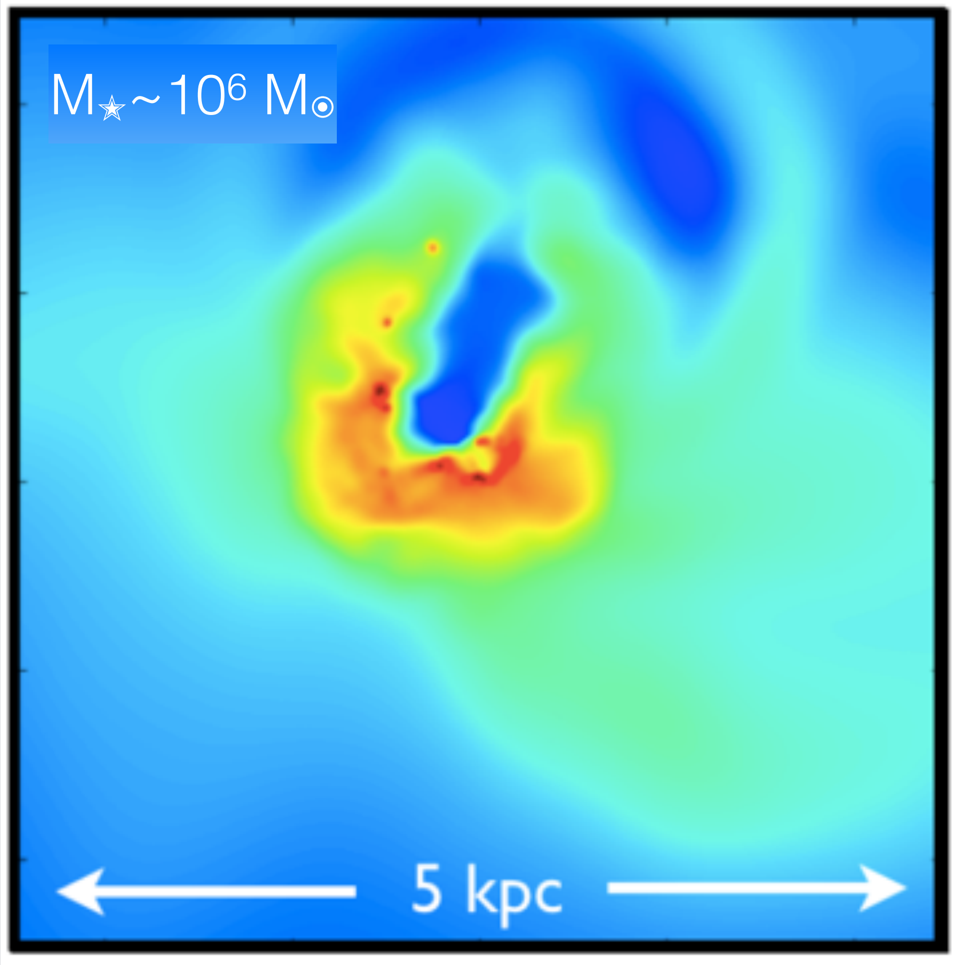
FORGED IN FIRE

CUSPS & CORES IN SMALL DWARF GALAXIES



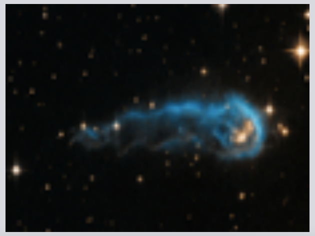
JAMES BULLOCK
UC Irvine

WITH: **JOSE OÑORBE**, MIKE BOYLAN-KOLCHIN, PHIL HOPKINS, DUSAN KERES

FIRE (Feedback In Realistic Environments)

