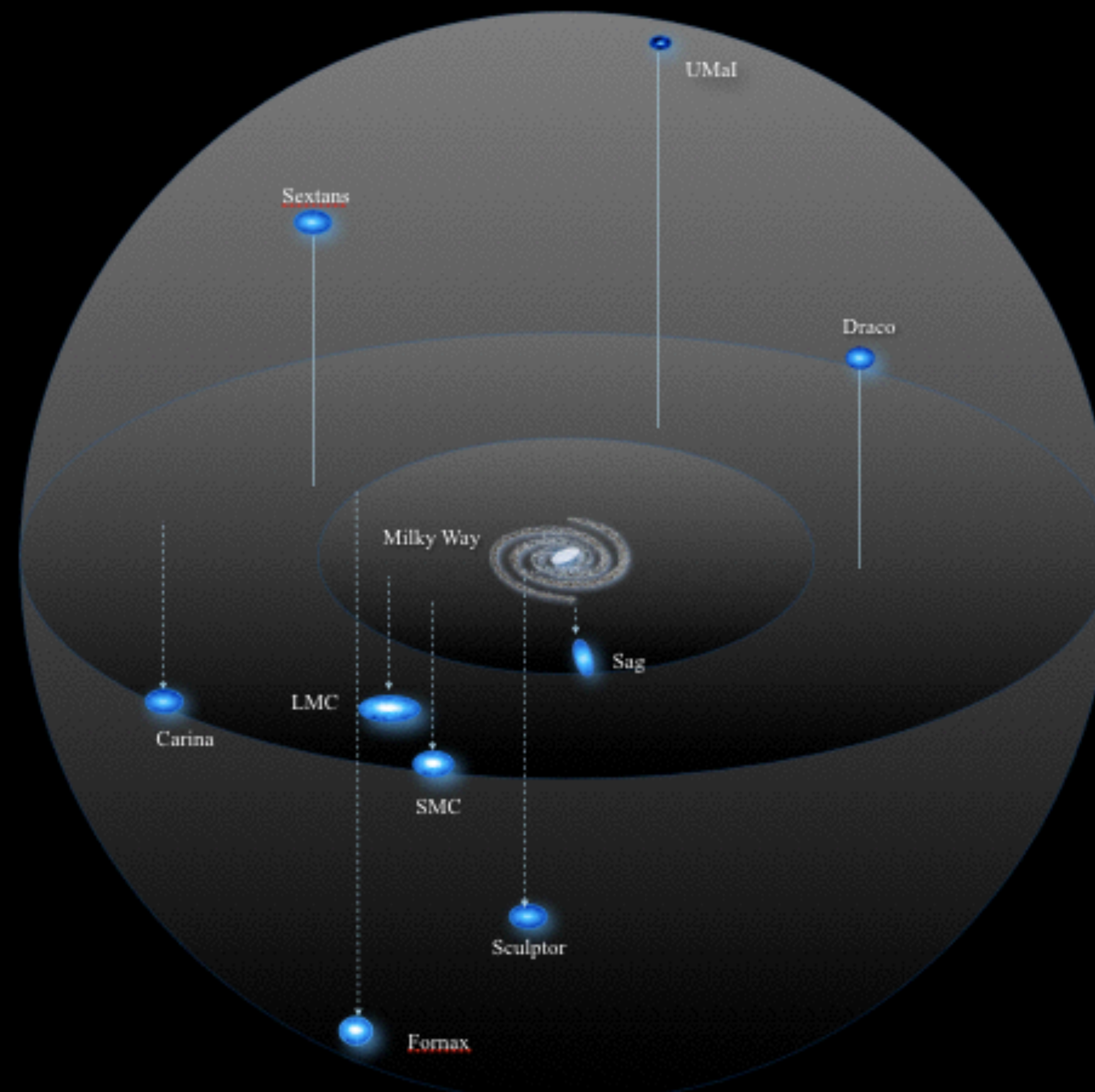
- **Introduction:**
  - What's interesting about the Local Group?
  - Zoom-in simulations of the Local Volume
- **The ELVIS Suite**
  - Paired *vs* Isolated Milky Way hosts
  - Abundance matching implications and LSST-era predictions
- **Too Big to Fail**
- **Summary**

WHY STUDY THE LOCAL GROUP?

- The smallest galaxies in the Universe can strongly constrain fundamental cosmological questions
- The Local Volume is the *only* region in the Universe where we can study these galaxies in great detail

WHY STUDY THE LOCAL GROUP?

Missing Satellites



Theory: N ≫ 1000

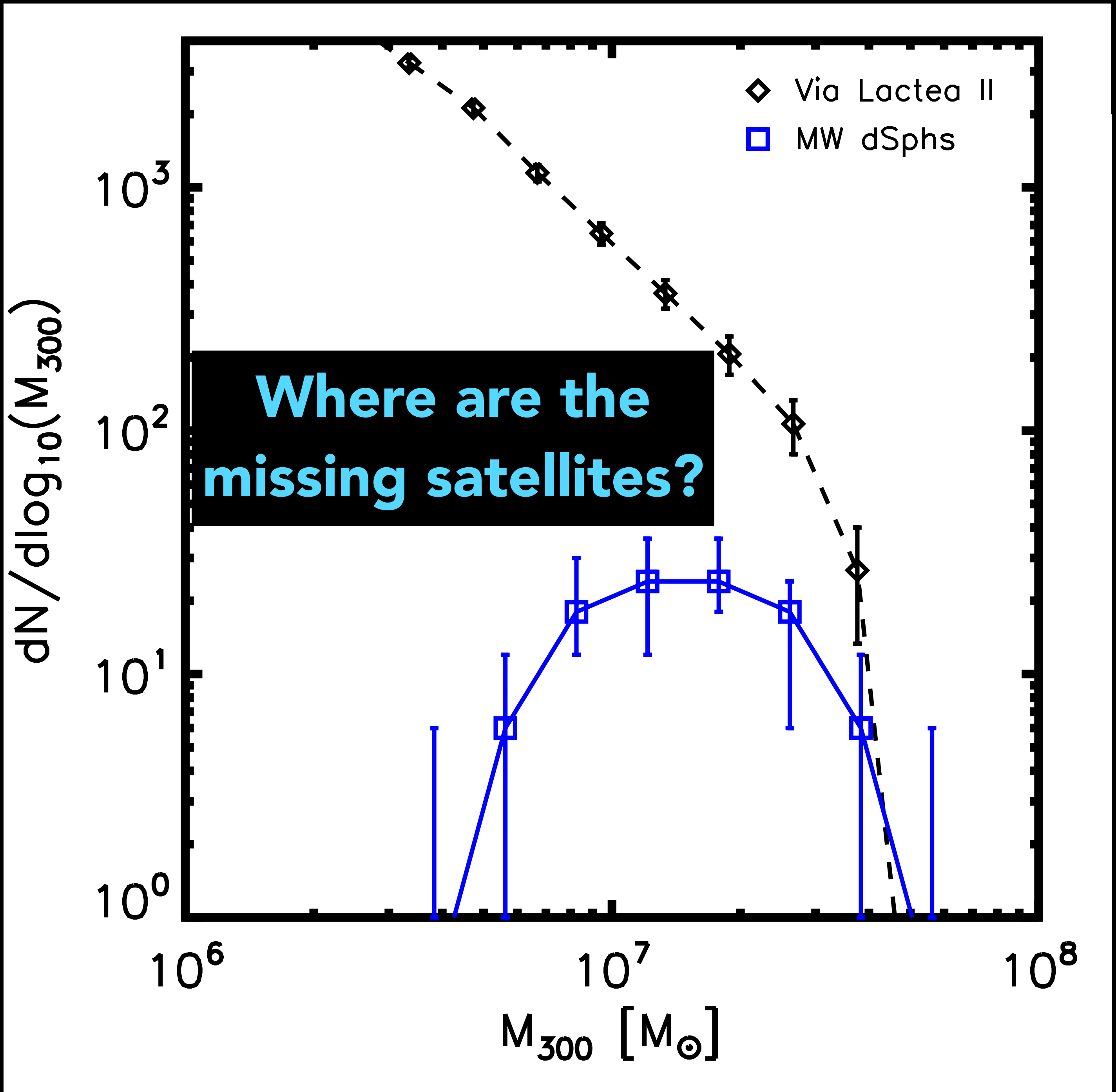
Observations: N_{bright}~10

Klypin et al. 1999; Moore et al. 1999; Kauffmann et al. 1993

WHY STUDY THE LOCAL GROUP?

Missing Satellites

Bullock, 2010

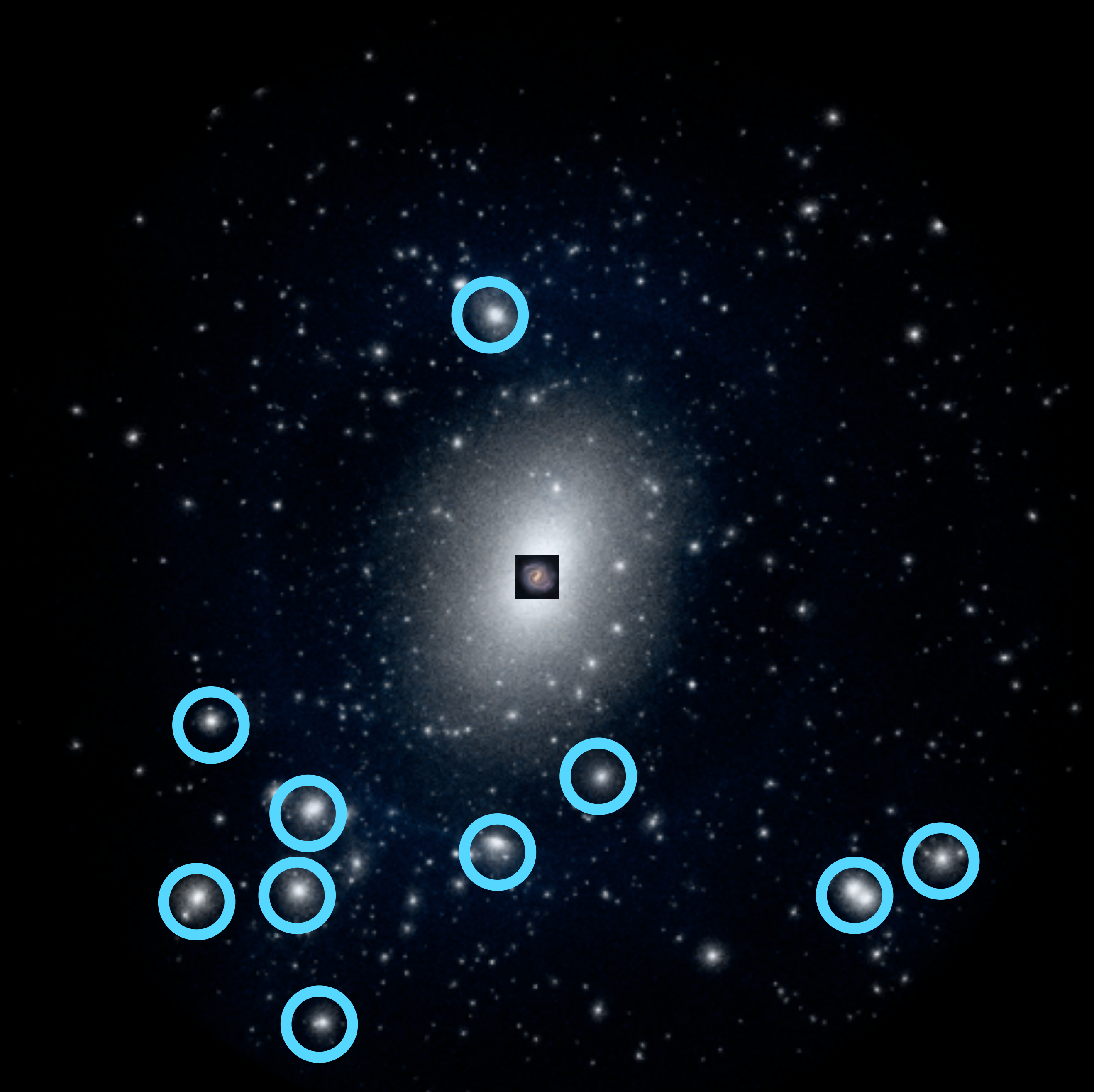


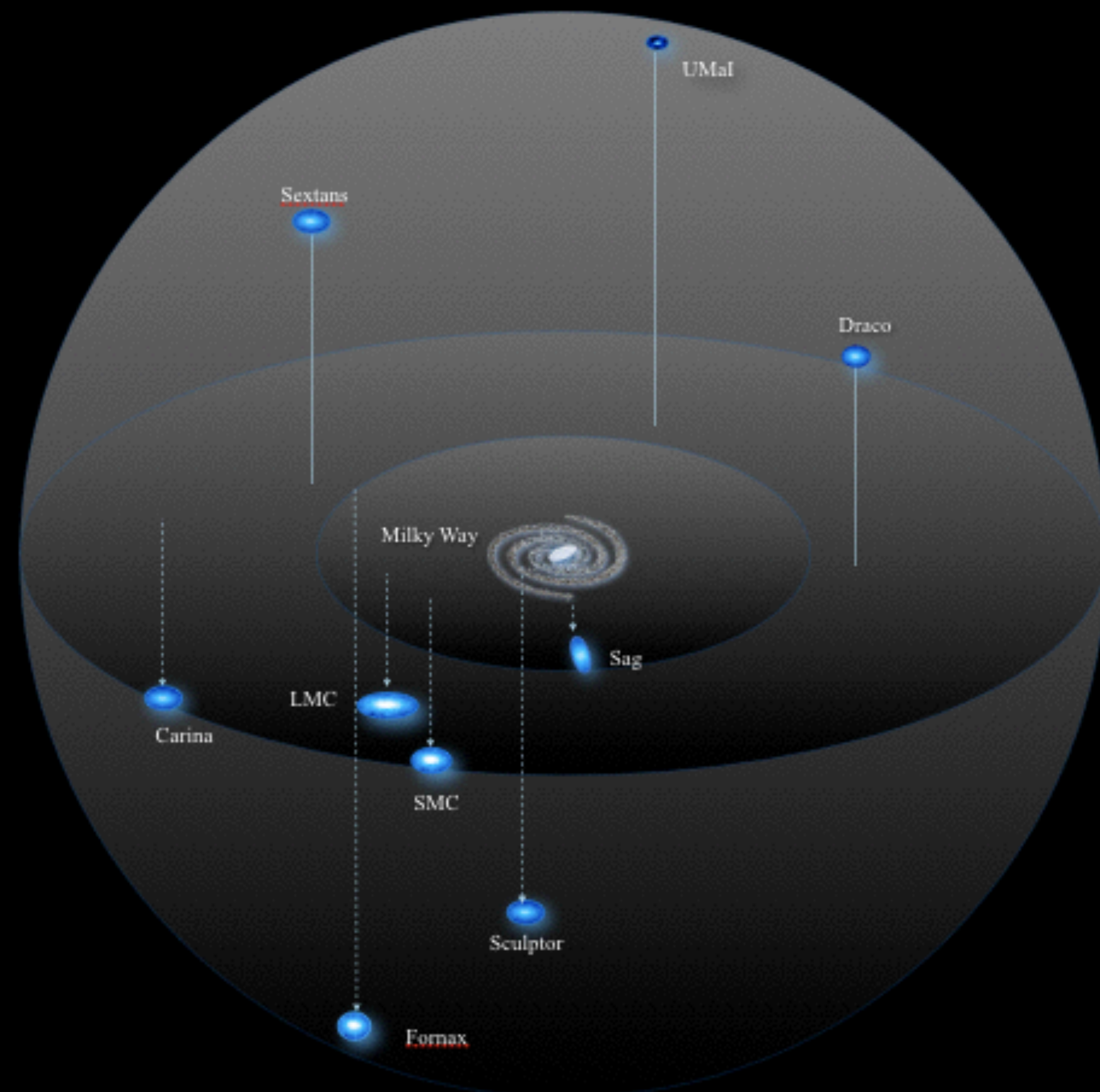
Is galaxy formation halted? Does M31 have an effect?

Does the same discrepancy exist in the field?

WHY STUDY THE LOCAL GROUP?

Missing Satellites



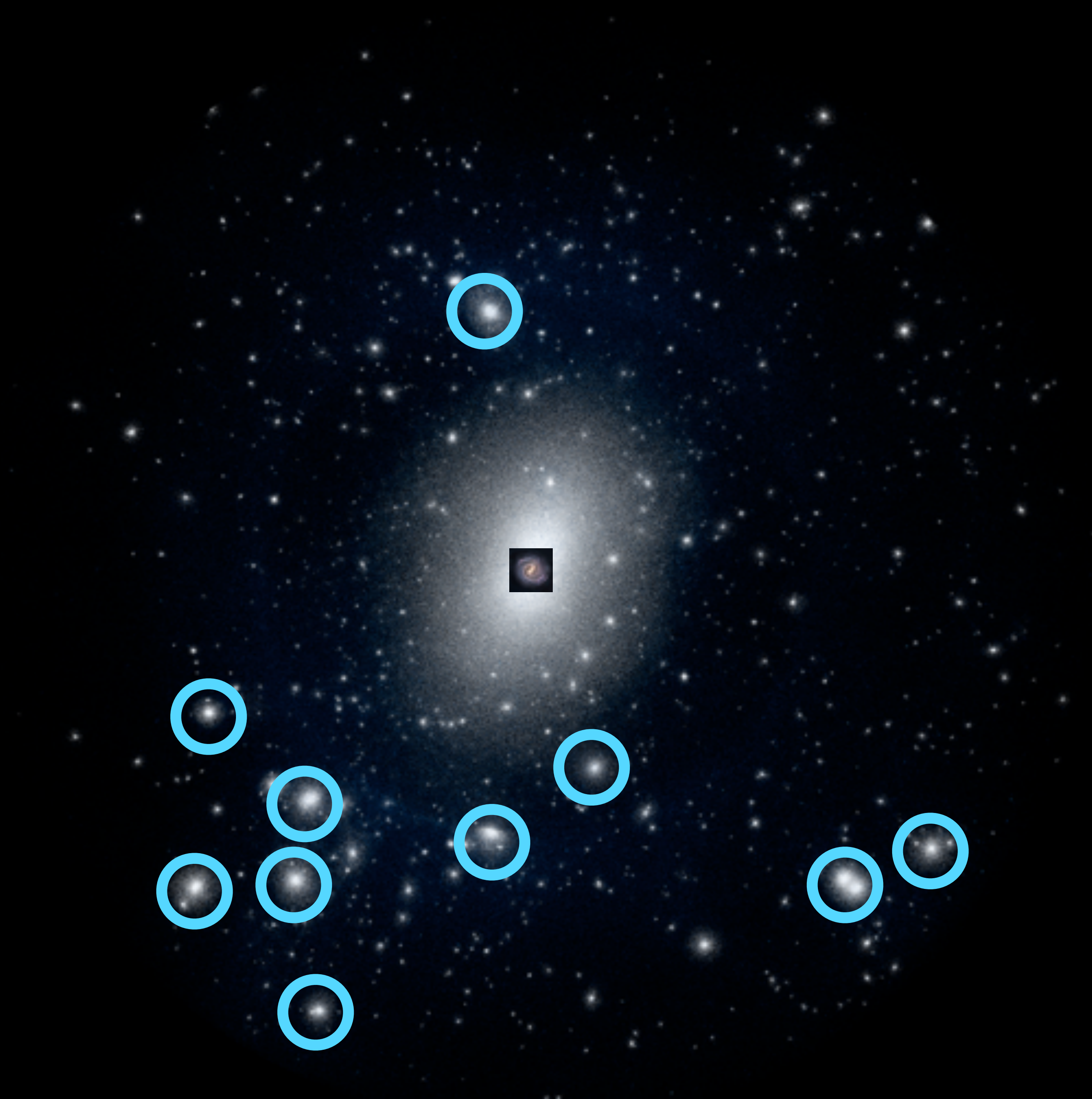


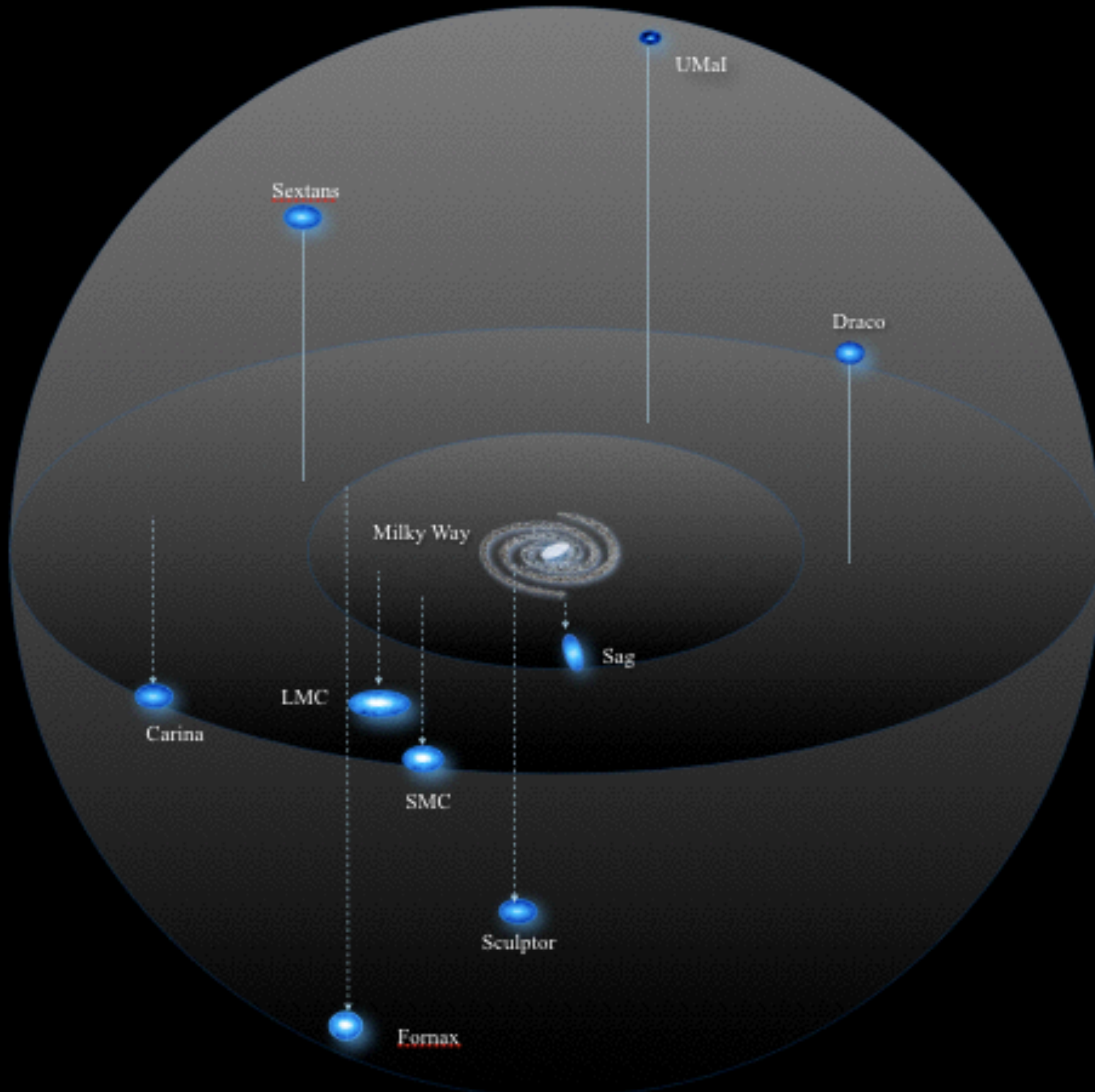
Obvious solution: only the largest clumps form stars and host galaxies

Klypin et al. 1999; Moore et al. 1999; Kauffmann et al. 1993

WHY STUDY THE LOCAL GROUP?

Missing Satellites



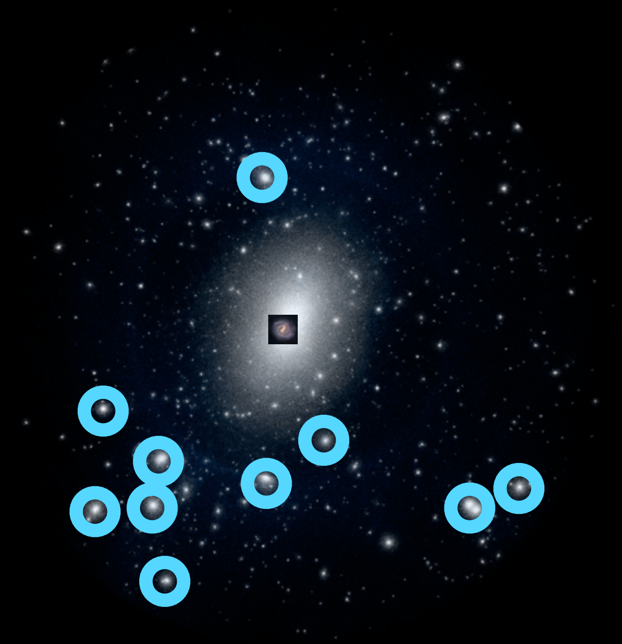


Does this actually work?

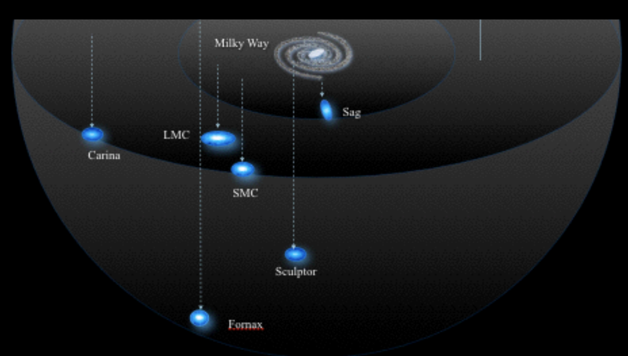
Klypin et al. 1999; Moore et al. 1999; Kauffmann et al. 1993

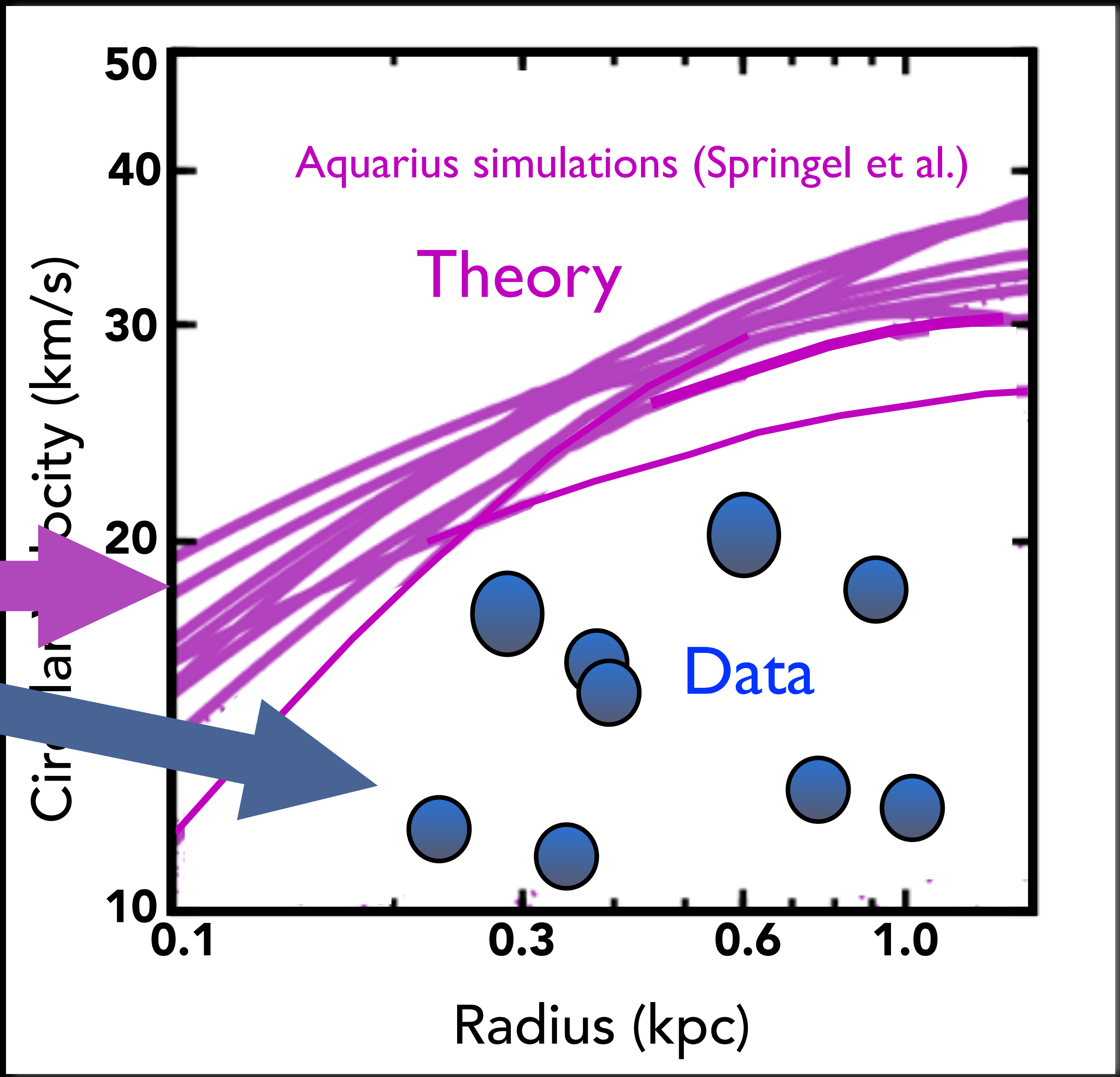
WHY STUDY THE LOCAL GROUP?

Too Big To Fail



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



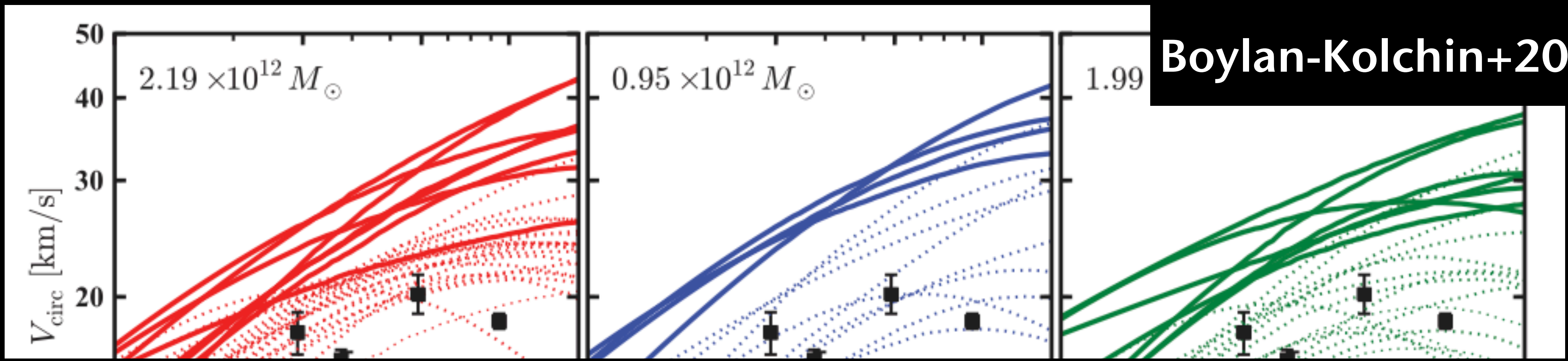


Does this actually work?

Boylan-Kolchin+2011,2012

WHY STUDY THE LOCAL GROUP?

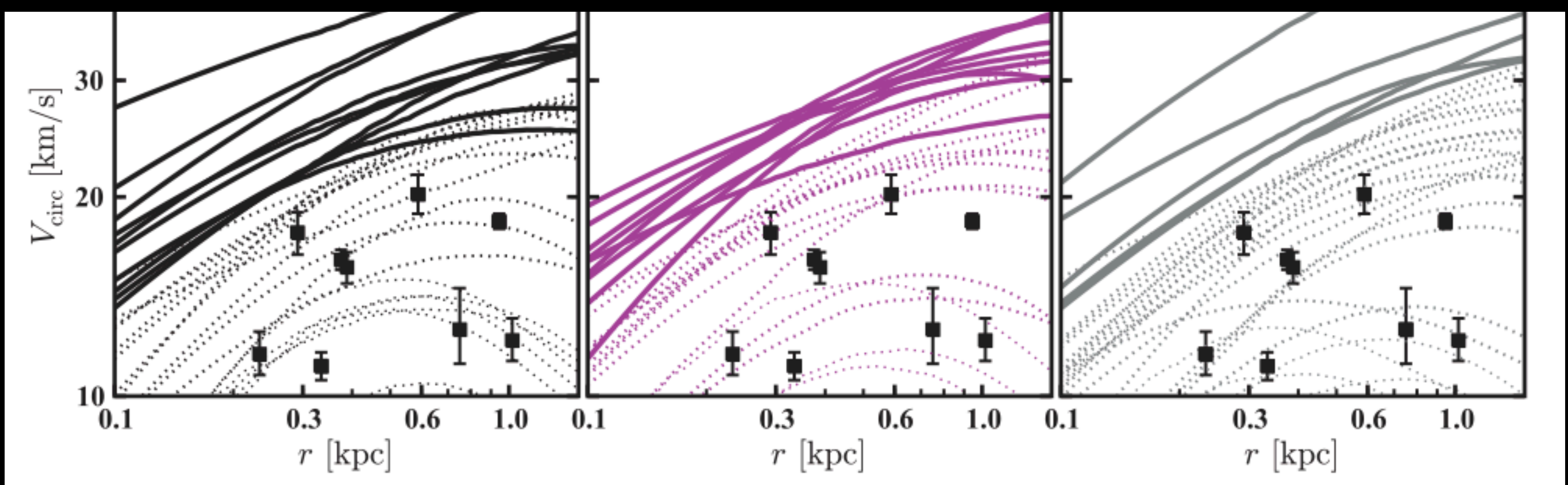
Too Big To Fail



Boylan-Kolchin+2011,2012

Evidence of environmental dependance:

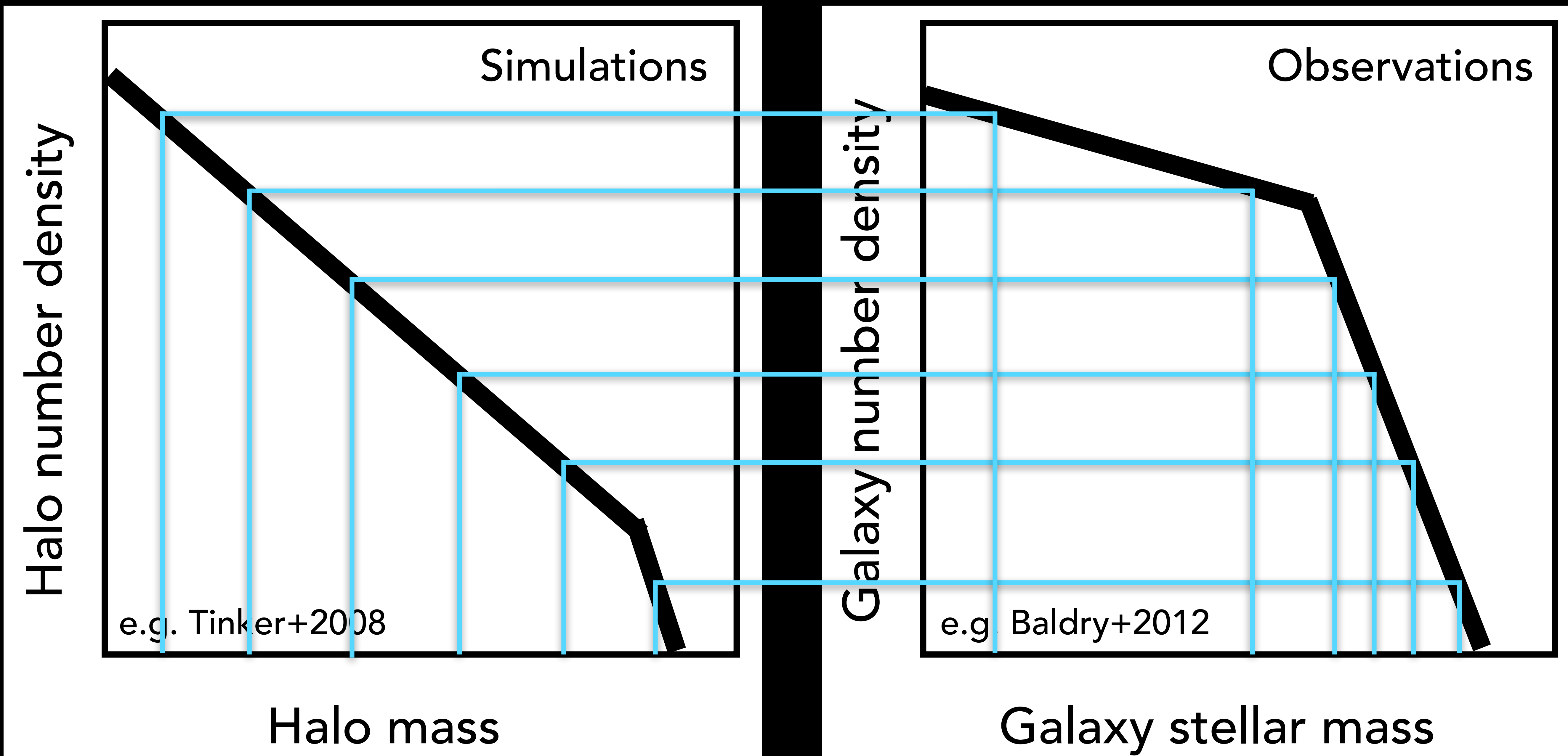
Is TBTF still a problem in the field?



Largest subhalos in DM-only MWs cannot host the dSphs

WHY STUDY THE LOCAL GROUP?

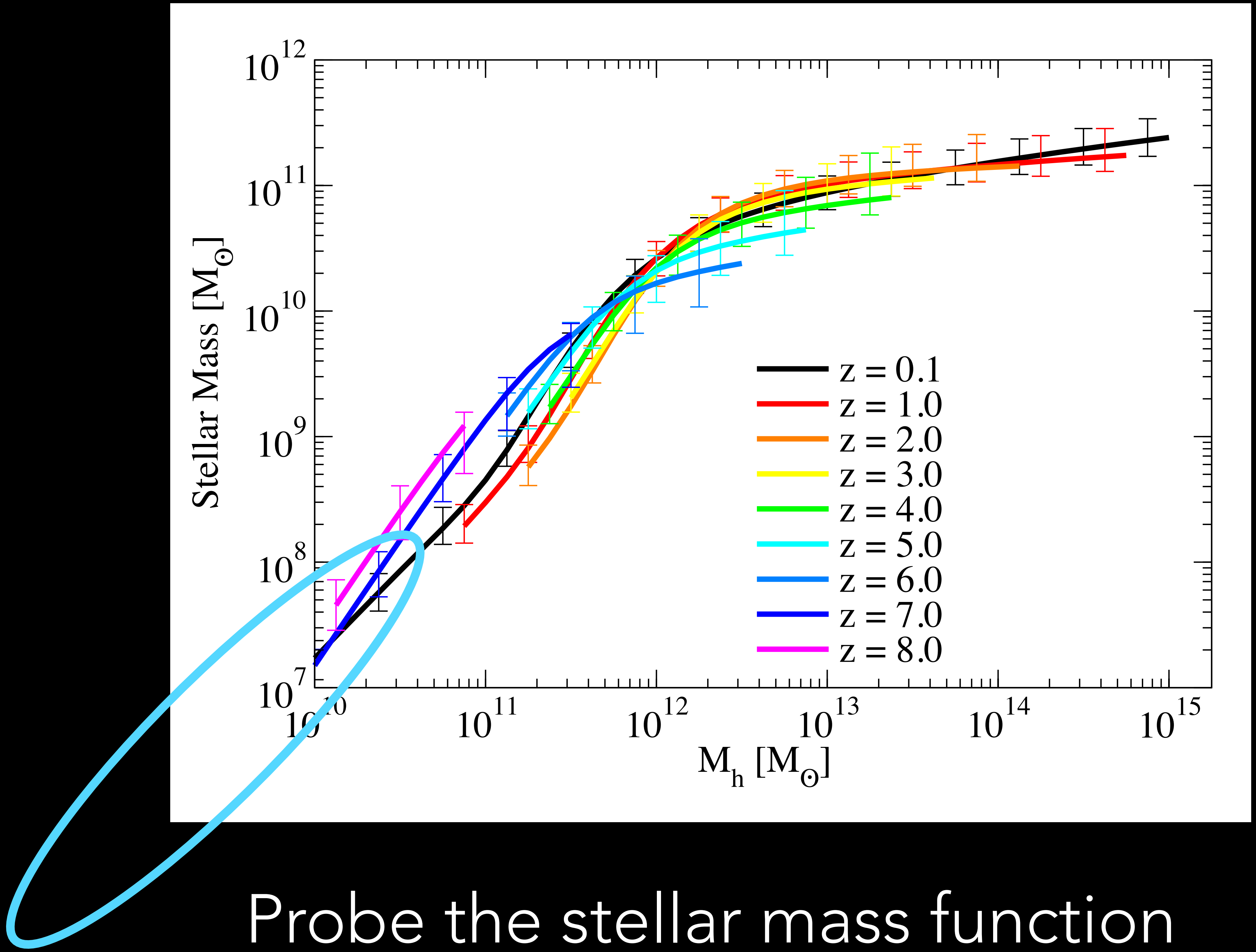
Abundance Matching



Match up masses at fixed number density to derive a relationship between halo mass and galaxy stellar mass

WHY STUDY THE LOCAL GROUP?

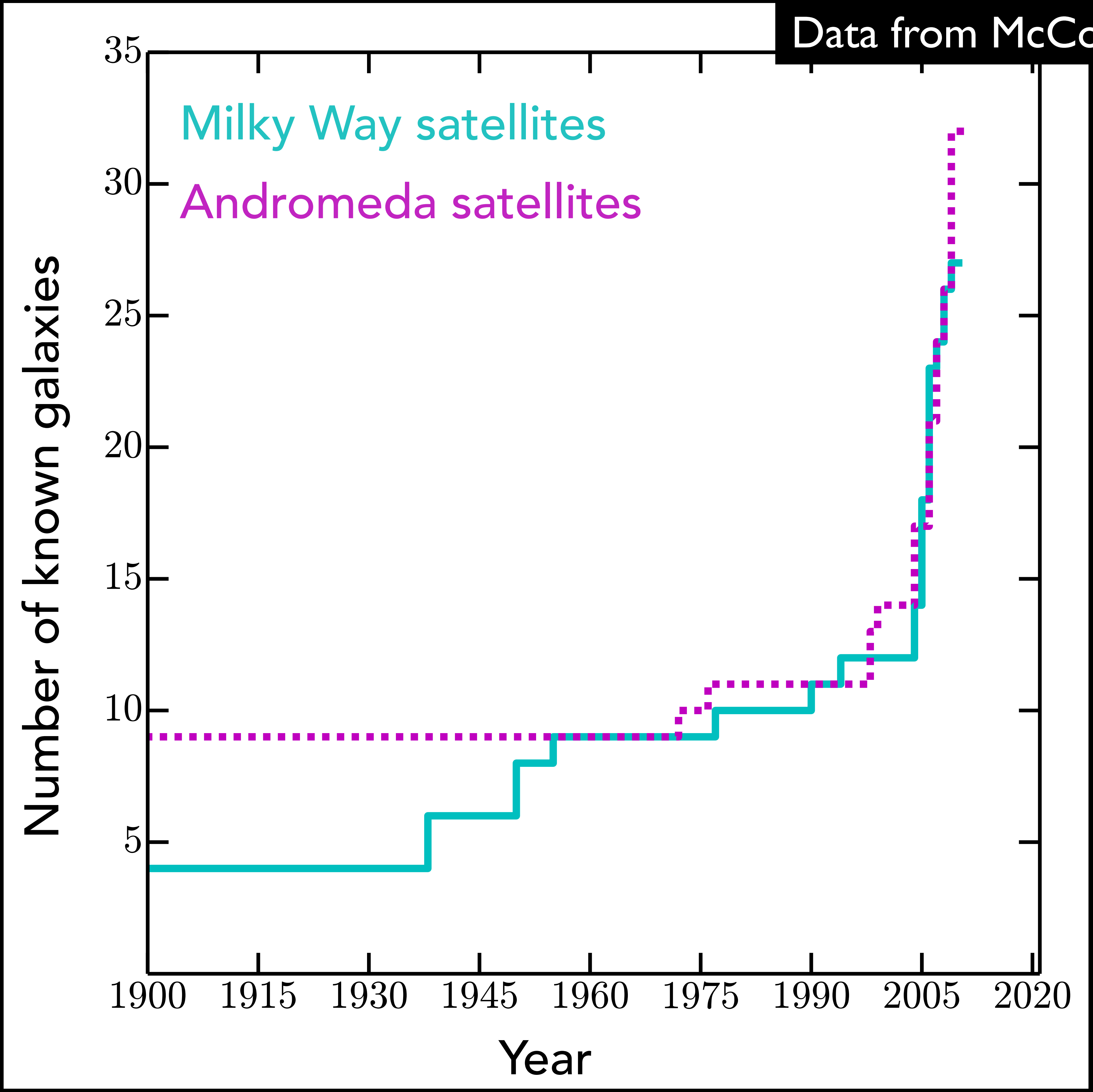
Abundance Matching



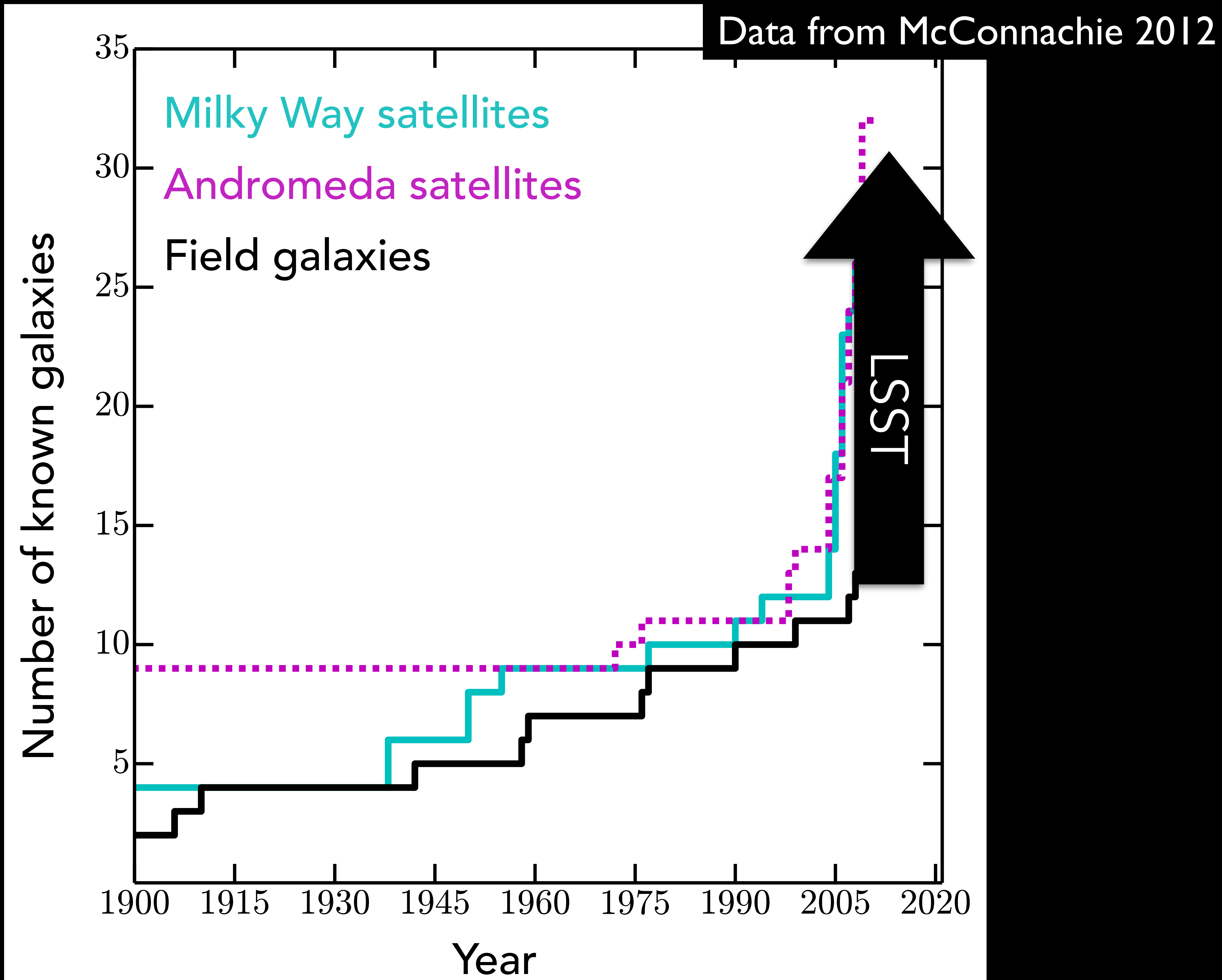
Behroozi+2013

Probe the stellar mass function down to $M_\star \sim 10^5\,M_{sun}$ and test AM extrapolations

THE INCREASINGLY-LESS-LOCAL GROUP



THE INCREASINGLY-LESS-LOCAL GROUP



ZOOM-IN SIMULATIONS

General idea:

Focus on a small piece of a large volume,
chosen to host some interesting object

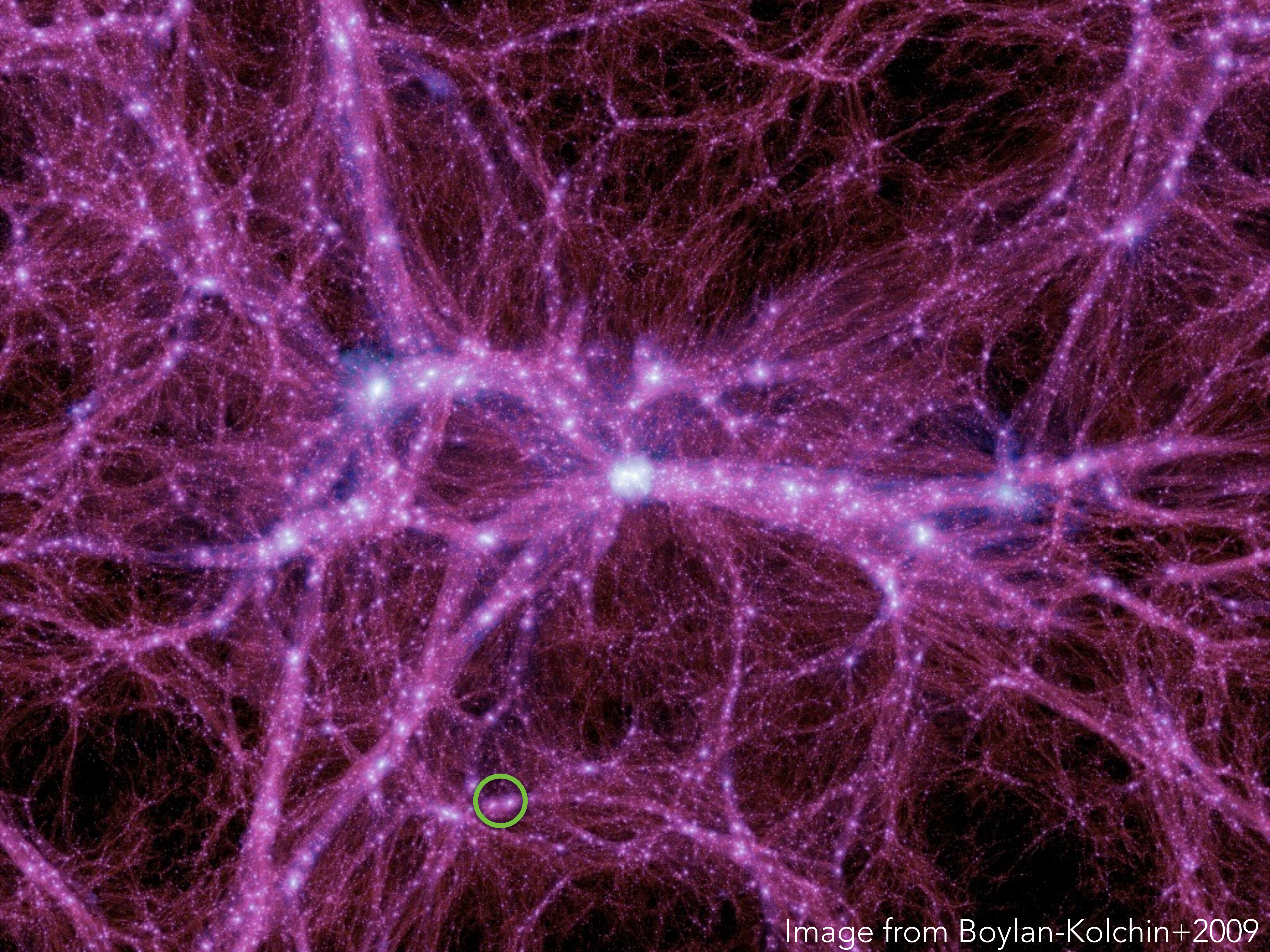
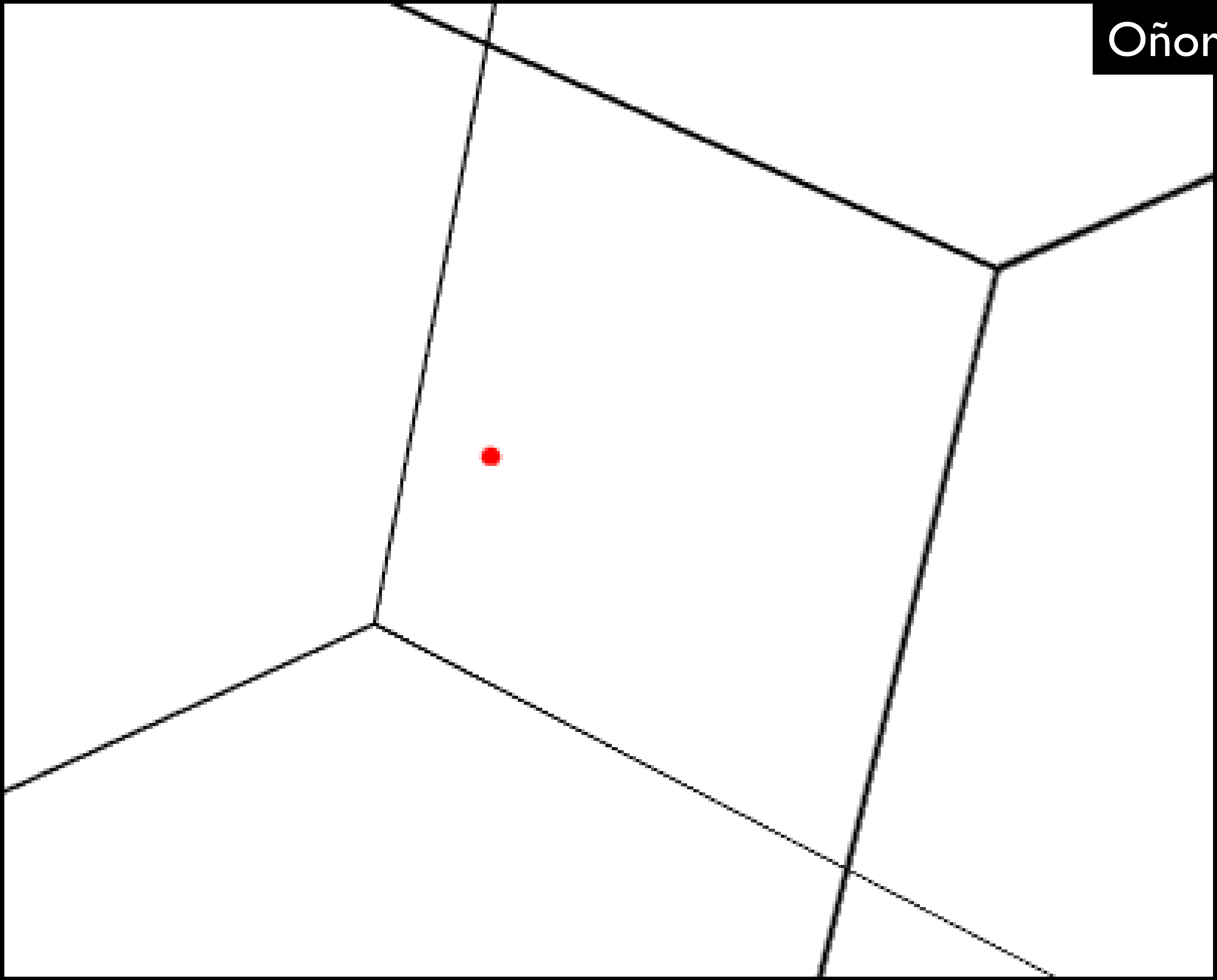