HOPKINS, KERES, OÑORBE, FAUCHER-GIGUERE, QUATAERT, MURRAY, JSB

Radiation pressure



Stellar winds

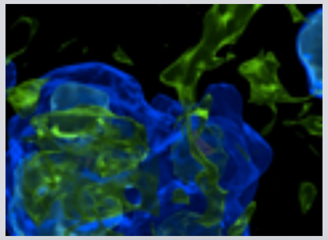
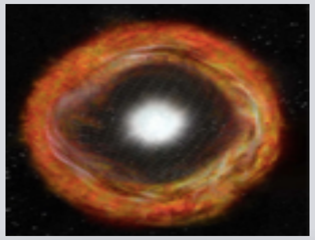
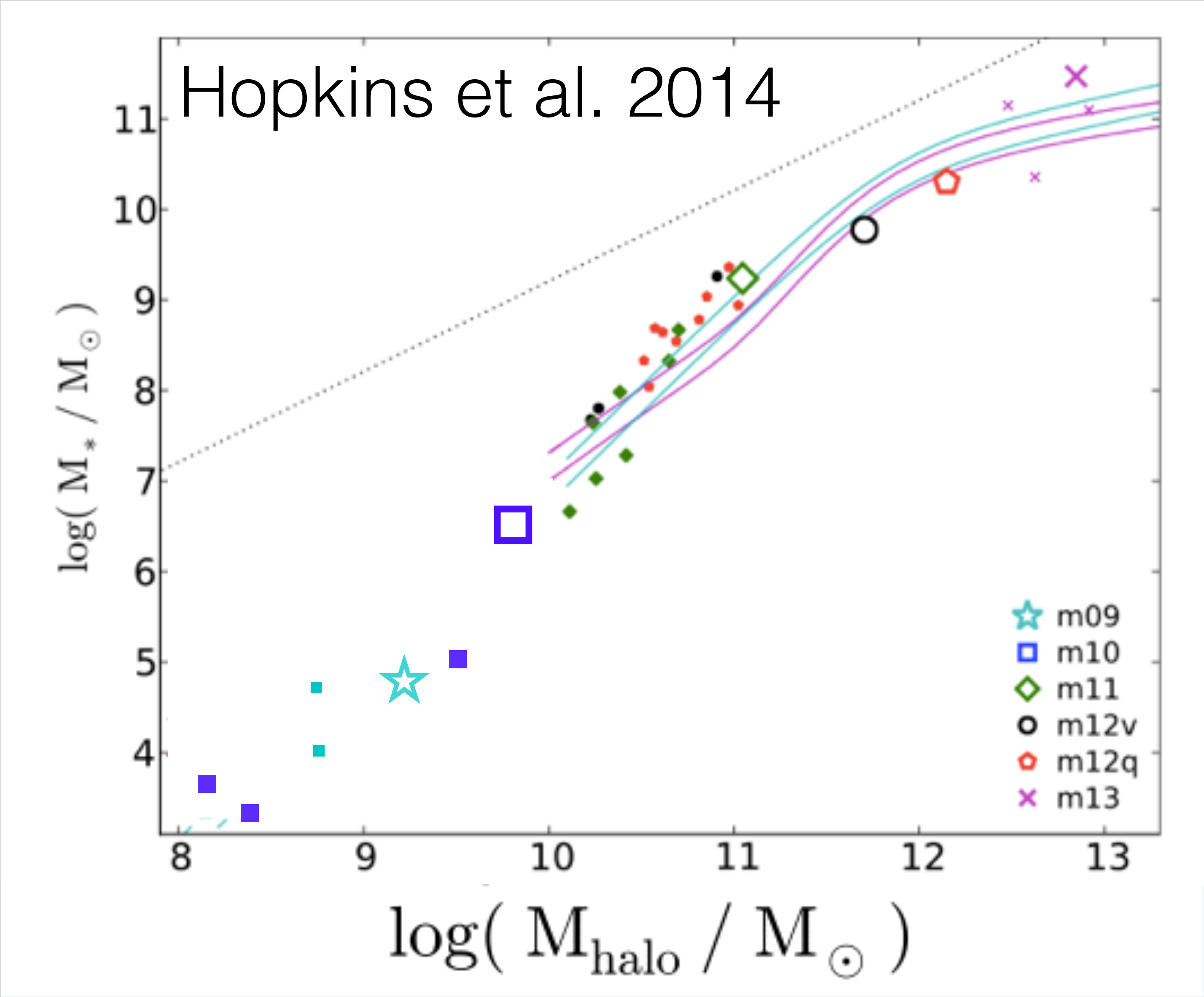


Photo-Ionization



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



FIRE (Feedback In Realistic Environments)

HOPKINS, KERES, OÑORBE, FAUCHER-GIGUERE, QUATAERT, MURRAY, JSB

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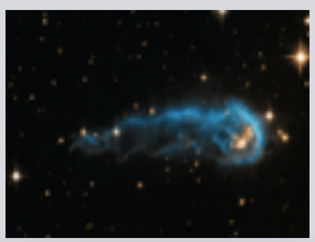
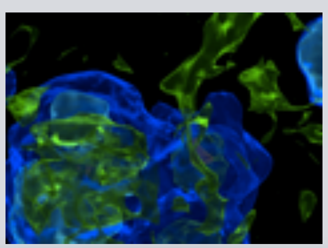