Image from Boylan-Kolchin+2009

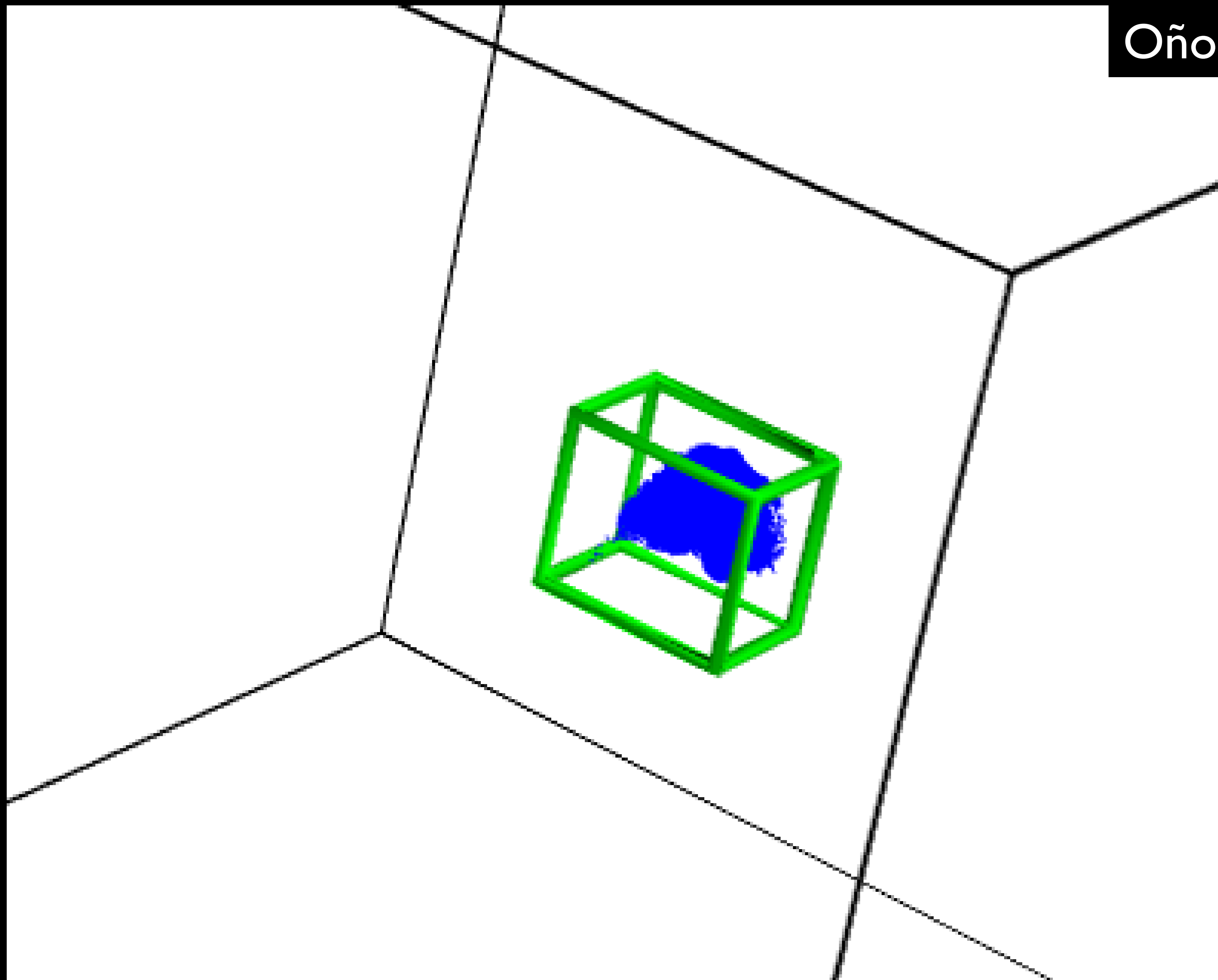
ZOOM-IN SIMULATIONS: LAGRANGE VOLUMES

Oñorbe, SGK+2014



Select the particles around some halo(s) of interest…

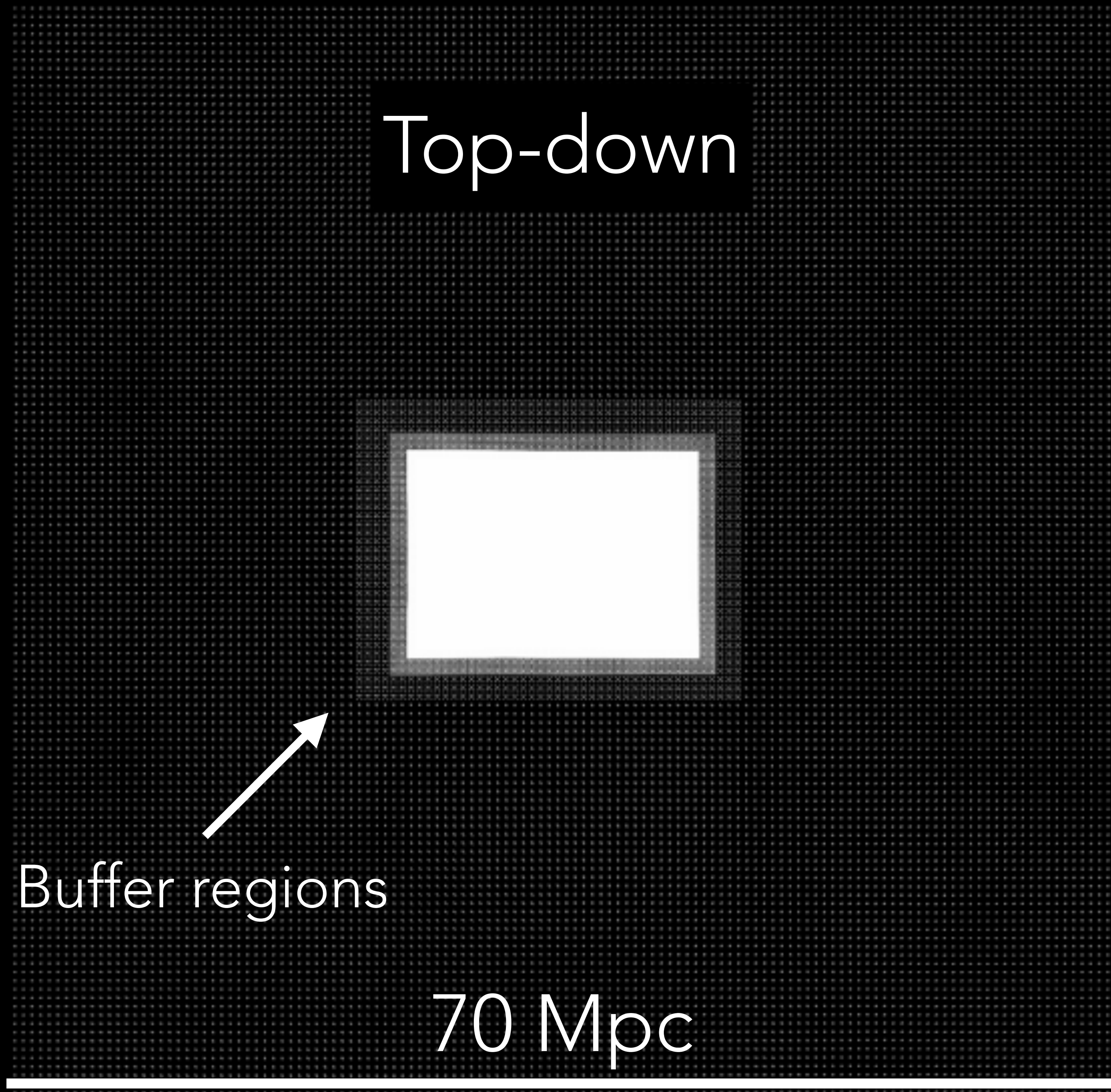
ZOOM-IN SIMULATIONS: LAGRANGE VOLUMES



Oñorbe, SGK+2014

...and calculate the volume that contains all those particles in the initial conditions

ZOOM-IN SIMULATIONS



Recreate the same initial conditions, but oversample the Lagrange volume with high resolution particles

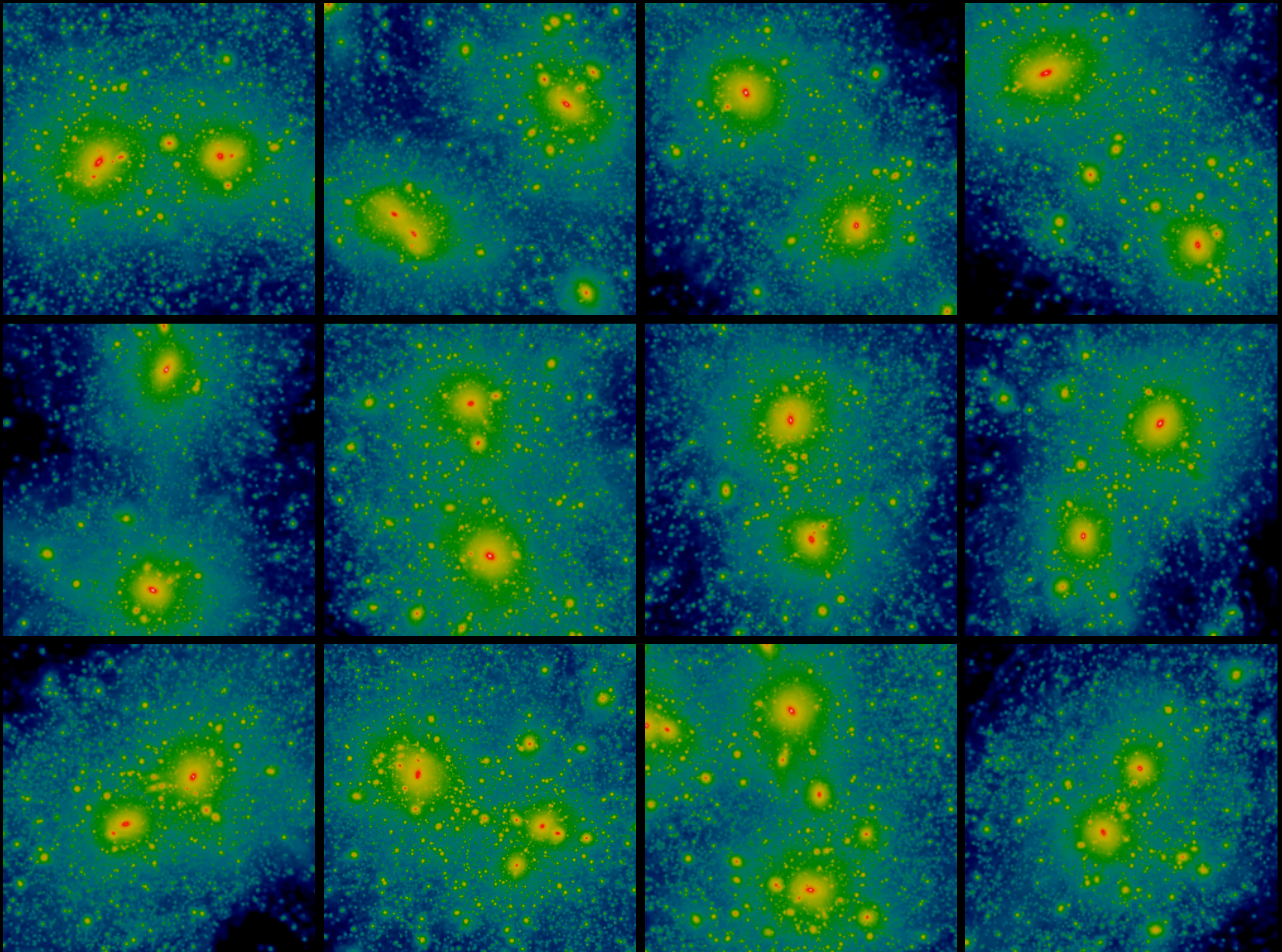

$t = 18.815$ Myr, $z = 93.125$
1 Mpc

SIMULATING THE LOCAL GROUP WITH *ELVIS*

- Twenty-four paired halos in LG-like pairs
- Twenty-four mass-matched isolated analogues

All of the ELVIS data are **publicly available** at
localgroup.ps.uci.edu/elvis/data.html

- Up to 15 million particles within R_v and up to 61 million within uncontaminated regions, which are as large as 43 Mpc^3

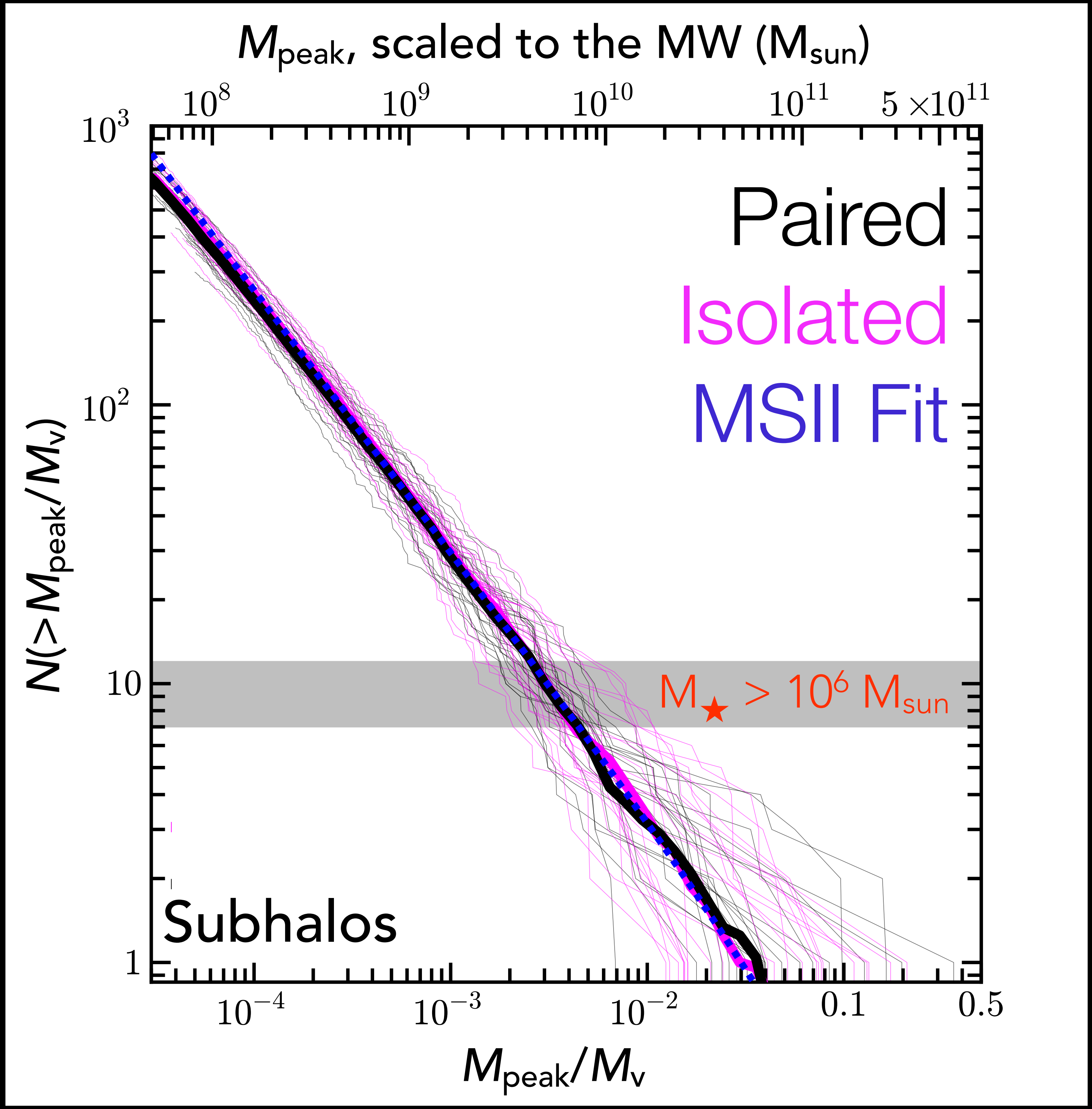


FIRST ELVIS RESULTS

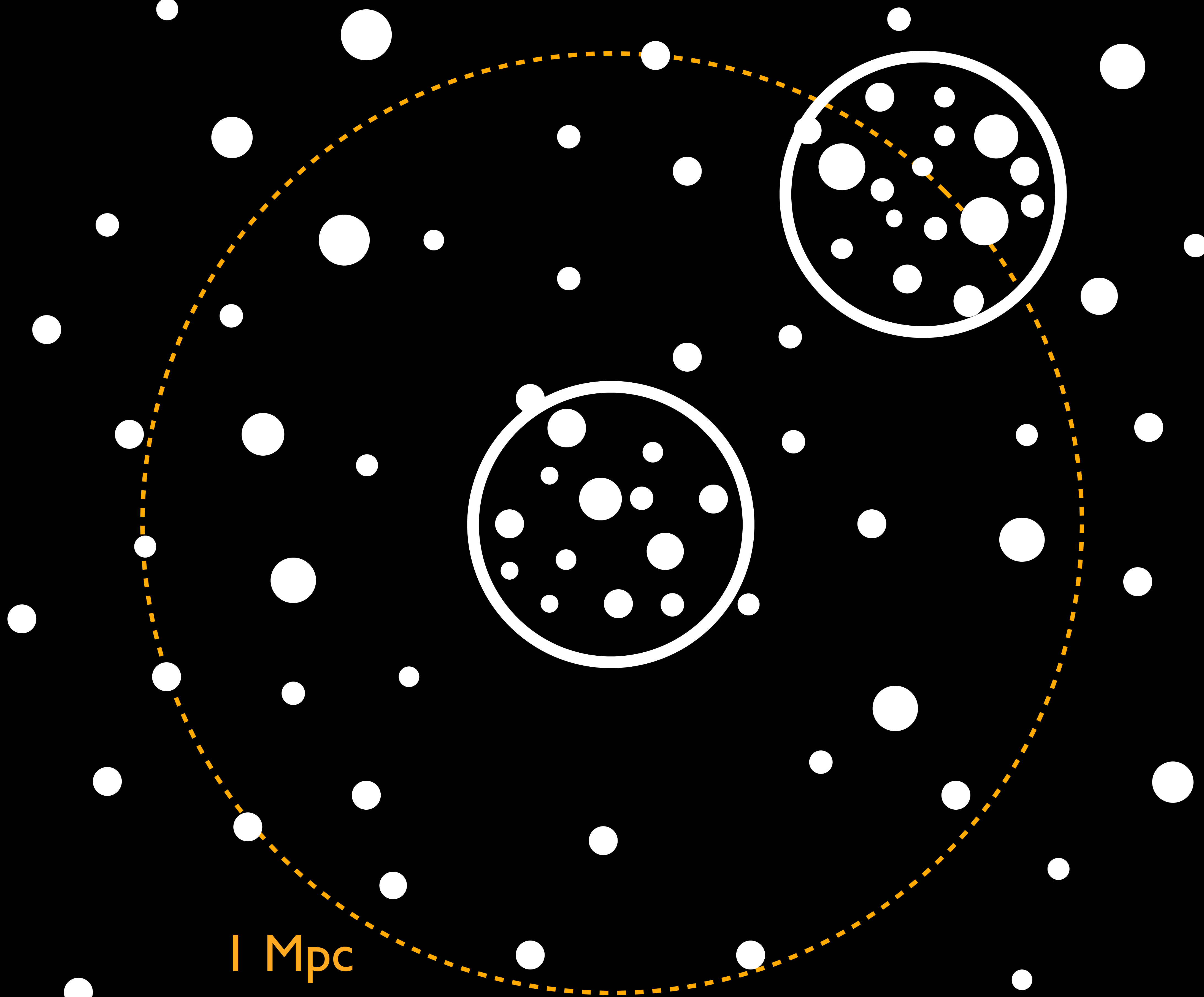
ELVIS RESULTS

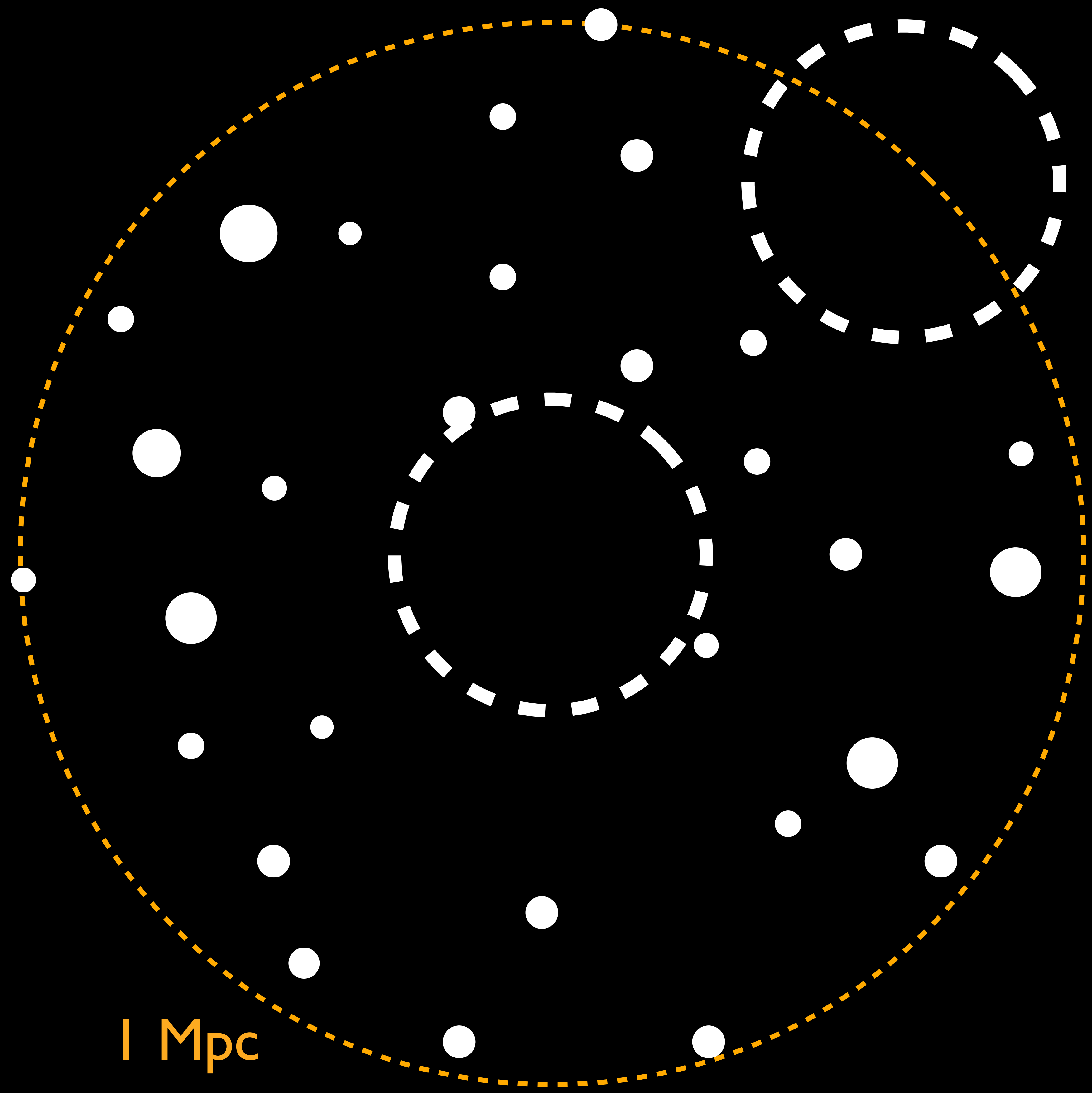
Paired vs Isolated Systems: R_{vir}

SGK+2014a



Normalized subhalo mass functions agree perfectly

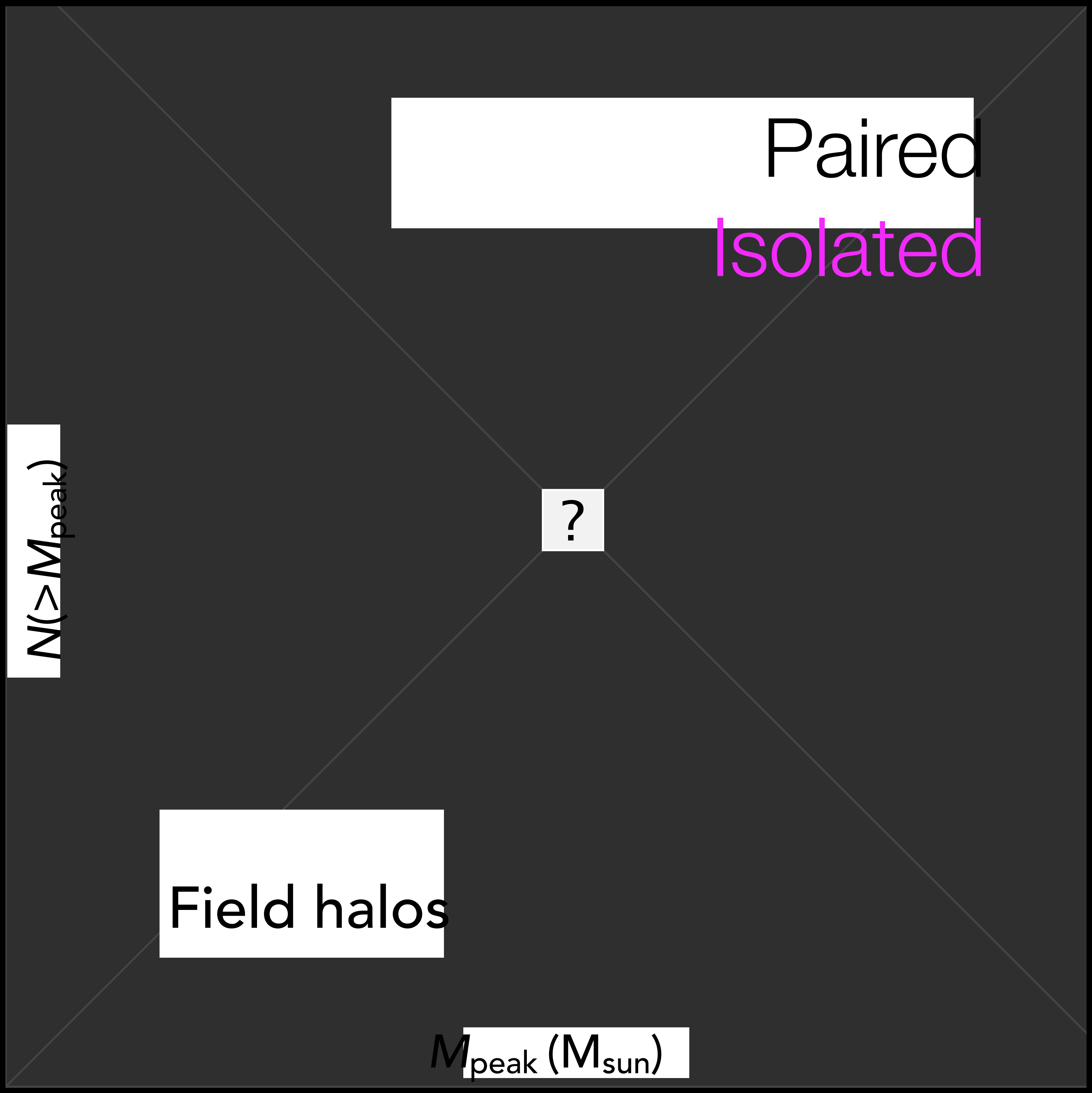

1 Mpc


1 Mpc

ELVIS RESULTS

Paired vs Isolated Systems: Field

SGK+2014a



Local field mass functions are offset by ~80%

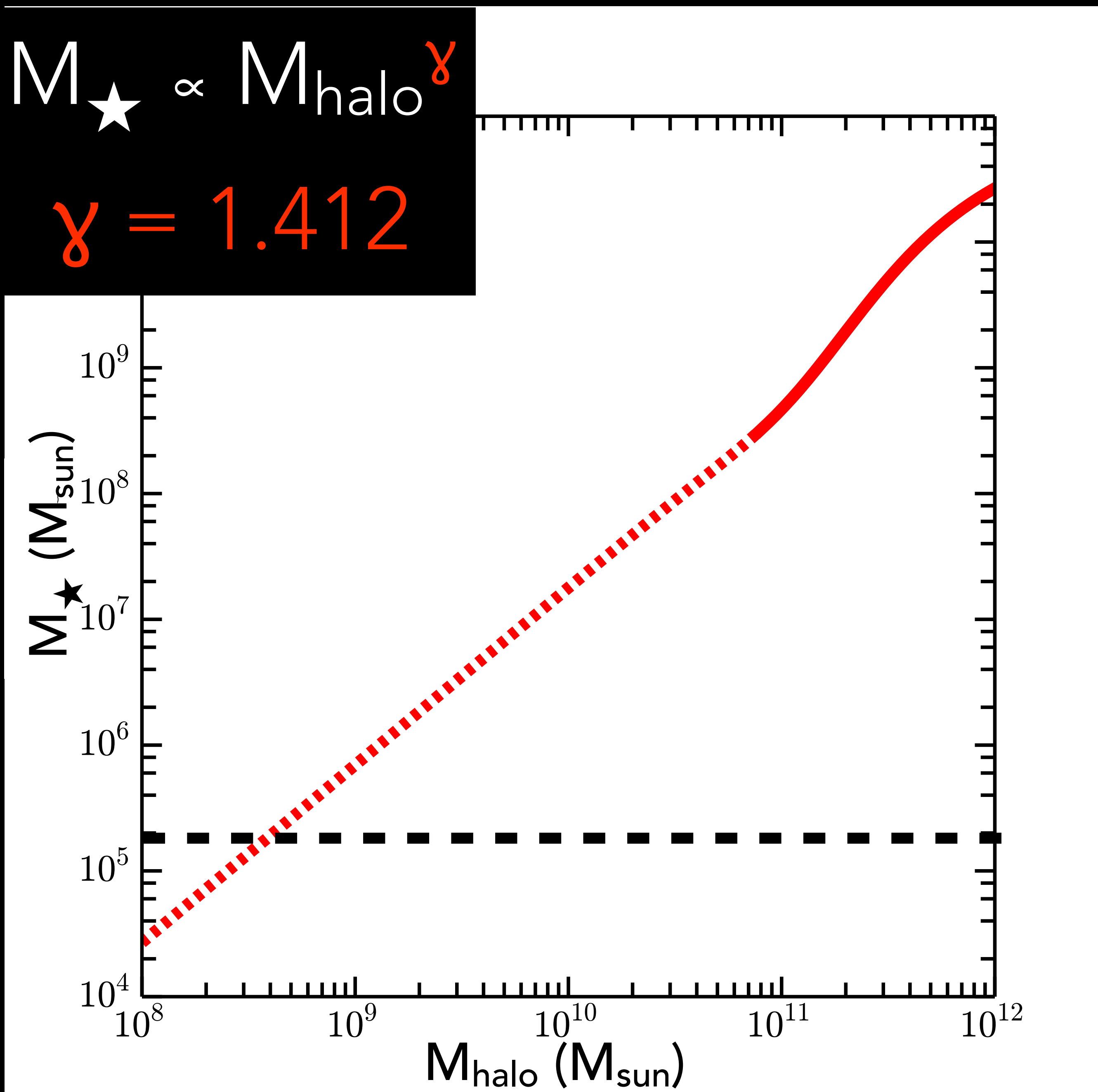
ELVIS RESULTS: TAKE AWAY

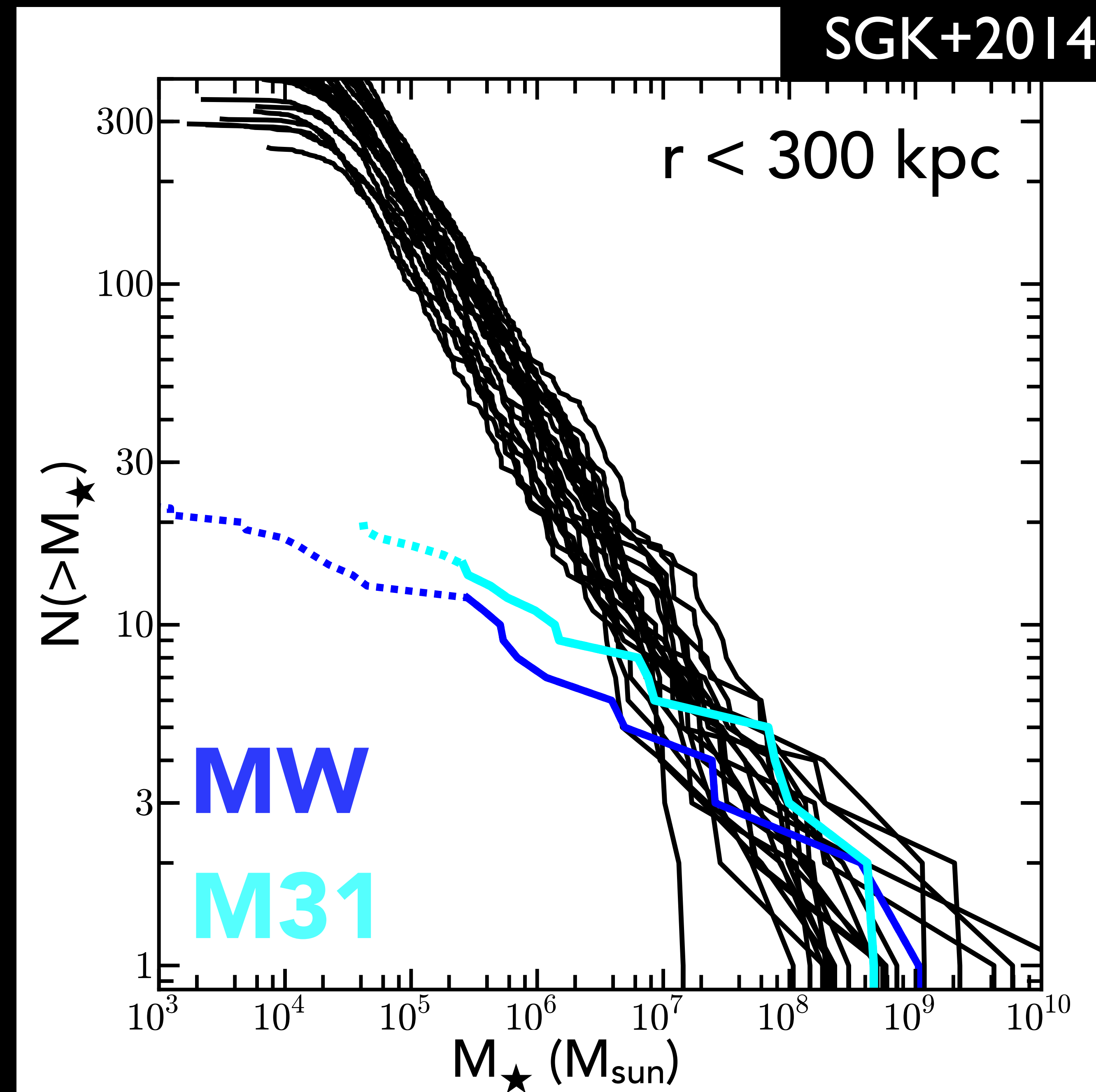
You ***must*** account for Andromeda (M31)
when studying the field around the Milky Way

IMPLICATIONS FOR ABUNDANCE MATCHING

ELVIS RESULTS

Abundance matching implications

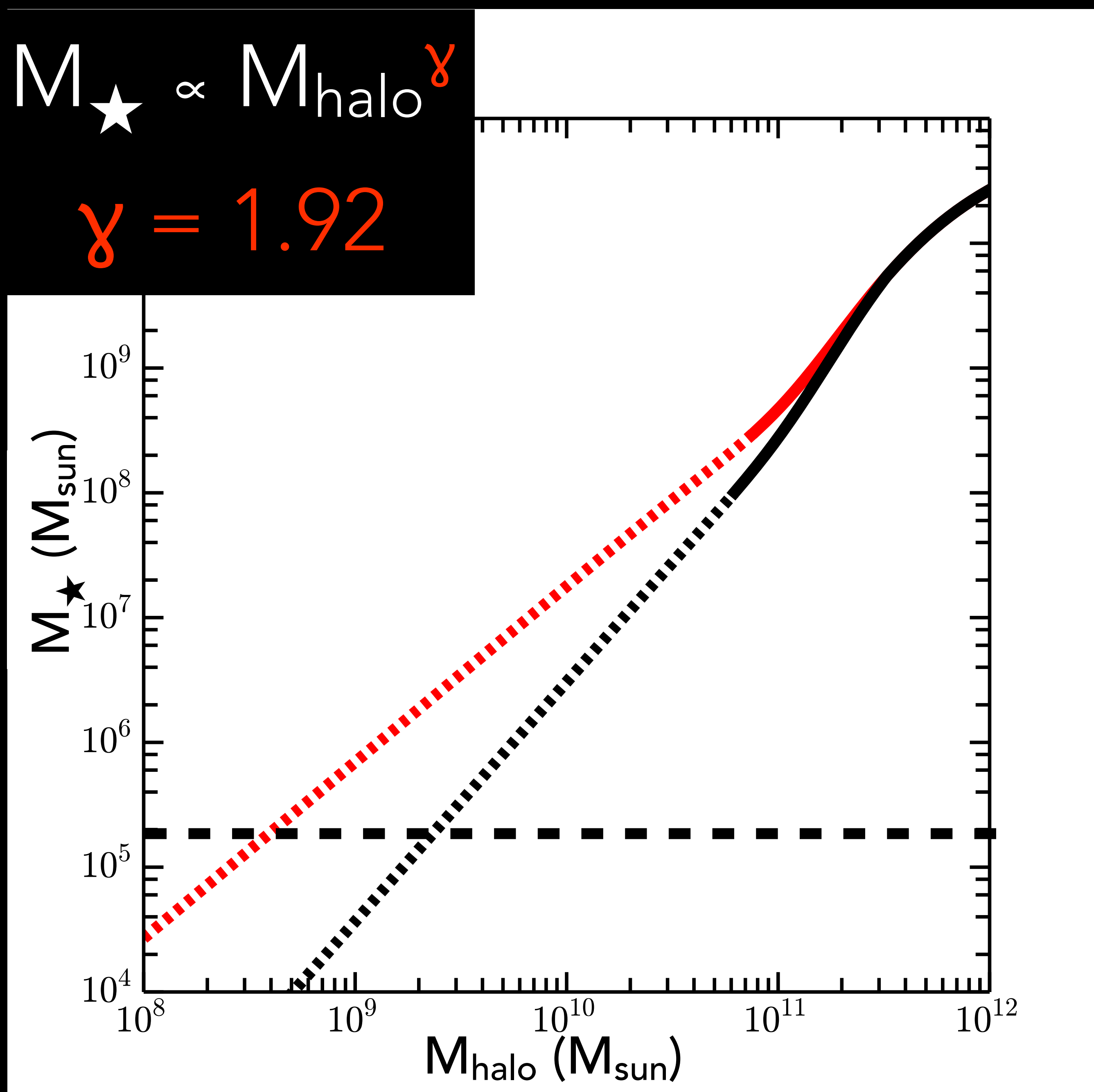


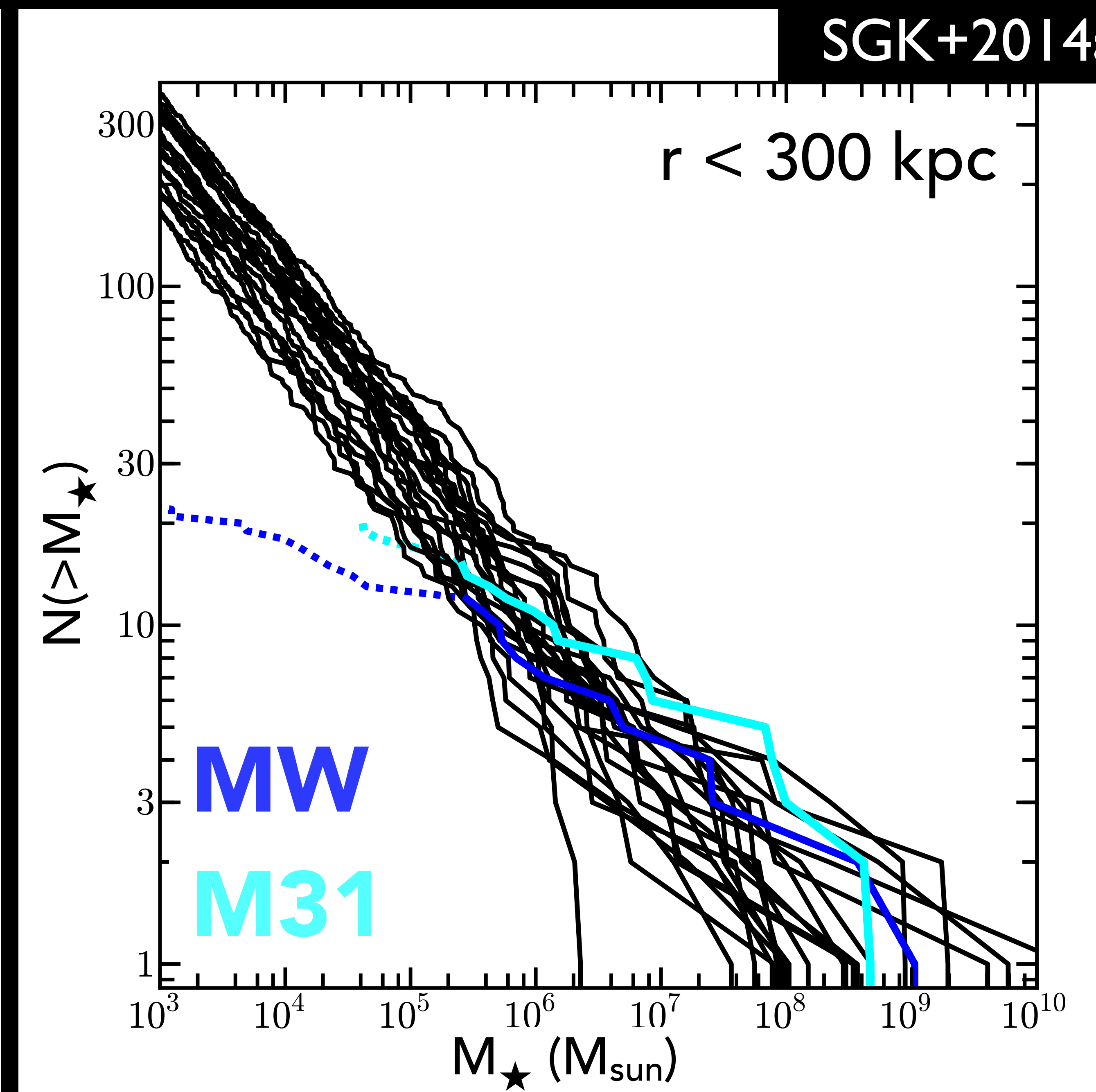


Behroozi+2013 abundance matching predicts too many low mass galaxies

ELVIS RESULTS

Abundance matching implications

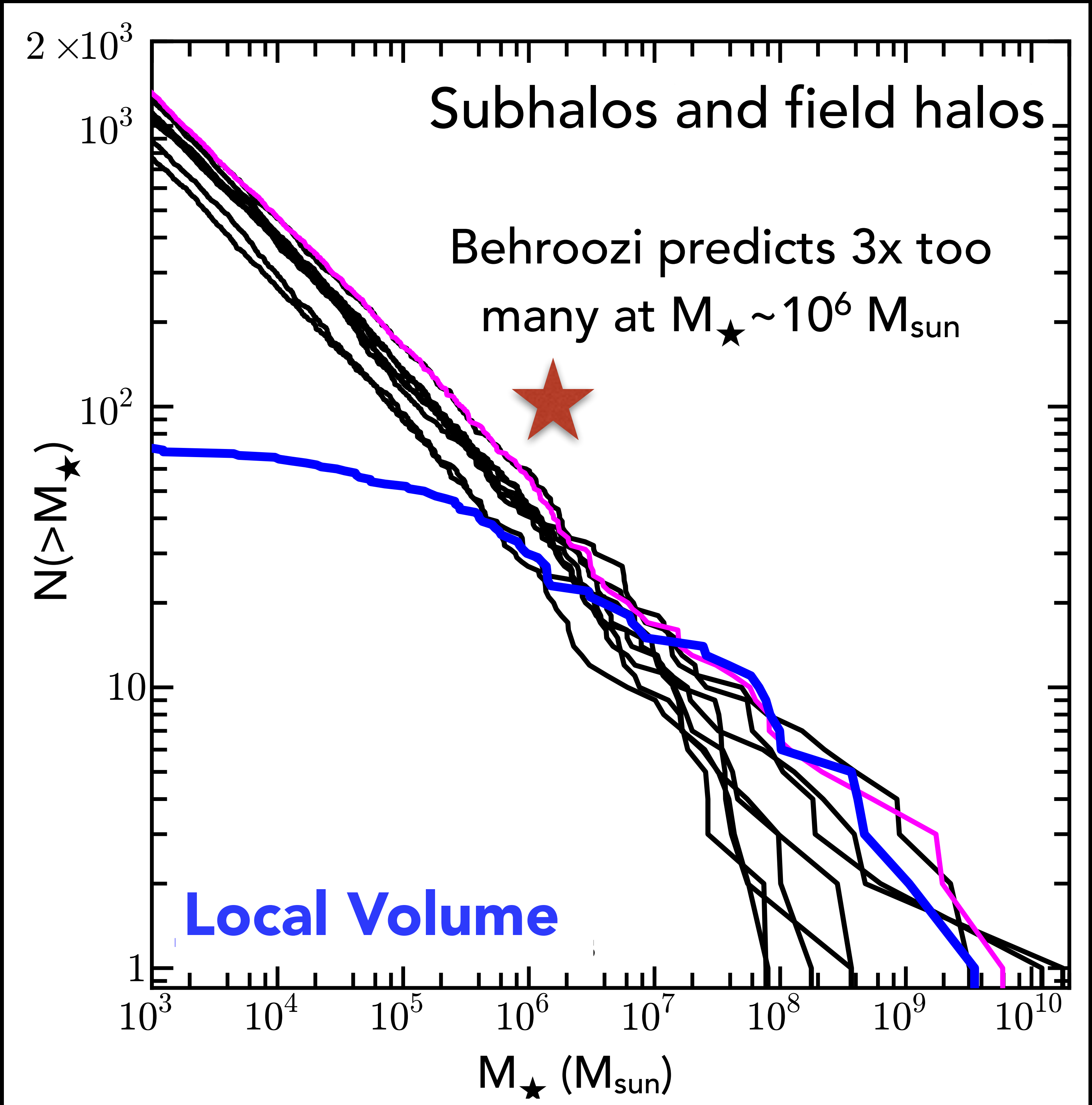




Modified Behroozi+2013 using a shallower low-mass slope (Baldry+2012) agrees well

ELVIS RESULTS

Predictions for LSST



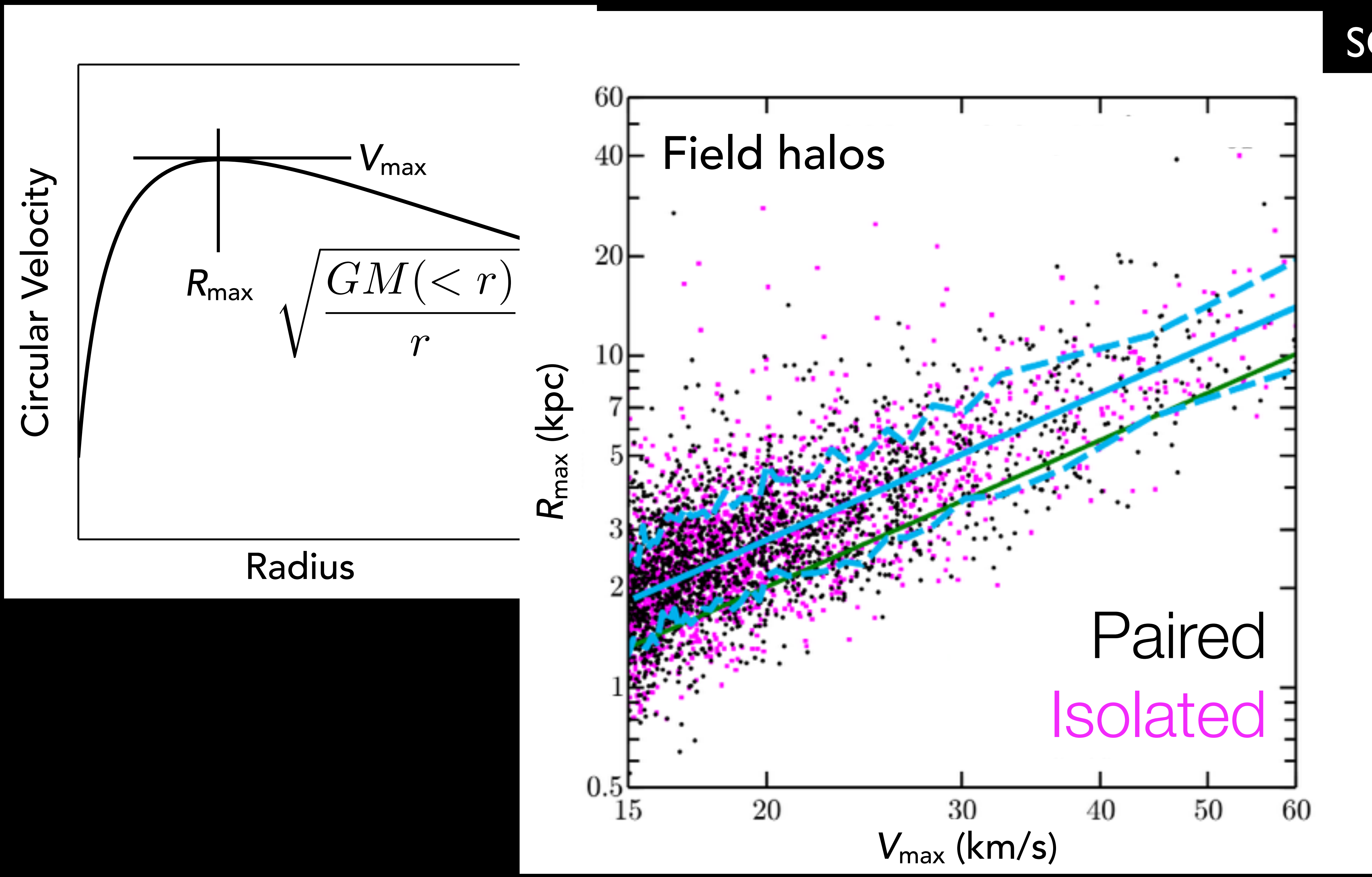
$M_\star \propto M_{halo}^{\gamma}$

$\gamma = 1.92$

SGK+2014a

ELVIS RESULTS: AM AT LOW $M_\star$

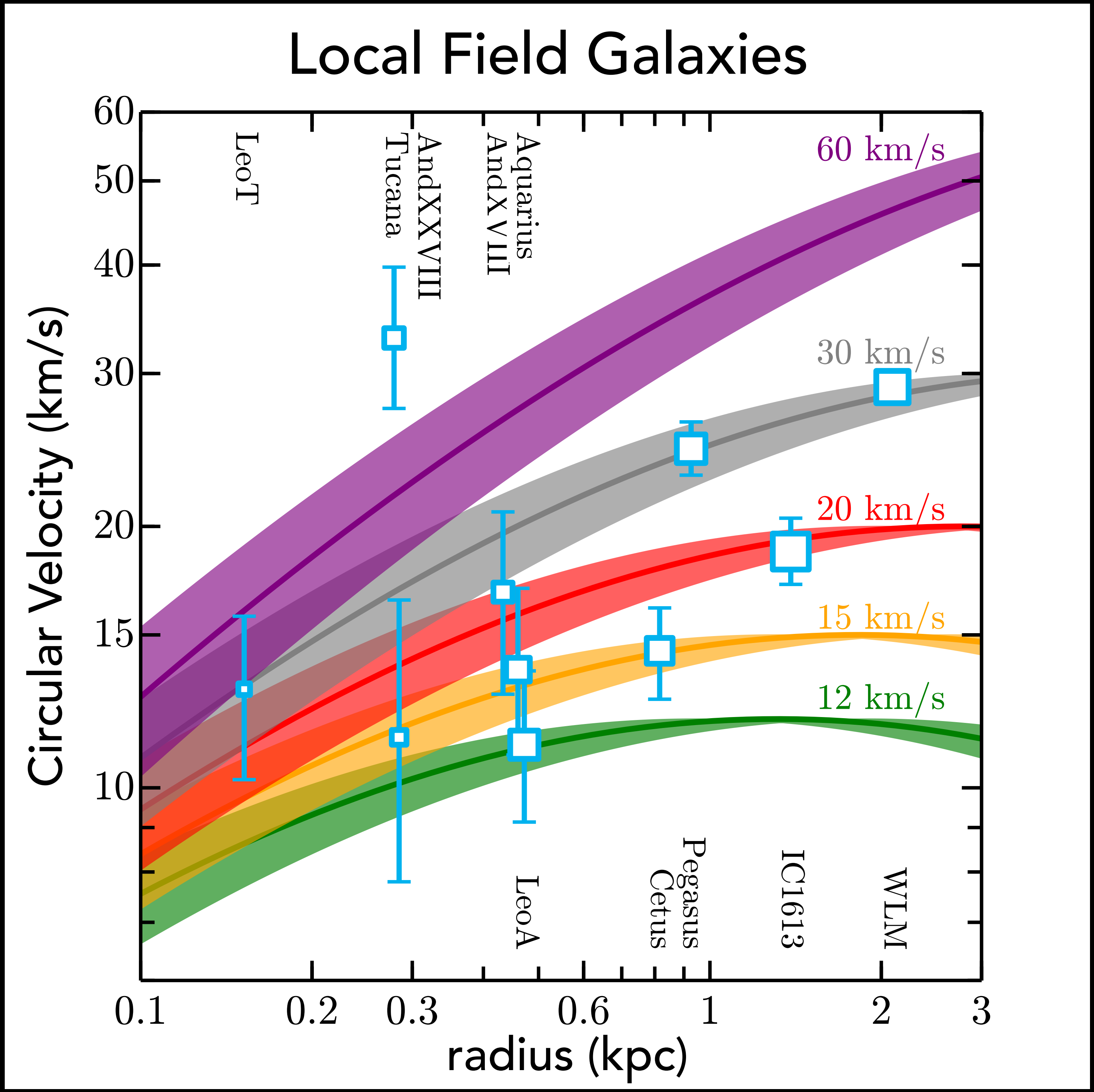
SGK+2014b



This relation constrains the region in V_{circ}-r space that a typical halo of a given V_{max} occupies

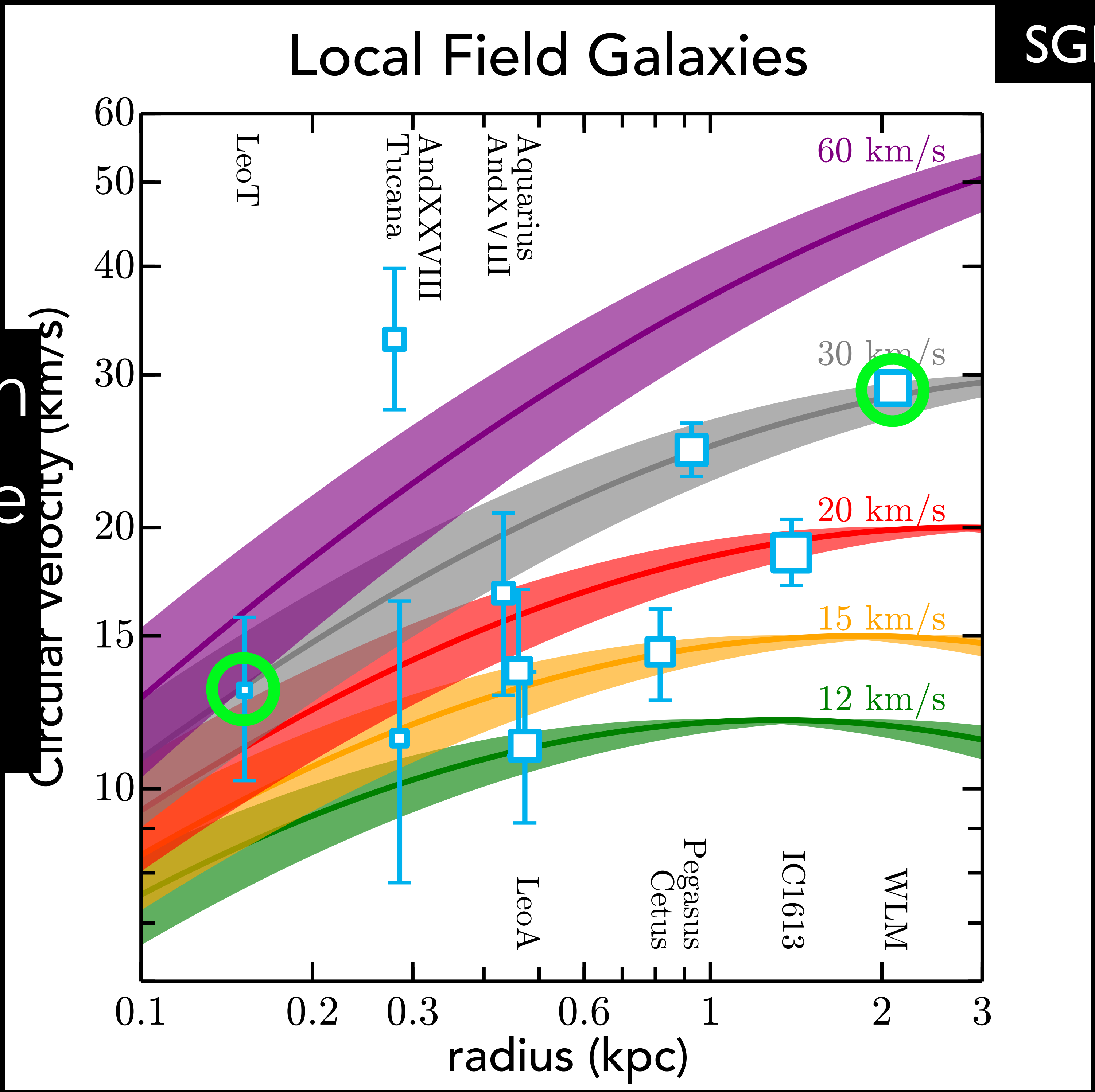
ELVIS RESULTS: AM AT LOW $M_\star$

SGK+2014b



Assuming a universal density profile, we can estimate V_{max} for galaxies in the Local Group

ELVIS RESULTS: AM AT LOW $M_\star$



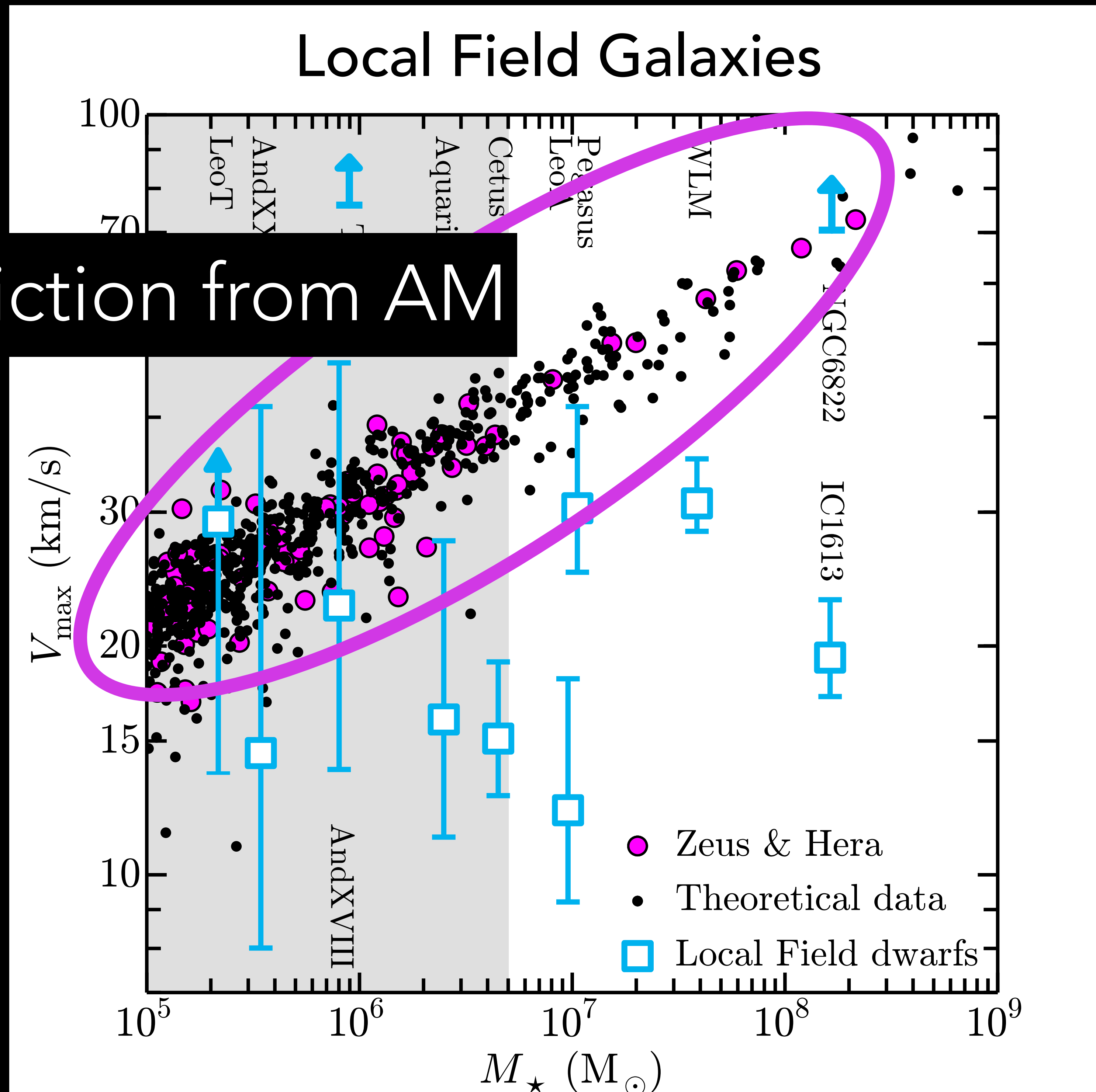
SGK+2014b

Leo T and WLM can live in the same size halo, but WLM is ~500x brighter!

Assuming a universal density profile, we can estimate V_{max} for galaxies in the Local Group

ELVIS RESULTS: AM AT LOW $M_\star$

SGK+2014b



c.f. Strigari+2008 and
Boylan-Kolchin+2012
for MW satellites

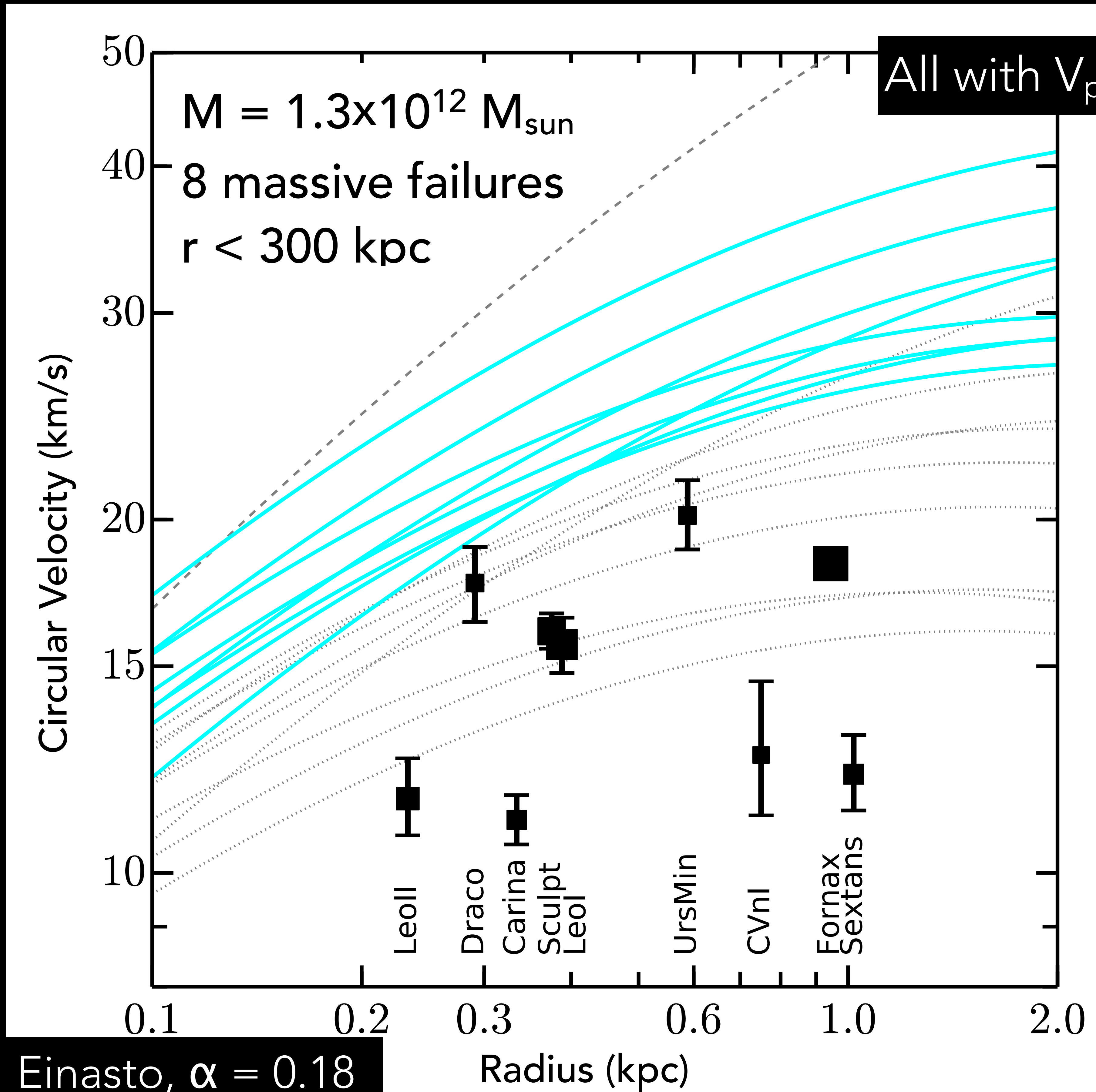
There appears to be *no trend at all* between $M_\star$ and V_{max} for galaxies in the Local Field

AM AT LOW $M_{\star}$: TAKE AWAY

Need a **steep** stellar mass — halo mass relation,
if there is a relation between stellar mass and halo mass

TOO BIG TO FAIL

TOO BIG TO FAIL IN ELVIS



For experts: Einasto, α = 0.18

SGK+2014b

TOO BIG TO FAIL: EXPLANATIONS

- **Statistical Anomaly (e.g. Purcell & Zentner 2012)**
- **Baryons (see review by Pontzen & Governato 2014):**
  - Interactions with the central host (e.g. Zolotov+2012, Arraki+2014)
  - Supernovae feedback (e.g. Pontzen & Governato 2012)
- **Cosmology:**
  - Self-interacting dark matter (e.g. Vogelsberger+2012)
  - Warm Dark Matter (e.g. Anderhalden+2013)
  - More subtle changes to the initial power spectrum

plus other solutions that I won't discuss today

TOO BIG TO FAIL: EXPLANATIONS

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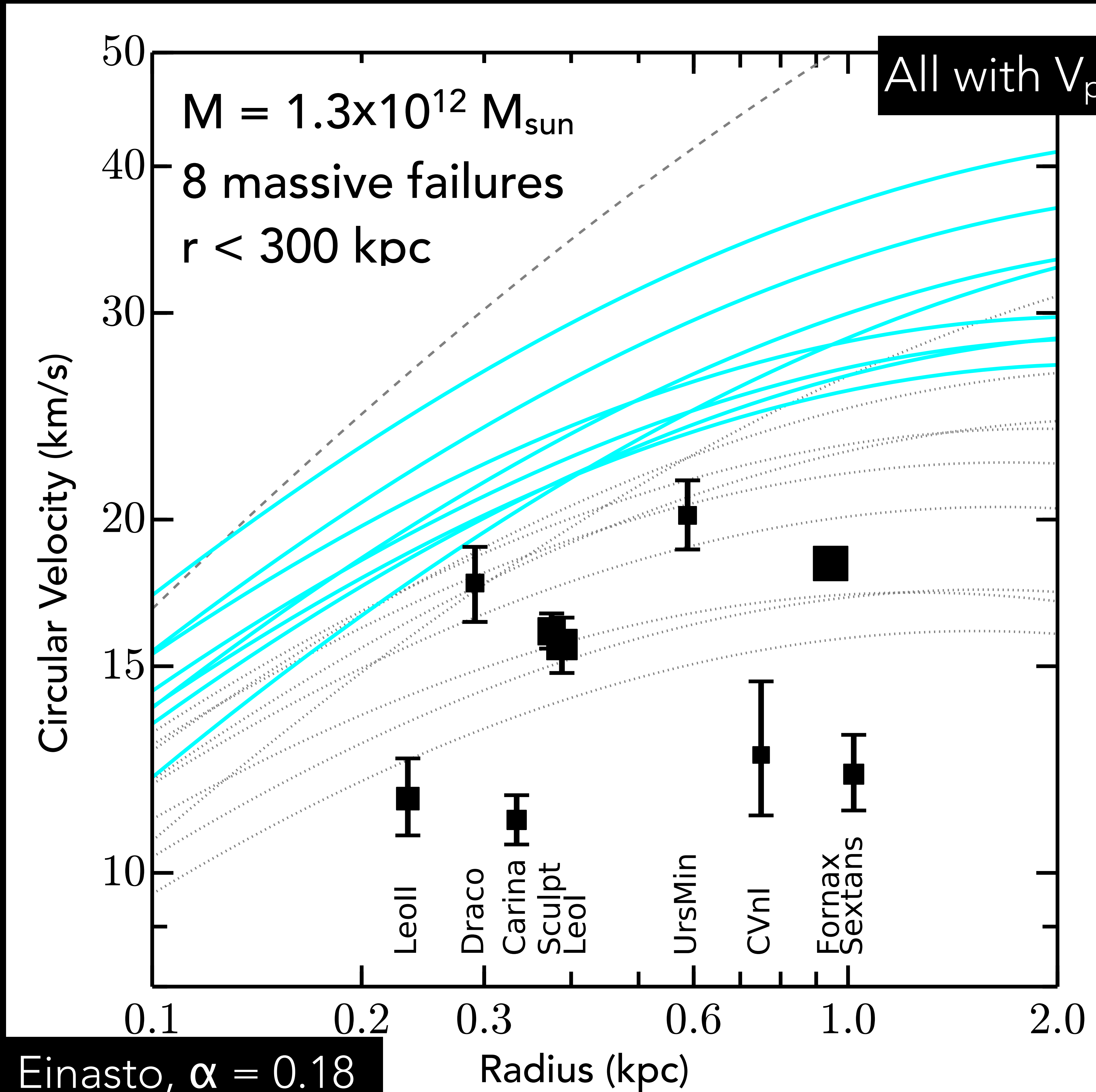

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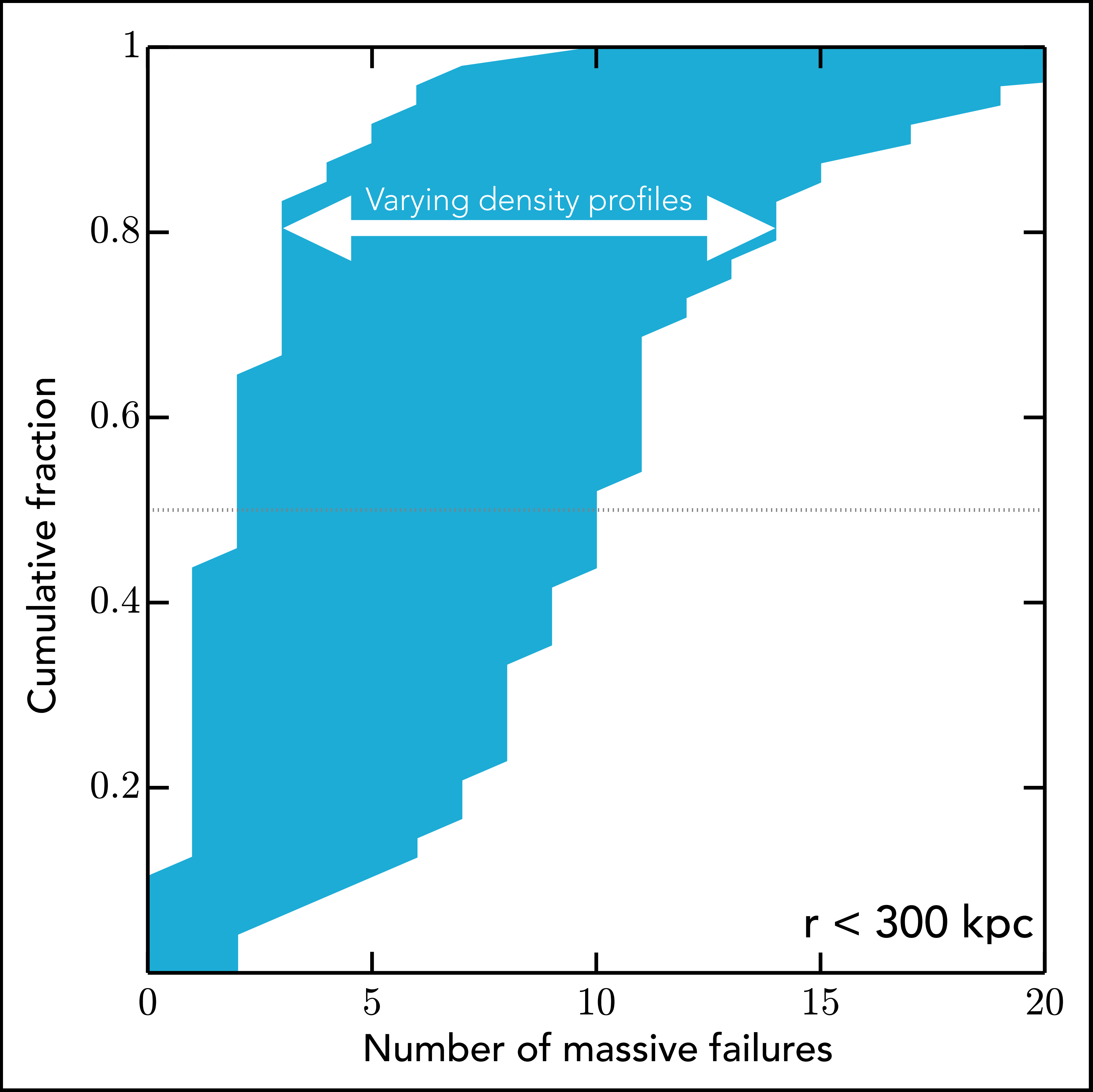
SGK+2014b

NUMBER OF FAILURES PER HOST



SGK+2014b

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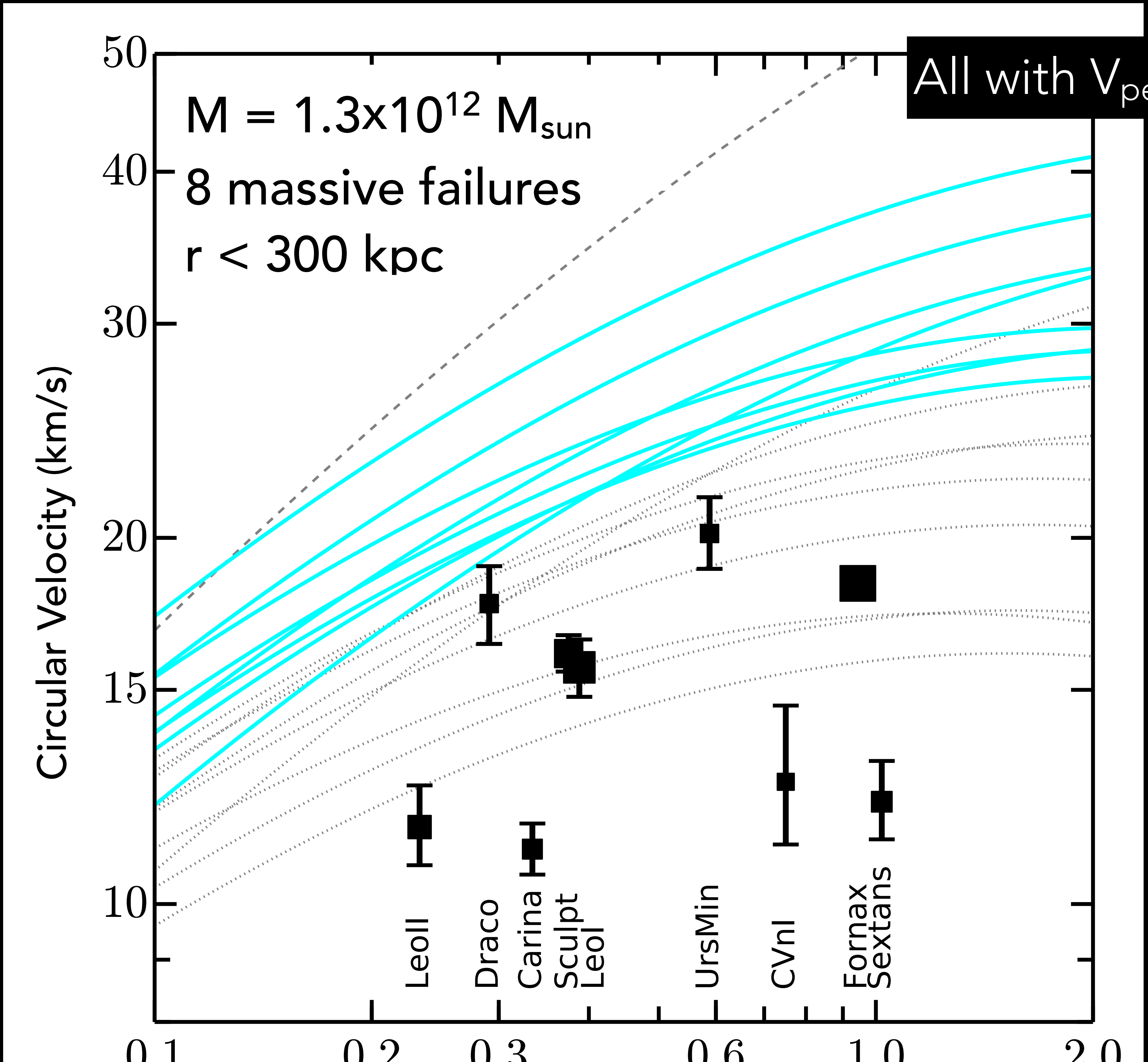

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SGK+2014b

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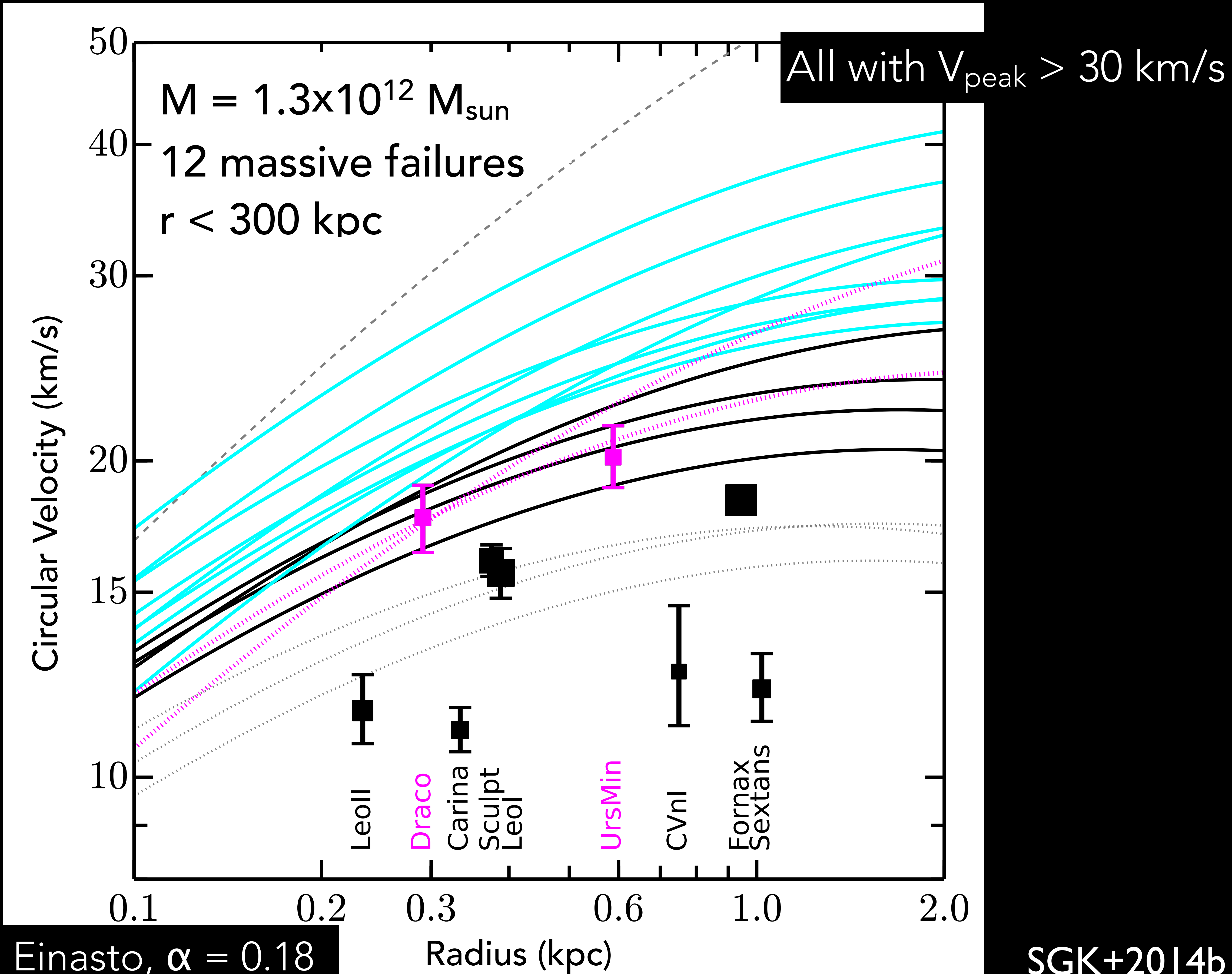

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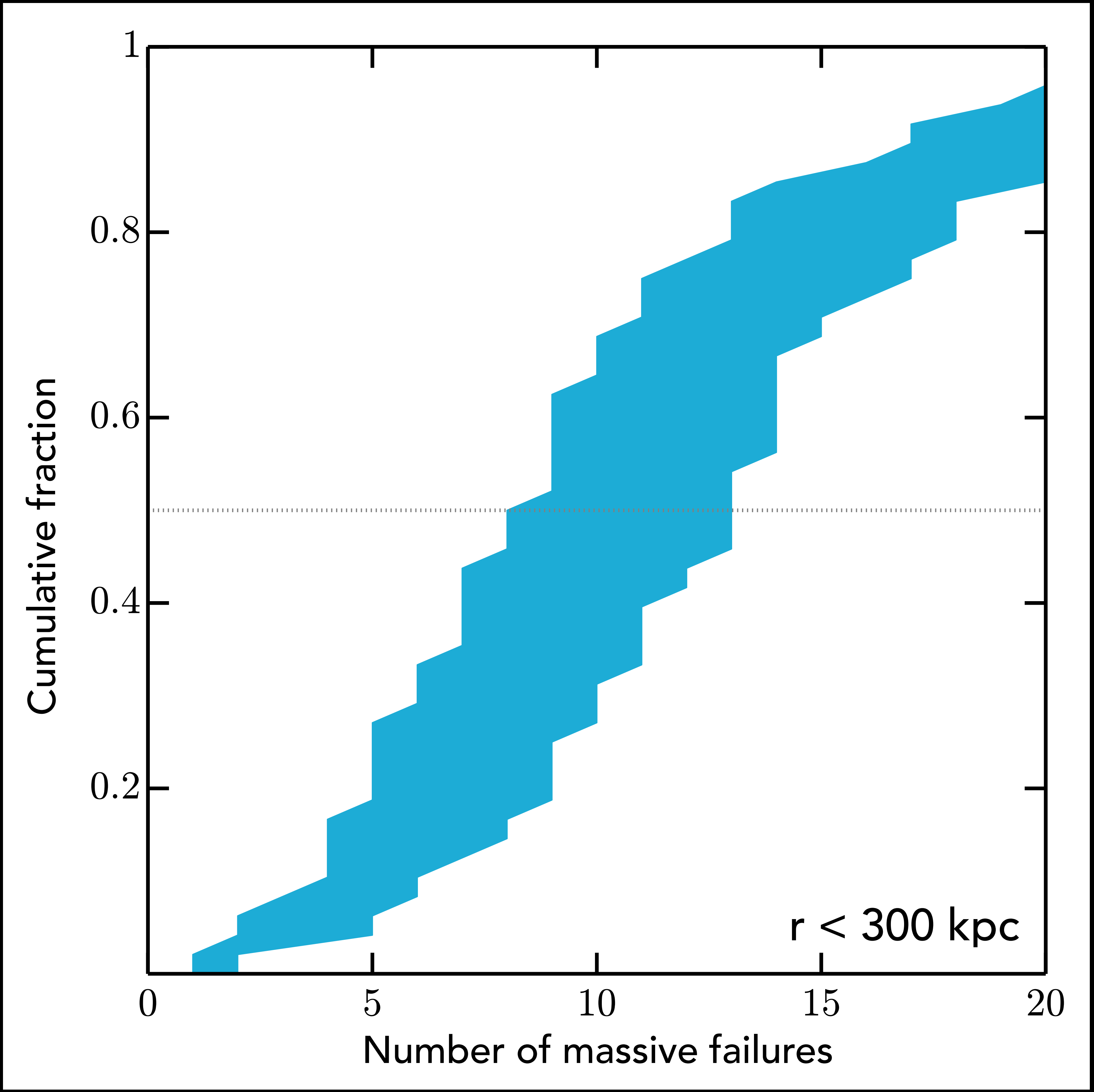
LEFTOVER HALOS PER HOST



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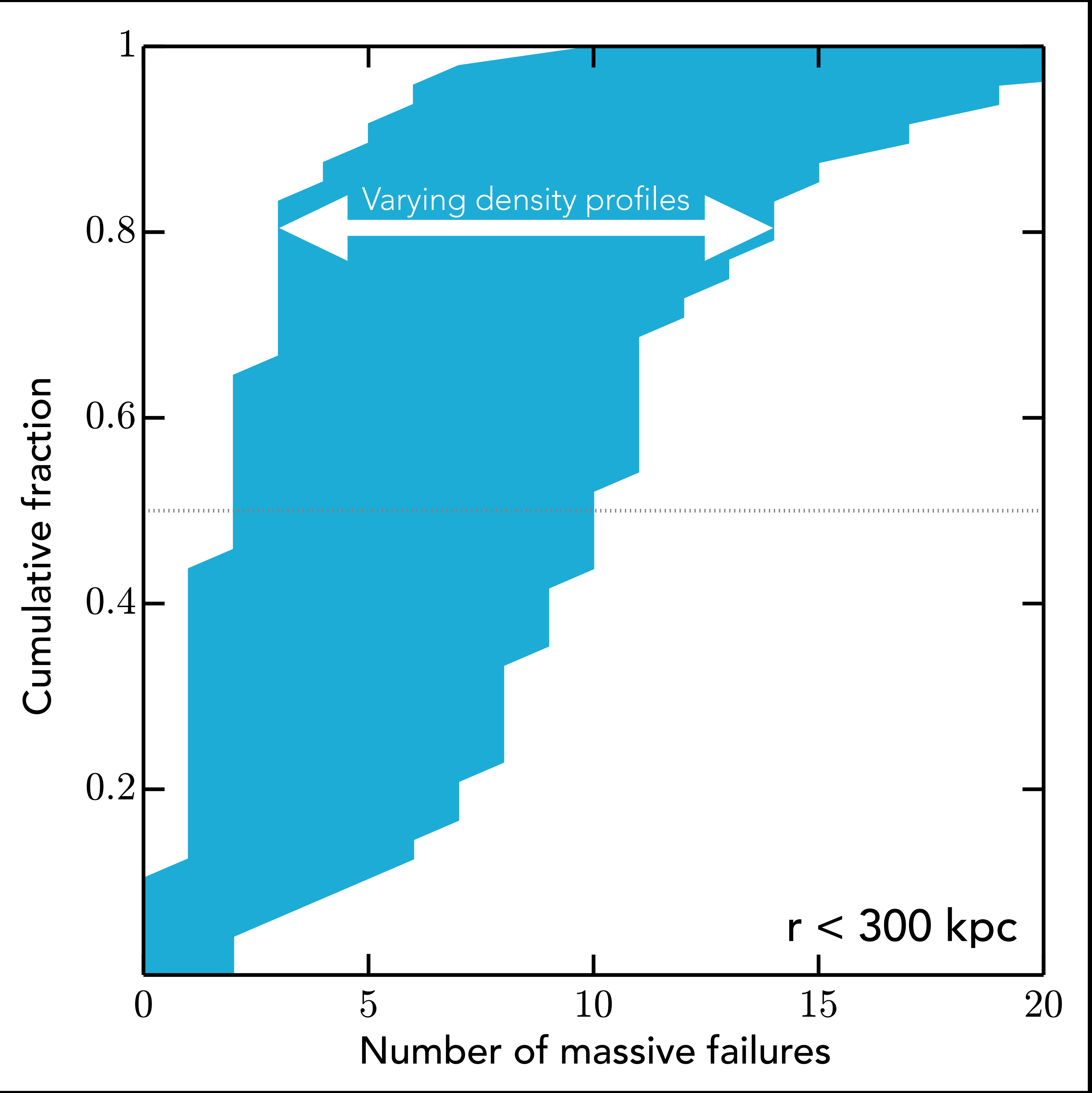

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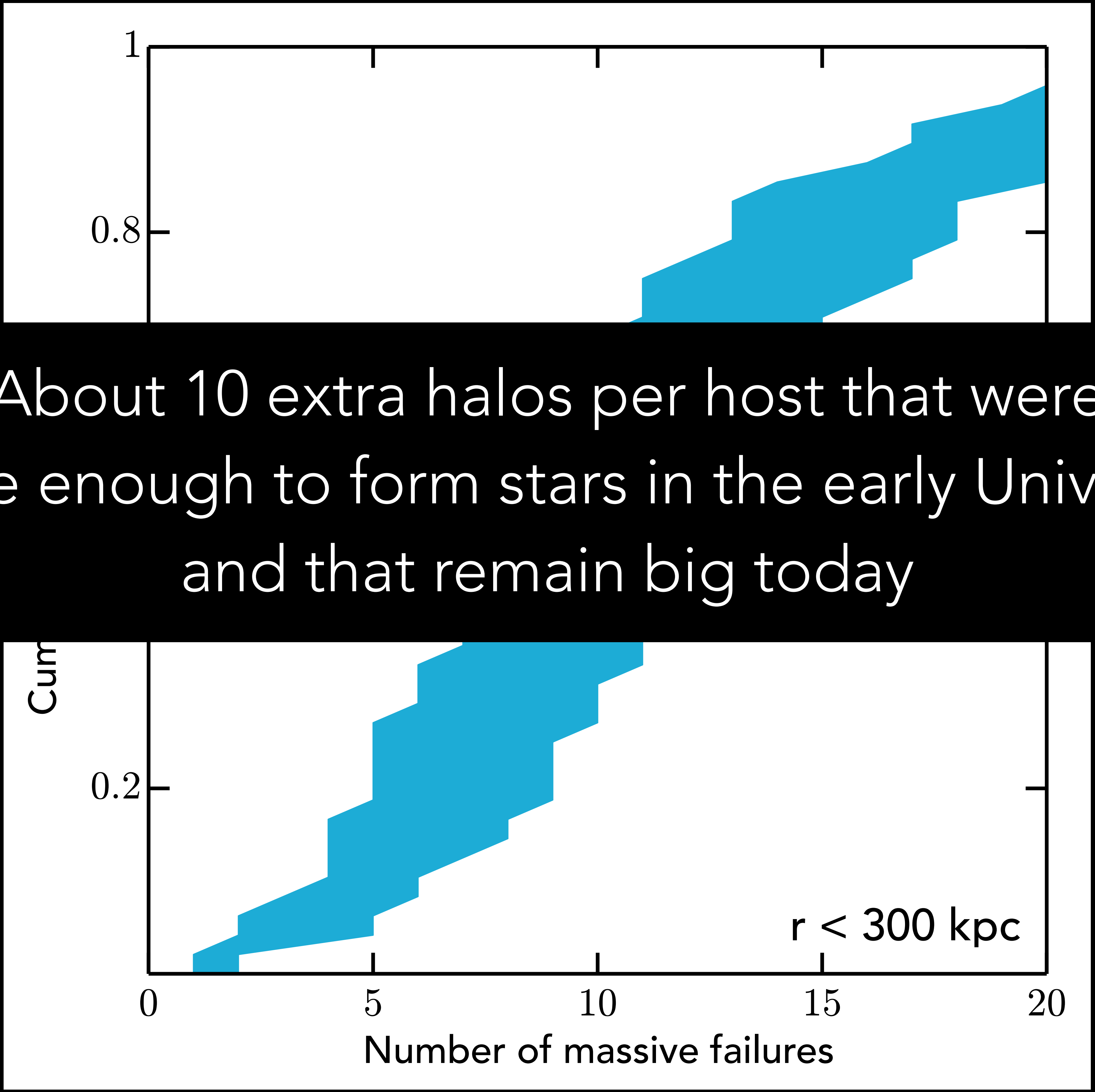
LEFTOVER HALOS PER HOST



About 10 extra halos per host that were large enough to form stars in the early Universe and that remain big today

SGK+2014b

TOO BIG TO FAIL: EXPLANATIONS

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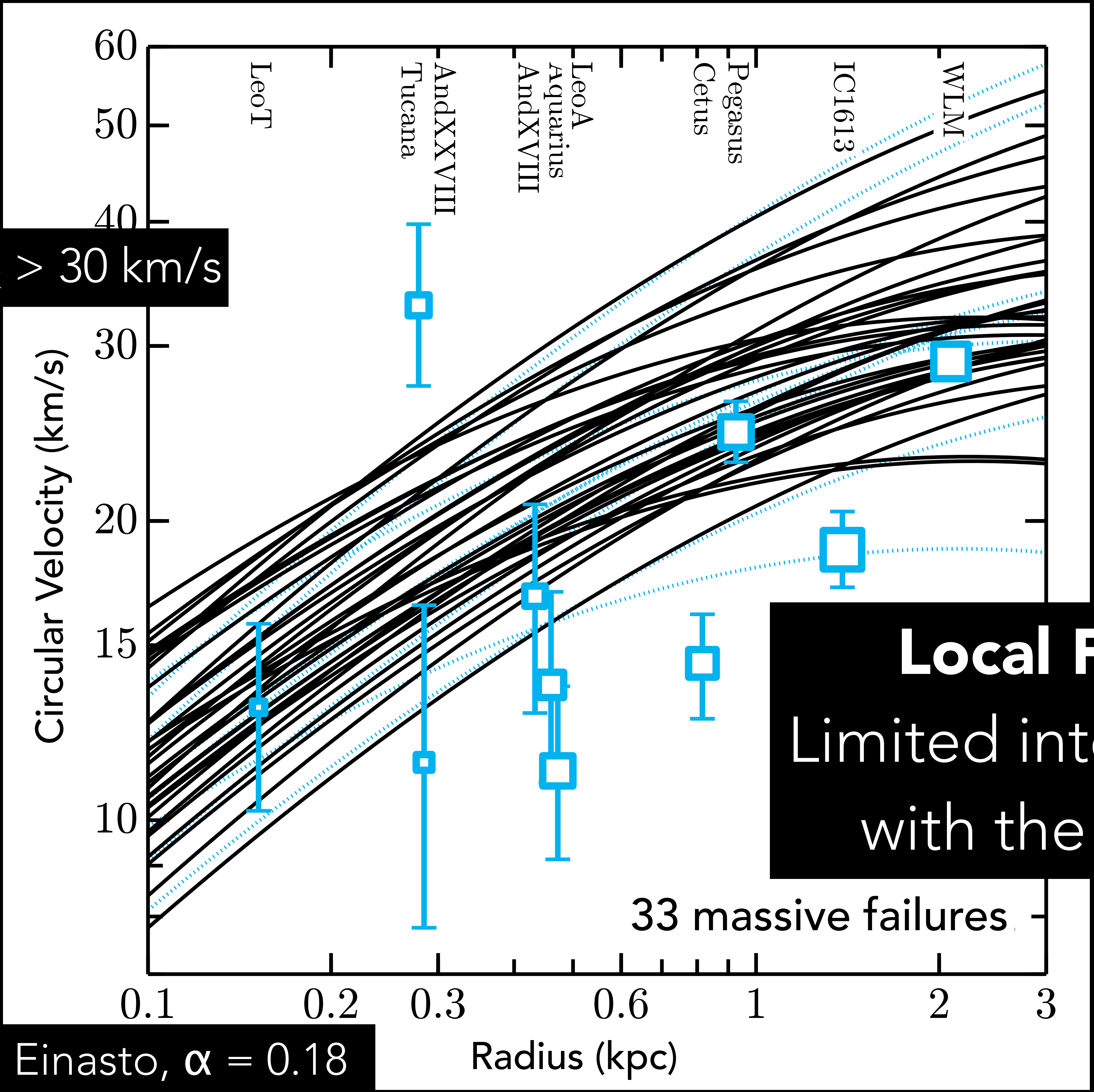
TBTF IN THE ELVIS FIELDS



All with V_{peak} > 30 km/s

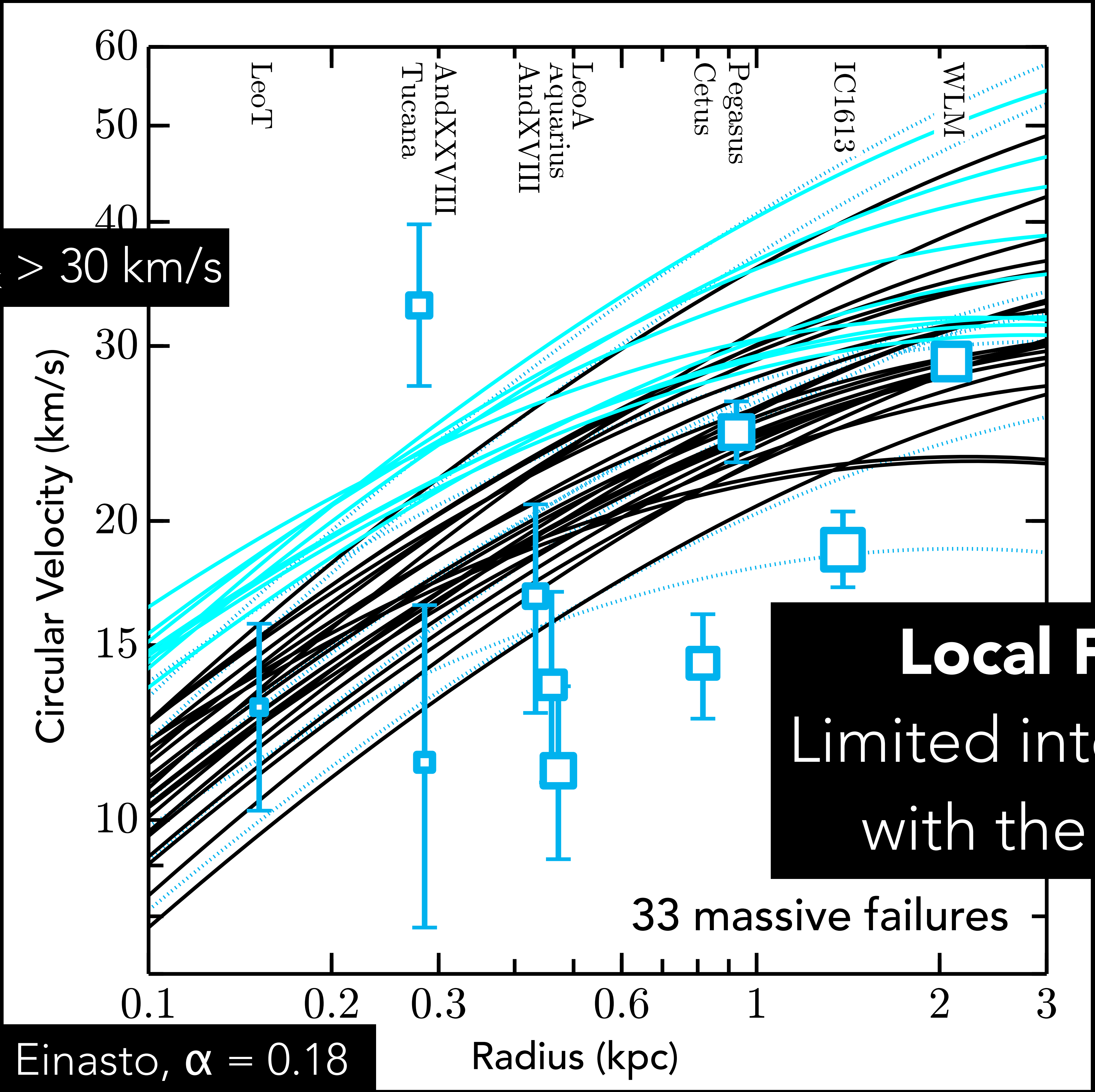
Local Field:
Limited interactions
with the giants

For experts: Einasto, α = 0.18

SGK+2014b

TBTF IN THE ELVIS FIELDS

All with V_{peak} > 30 km/s



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SGK+2014b

TBTF IN THE ELVIS FIELDS

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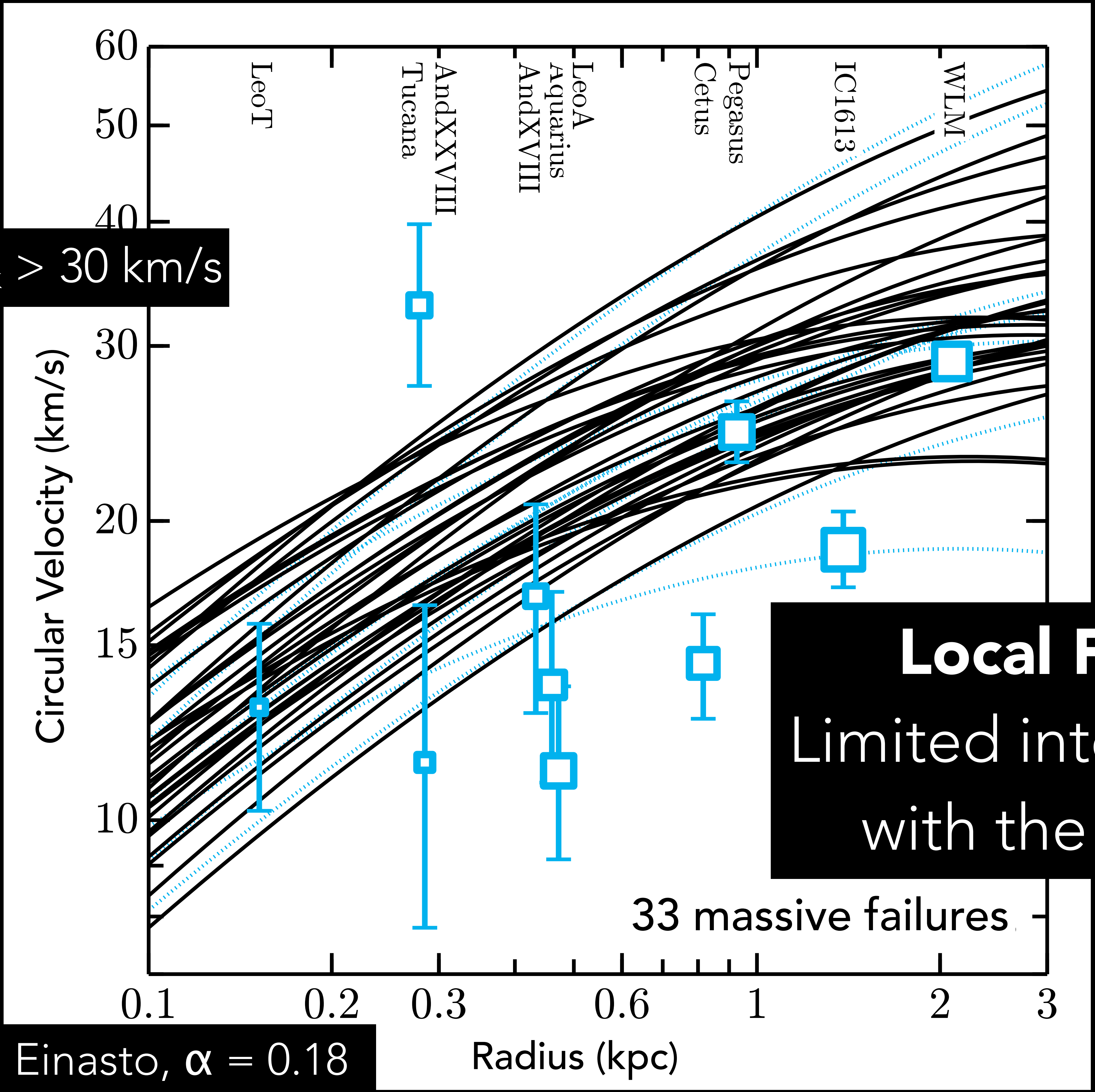

Local Field:

Limited interactions with the giants

For experts: Einasto, α = 0.18

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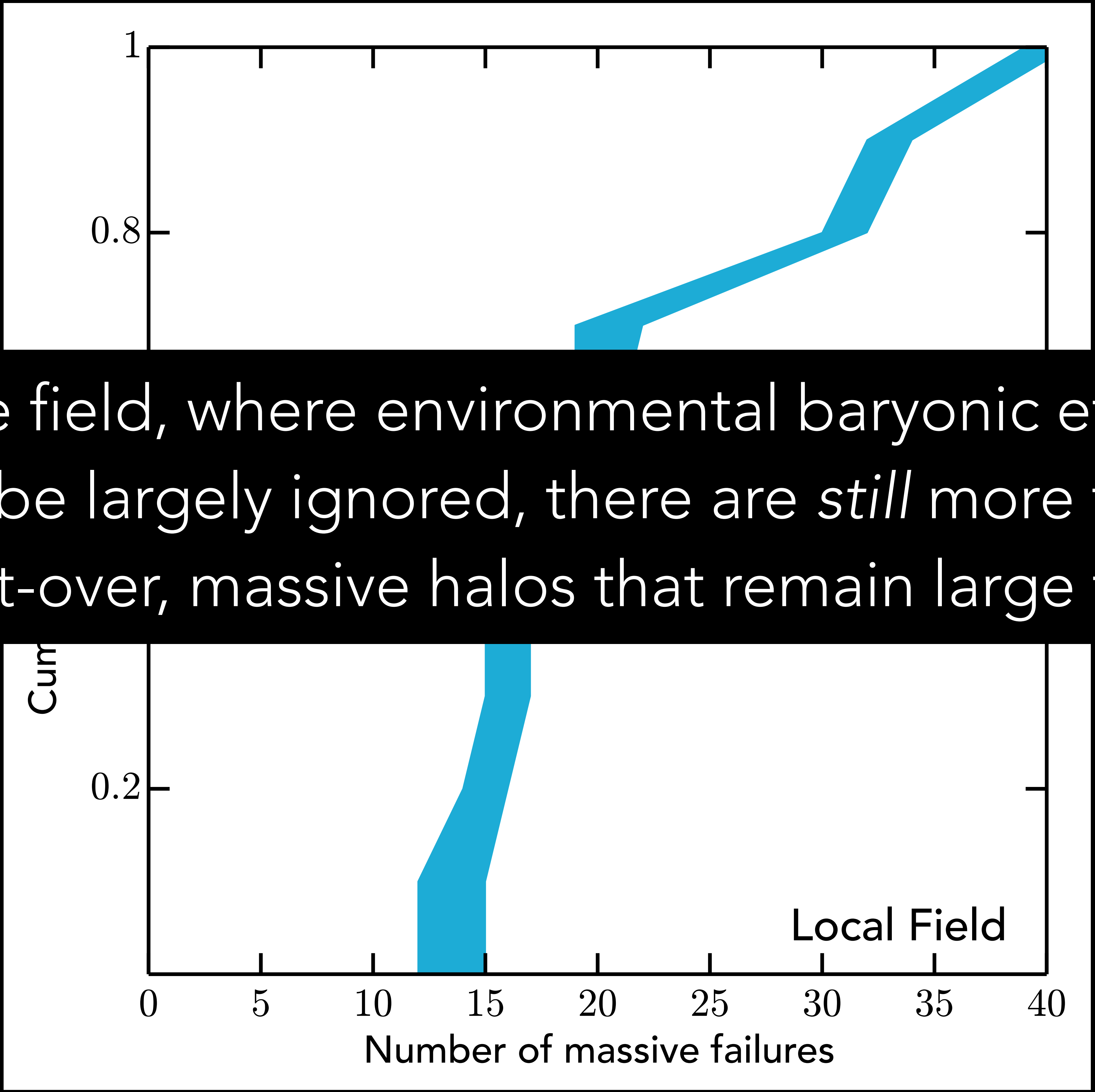
LEFT-OVER MASSIVE FIELD HALOS



In the field, where environmental baryonic effects can be largely ignored, there are *still* more than 15 left-over, massive halos that remain large today

SGK+2014b

TOO BIG TO FAIL IN ELVIS: TAKE AWAY

There are too many large, dense halos near the Milky Way relative to observations

(including in the field, where environmental baryonic solutions struggle)

TOO BIG TO FAIL: EXPLANATIONS

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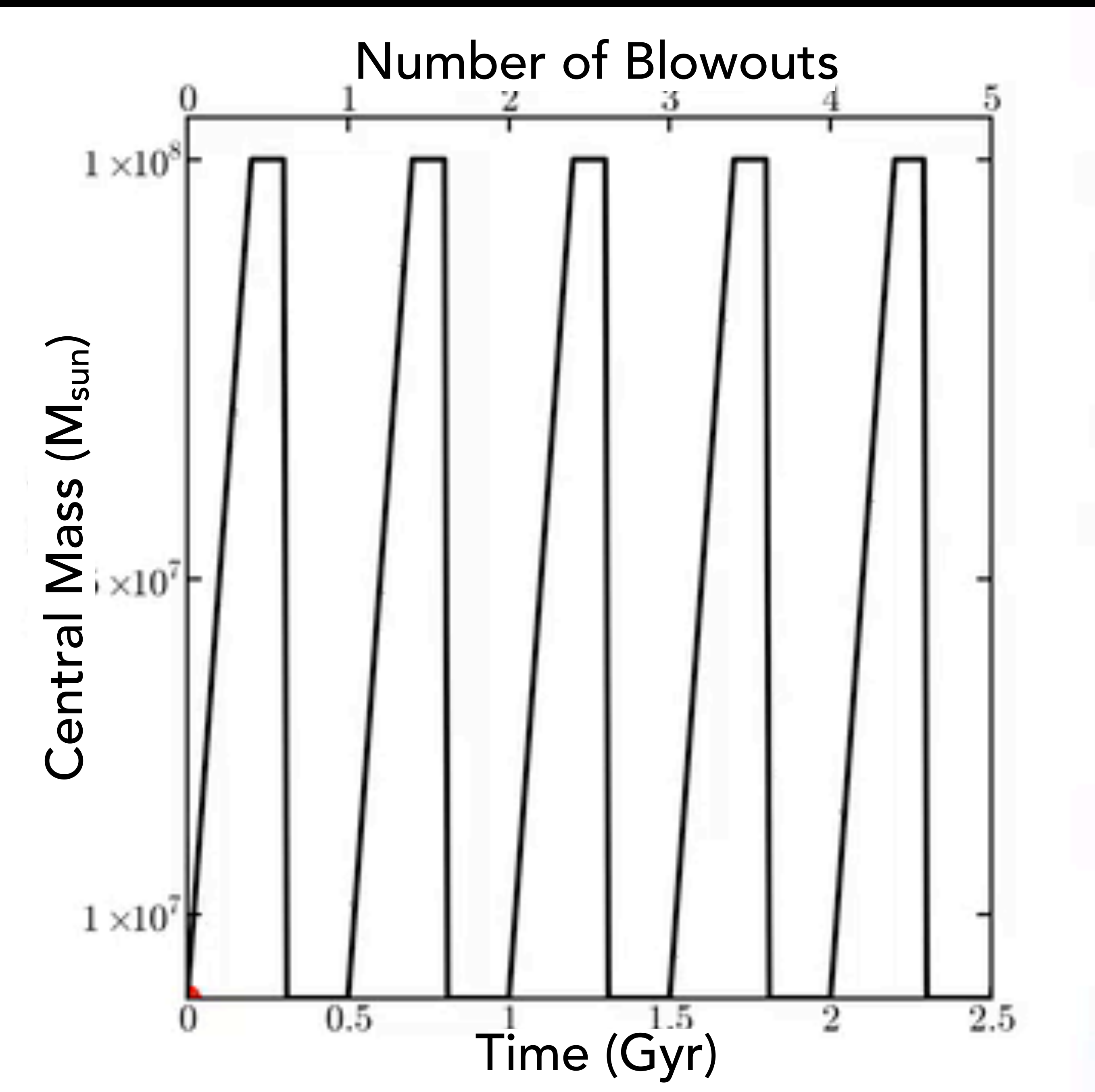
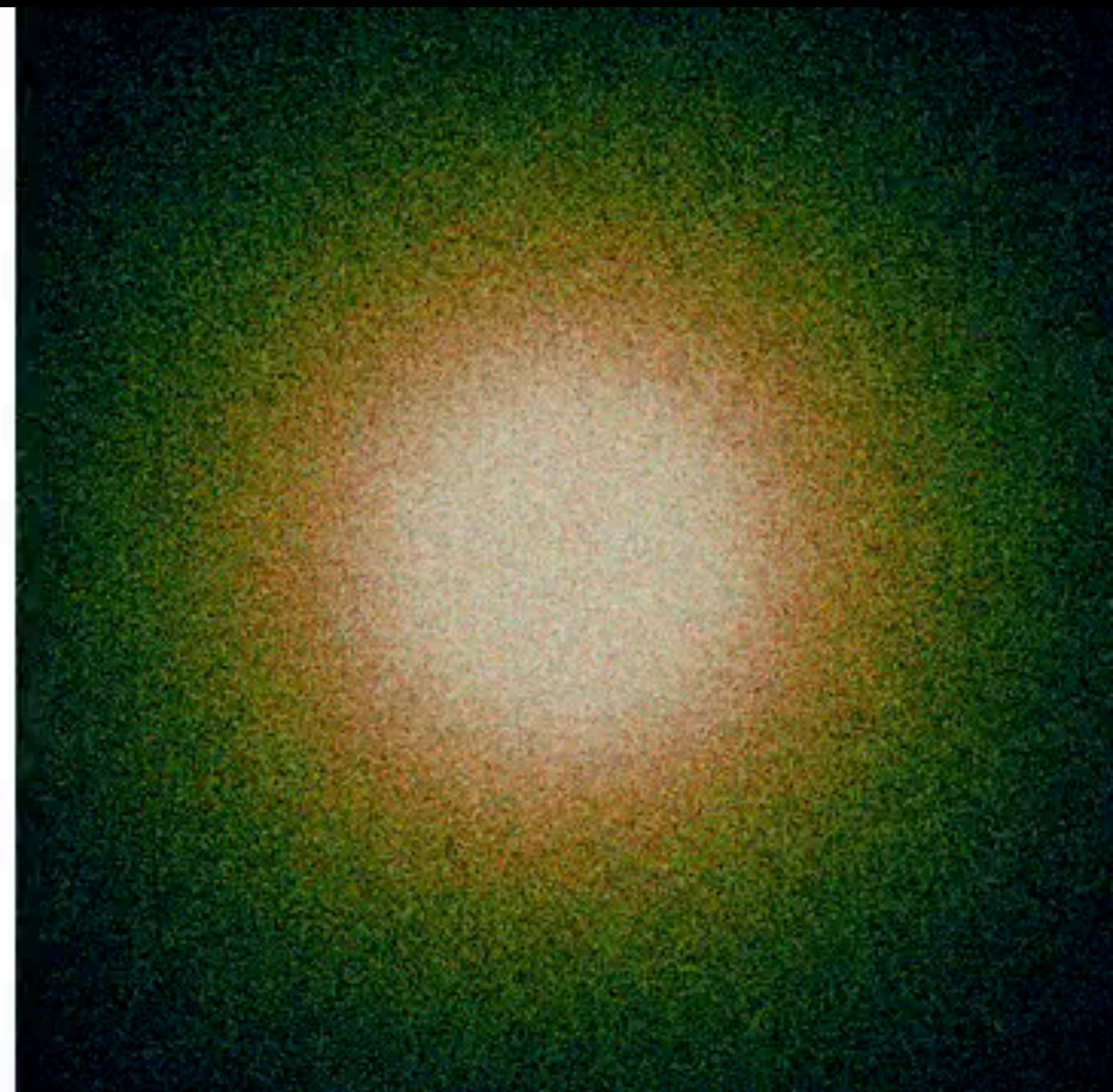
SUPERNOVAE FEEDBACK IN DWARFS

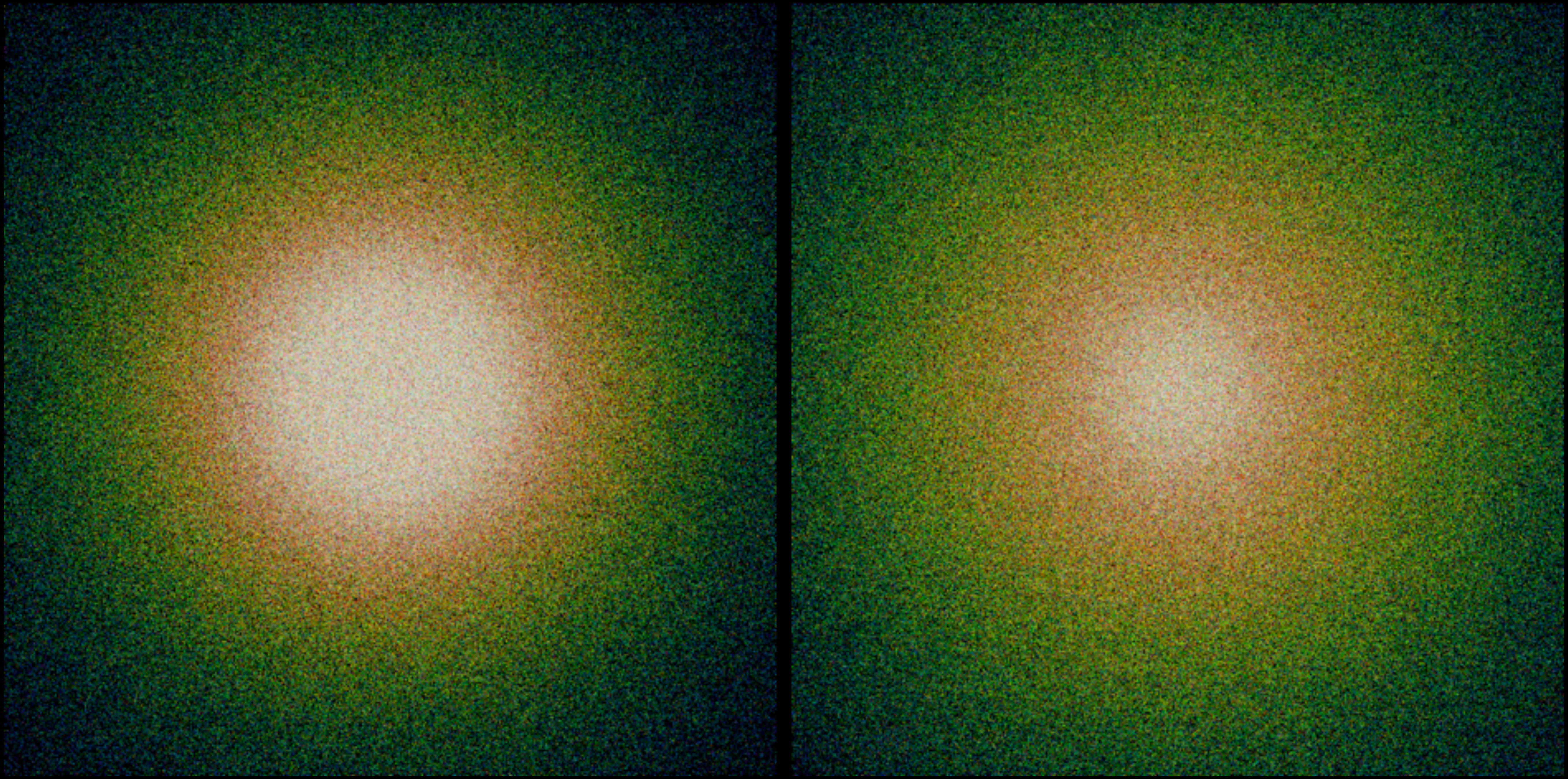
Calculate the energy required to turn a dense subhalo into one capable of hosting a classical dSph

SUPERNOVAE FEEDBACK IN DWARFS



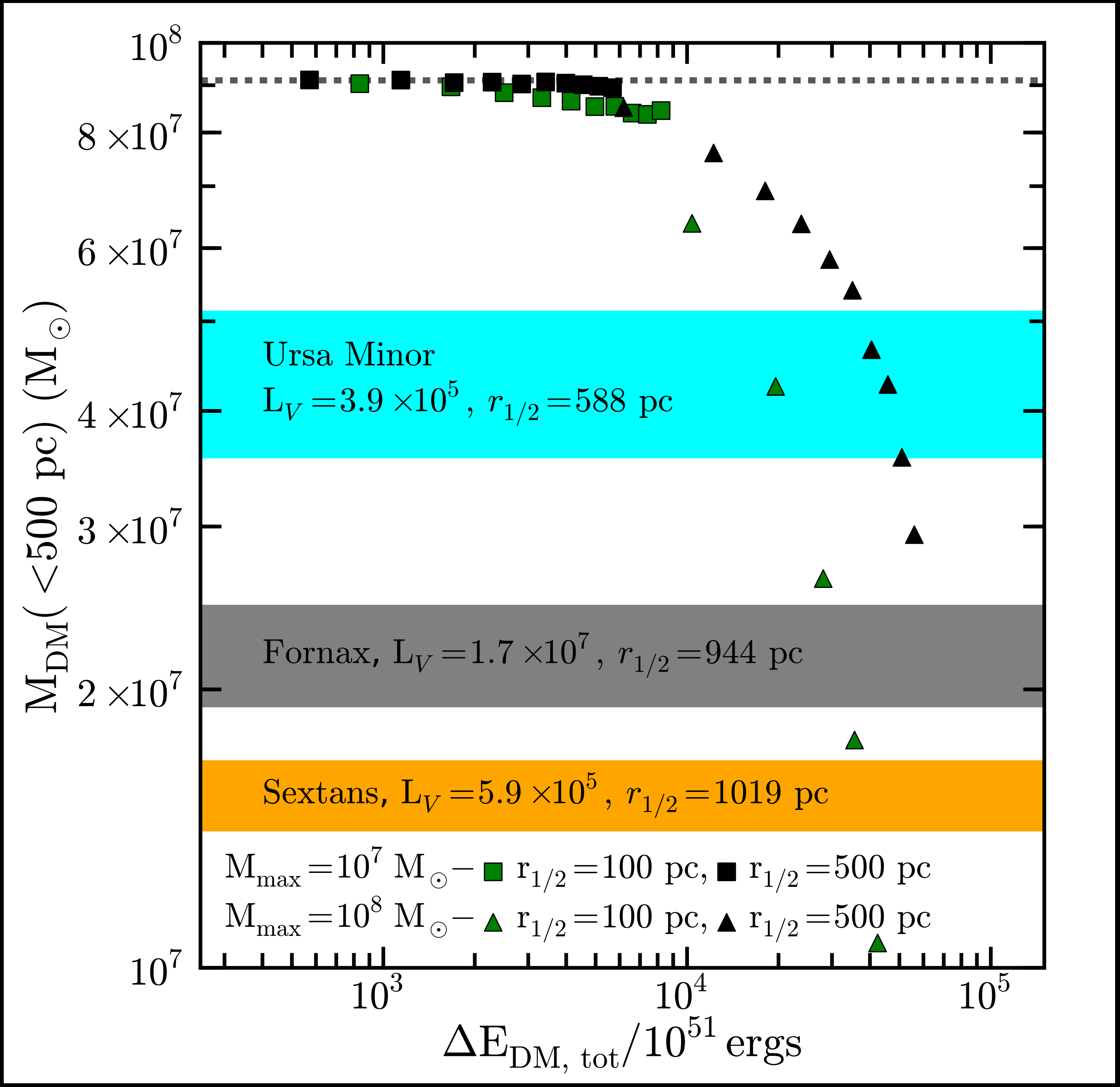


SUPERNOVAE FEEDBACK IN DWARFS



Before — After

SUPERNOVAE FEEDBACK IN DWARFS



SGK+2013

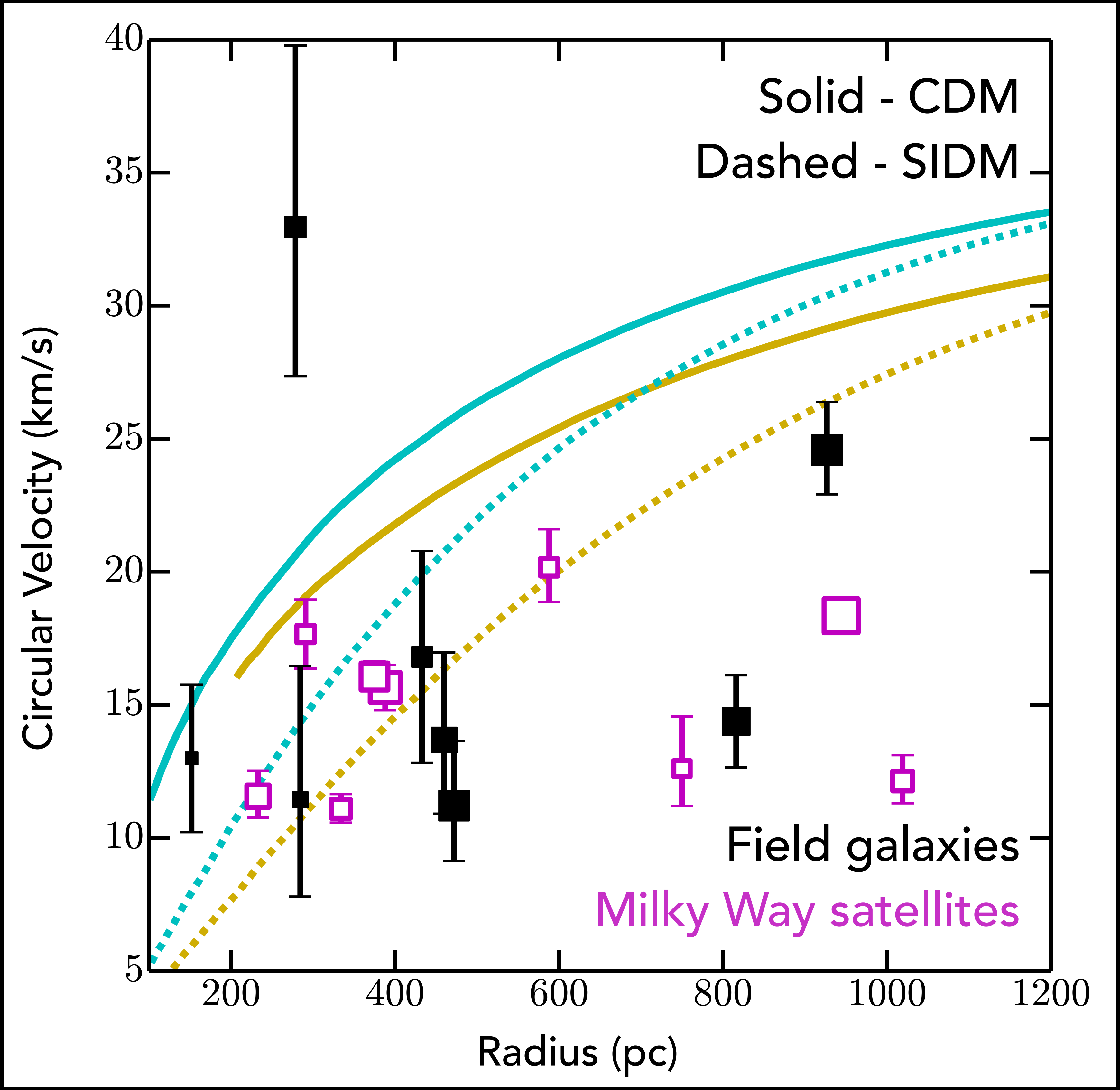
Not enough energy available in supernovae to solve TBTF by lowering the central masses of dwarfs

TOO BIG TO FAIL: EXPLANATIONS

- **Statistical Anomaly**
- **Baryons:**
  - Interactions with the central host (e.g. Zolotov+2012, Arraki+2014)
  - Supernovae feedback (e.g. Pontzen & Governato 2012)
- **Cosmology:**
  - Self-interacting dark matter (e.g. Vogelsberger+2012)
  - Warm Dark Matter (e.g. Anderhalden+2013)
  - More subtle changes to the initial power spectrum

DWARFS IN SELF-INTERACTING DM

Elbert+ in prep



Naturally form cores and alleviate TBTF with SIDM

TOO BIG TO FAIL: EXPLANATIONS

- **Statistical Anomaly**
- **Baryons:**
  - Interactions with the central host (e.g. Zolotov+2012, Arraki+2014)
  - Supernovae feedback (e.g. Pontzen & Governato 2012)
- **Cosmology:**
  - Self-interacting dark matter (e.g. Vogelsberger+2012)
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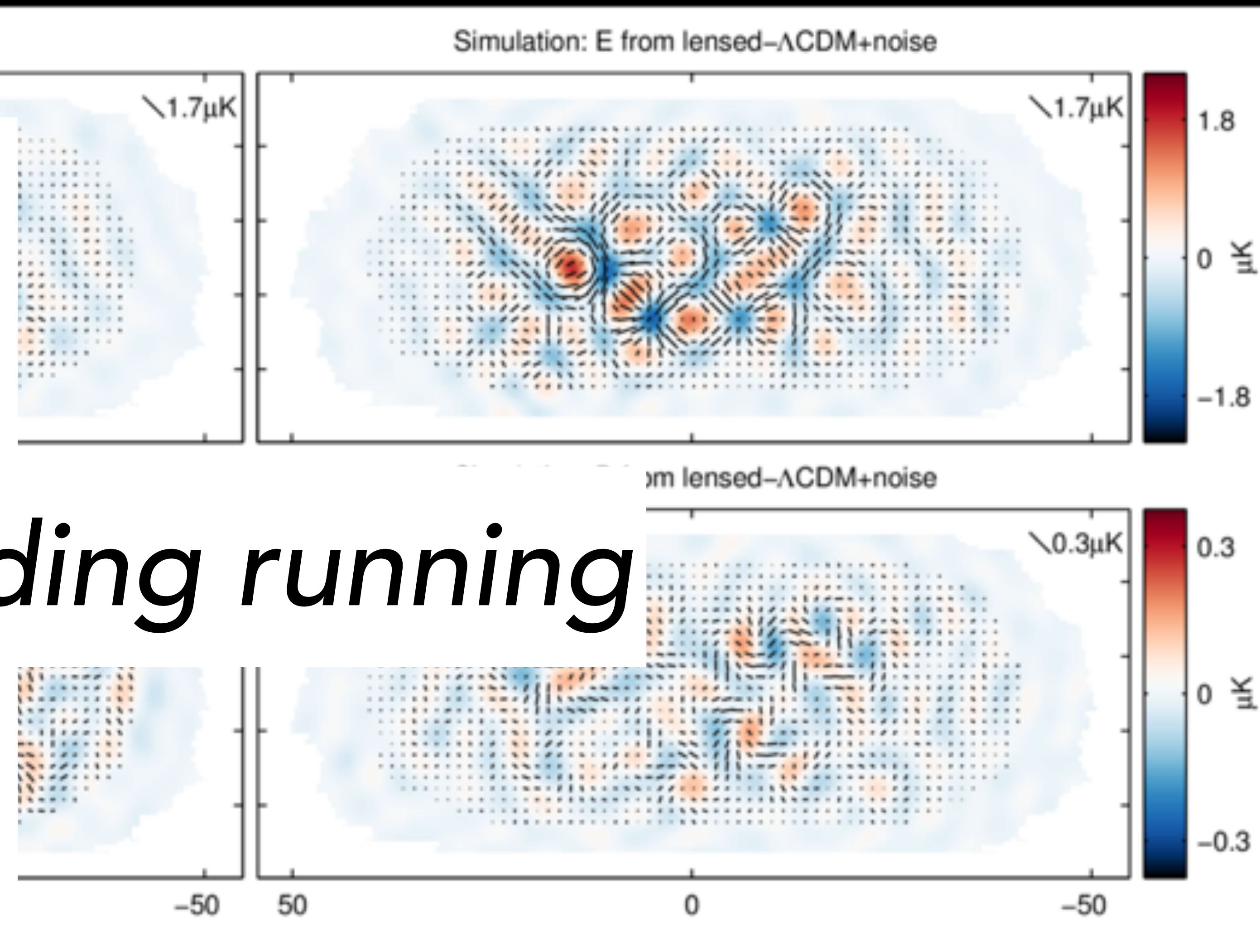
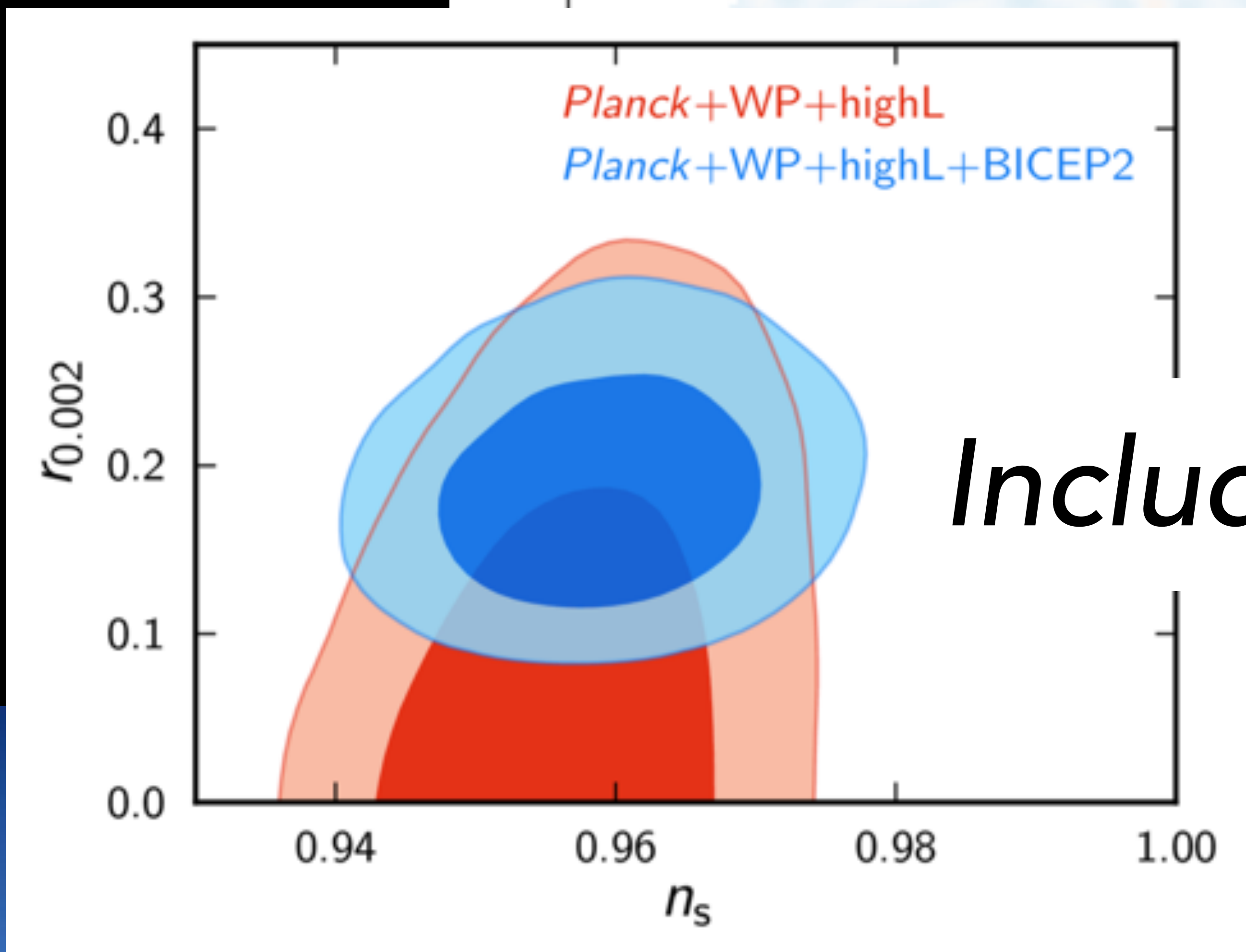
THE *BICEP2* EXPERIMENT

BICEP2 Collaboration, 2014

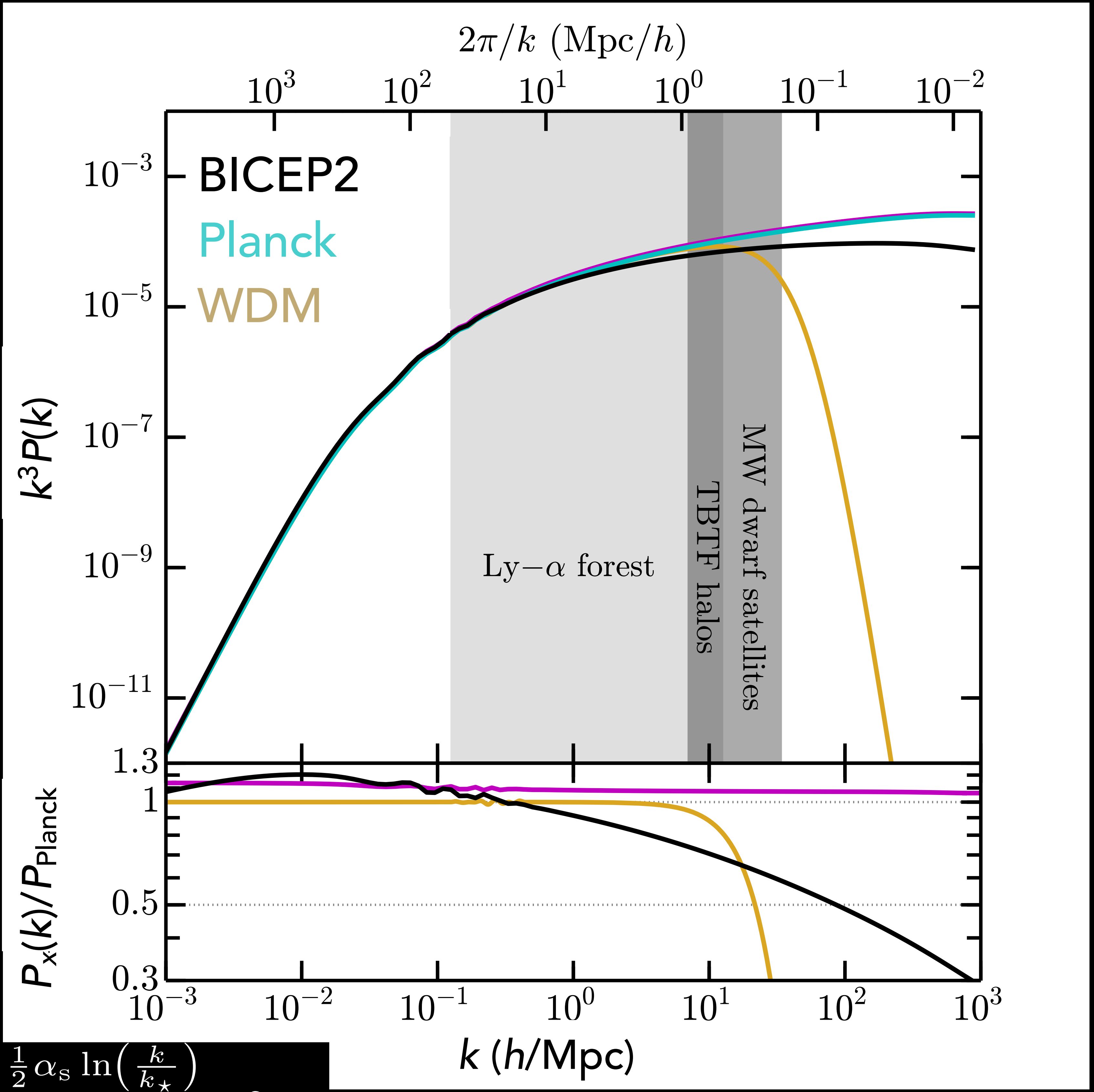




Including running

BICEP2 measurement requires a nontrivial power spectrum to avoid clashing with *Planck* constraints

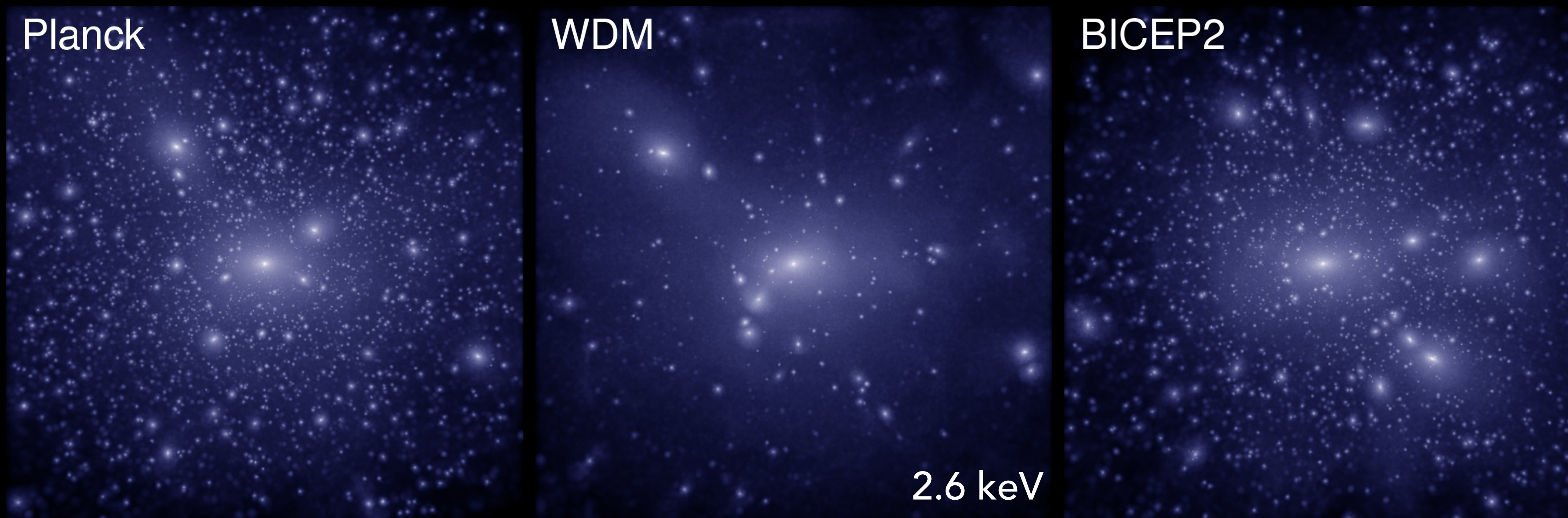
A "RUNNING" SPECTRAL INDEX

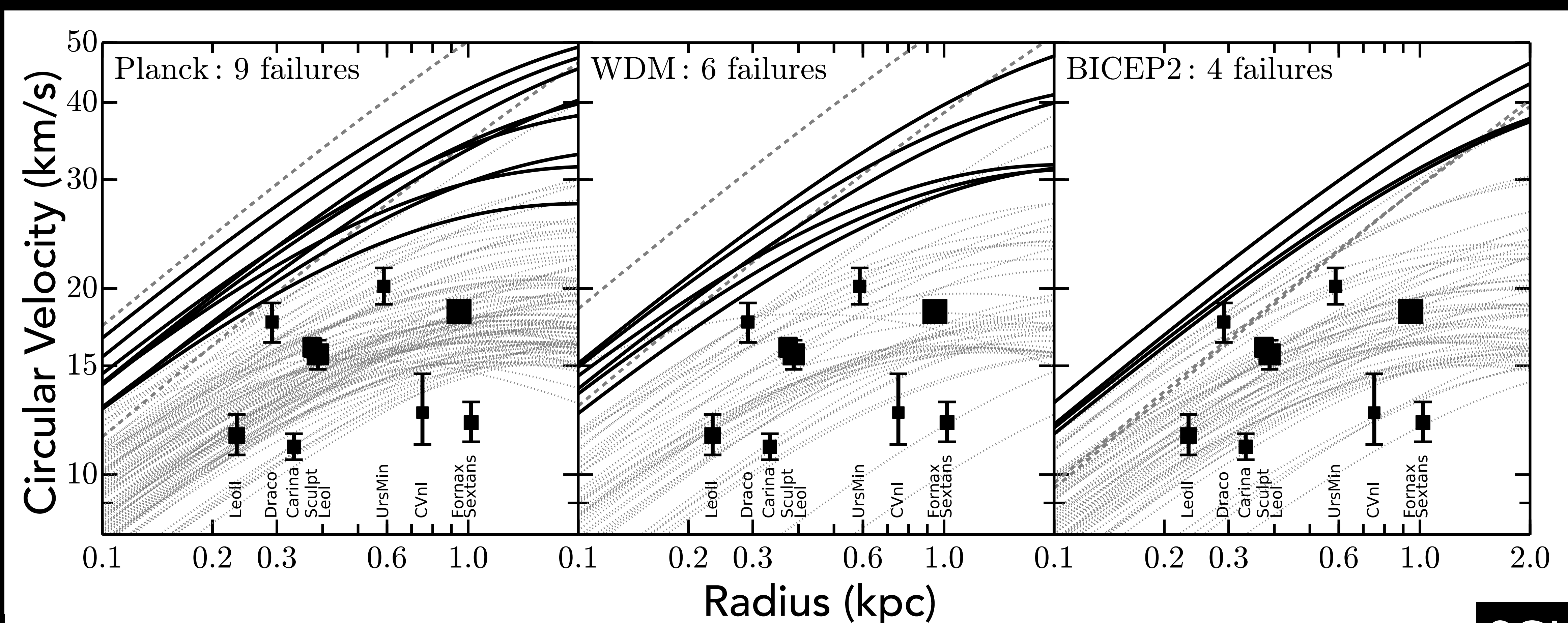


$$T'^2(k) = \left(\frac{k}{k_\star}\right)^{\frac{1}{2}\alpha_{\rm s}\ln\left(\frac{k}{k_\star}\right)} T^2(k)$$

SGK+2014c

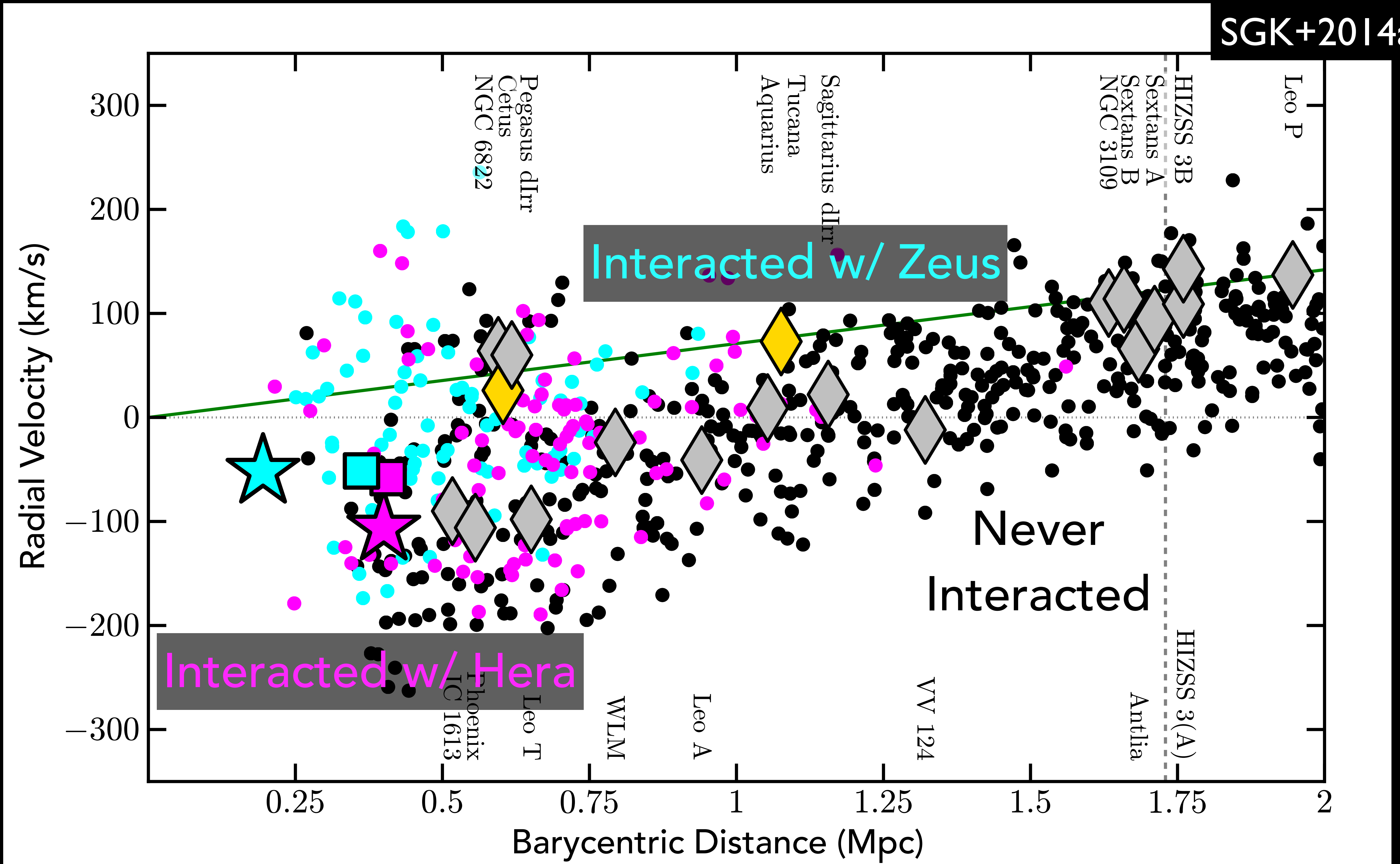
A "RUNNING" SPECTRAL INDEX





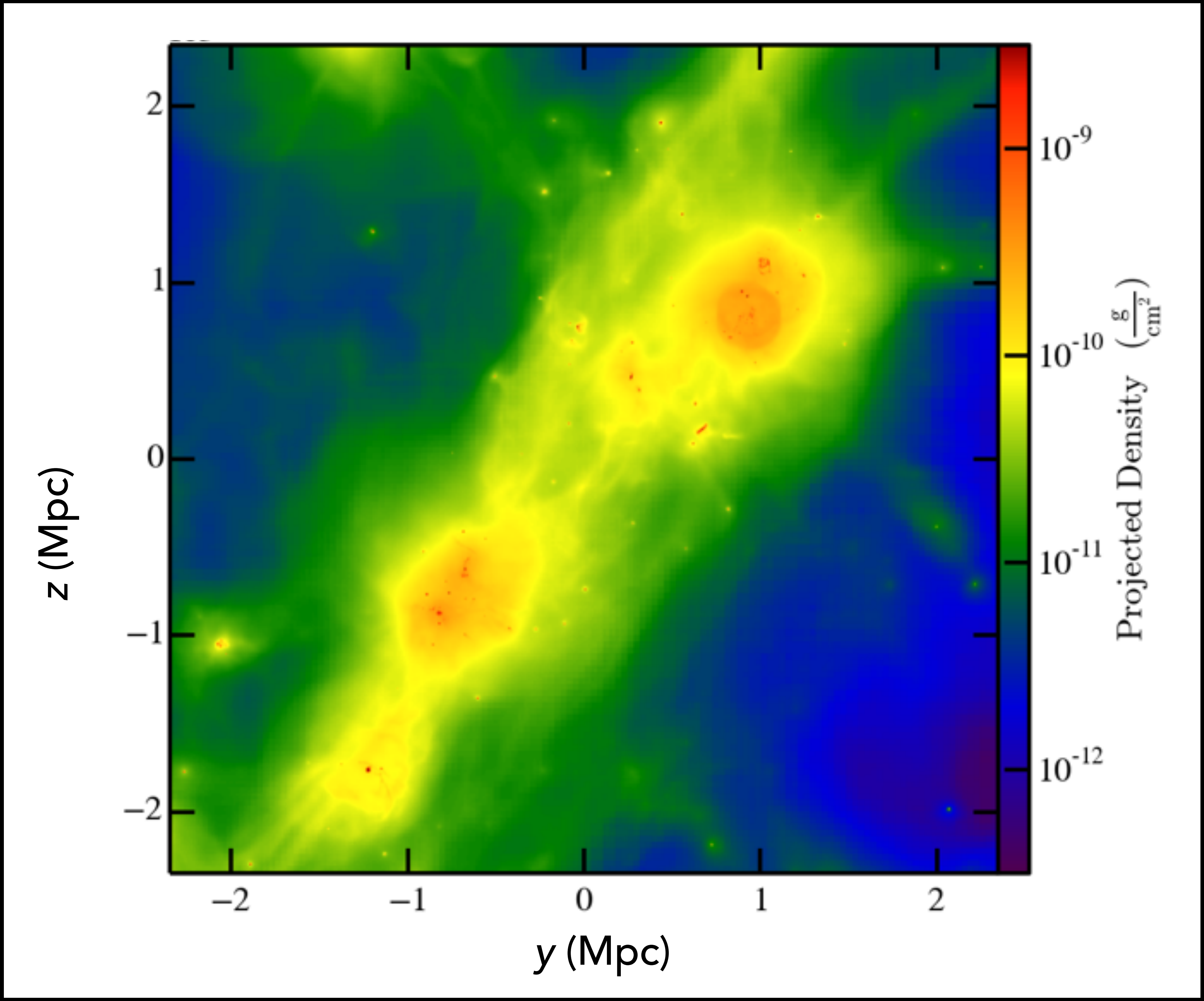
SGK+2014c

FUTURE WORK



Identifying backsplash galaxies in the Local Group

FUTURE WORK



ELVIS on **FIRE**: simulating the Local Volume with gas, including all the bells and whistles (Hopkins et al.)

CONCLUSIONS

The Local Group environment:

- We can constrain cosmology (e.g. the nature of dark matter and how dwarfs galaxies evolve) with the Local Field, but simulations ***must*** account for M31

Abundance matching:

- Comparing galaxy counts in the Local Group to halo counts in simulations reveals a steep relation between M_{star} and M_{halo}
  - ⇒ Small halos are ***really bad*** *at* forming stars
- *However*, if galaxies follow a universal density profile, there appears to be no relation between stellar mass and halo mass in the Local Field
  - ⇒ Stochastic galaxy formation? Breakdown of abundance matching?

Too Big to Fail:

- The ubiquity of large, over-dense halos near the MW and in the Local Field is a clue to how dwarf galaxies form, suggesting either that:
  a) Galaxies populate halos in an unexpected manner *or*
  b) Processes not included in standard dark matter-only simulations modify the central masses of even the largest dwarf halos
     i) **Baryons:** Need non-environmental effects, but not enough energy in supernovae
     ii) Cosmology: SIDM and modified power spectra are promising