Stellar winds



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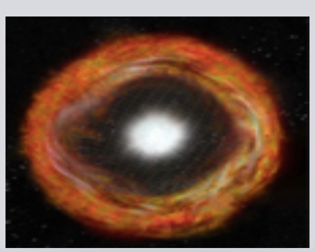

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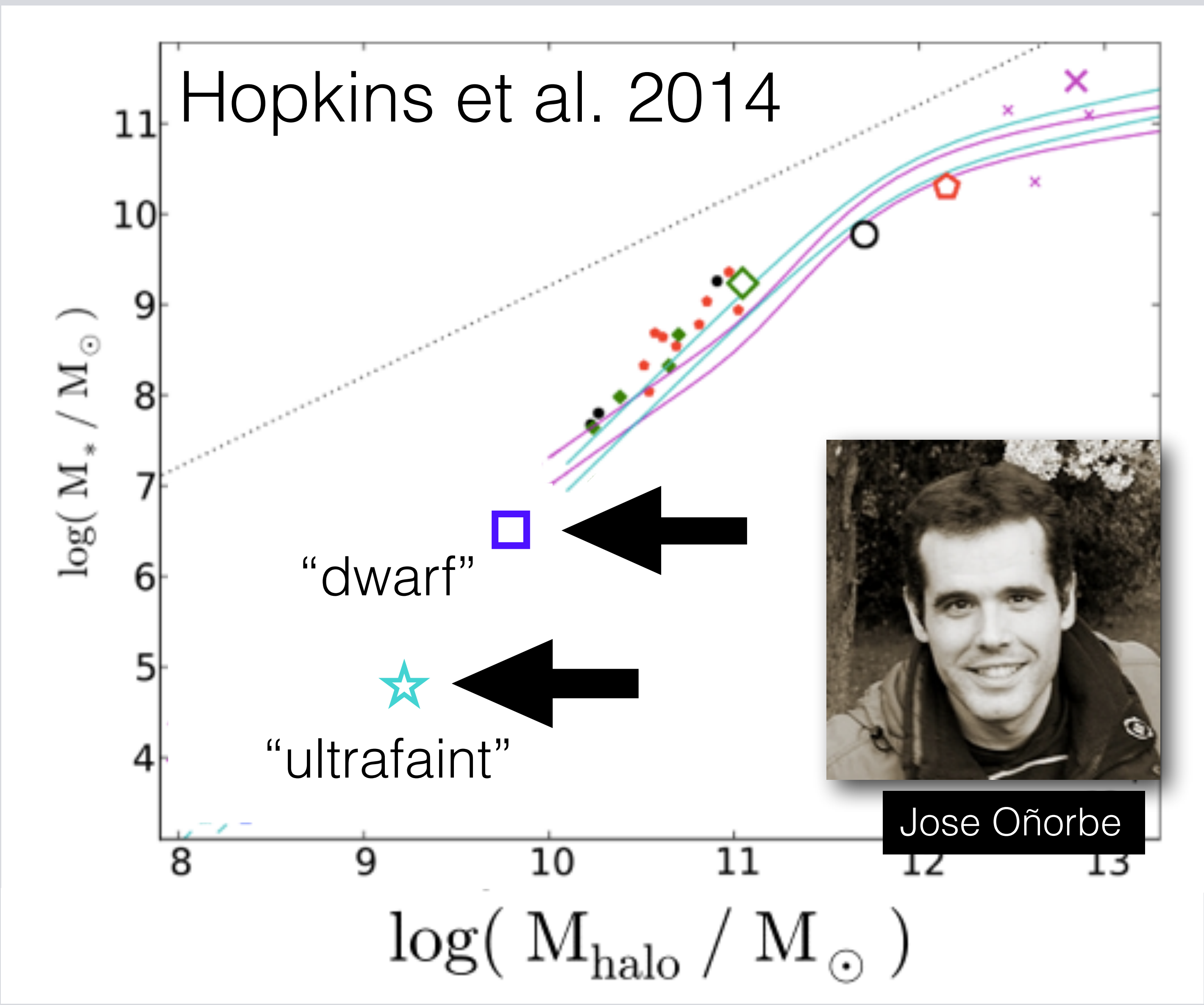
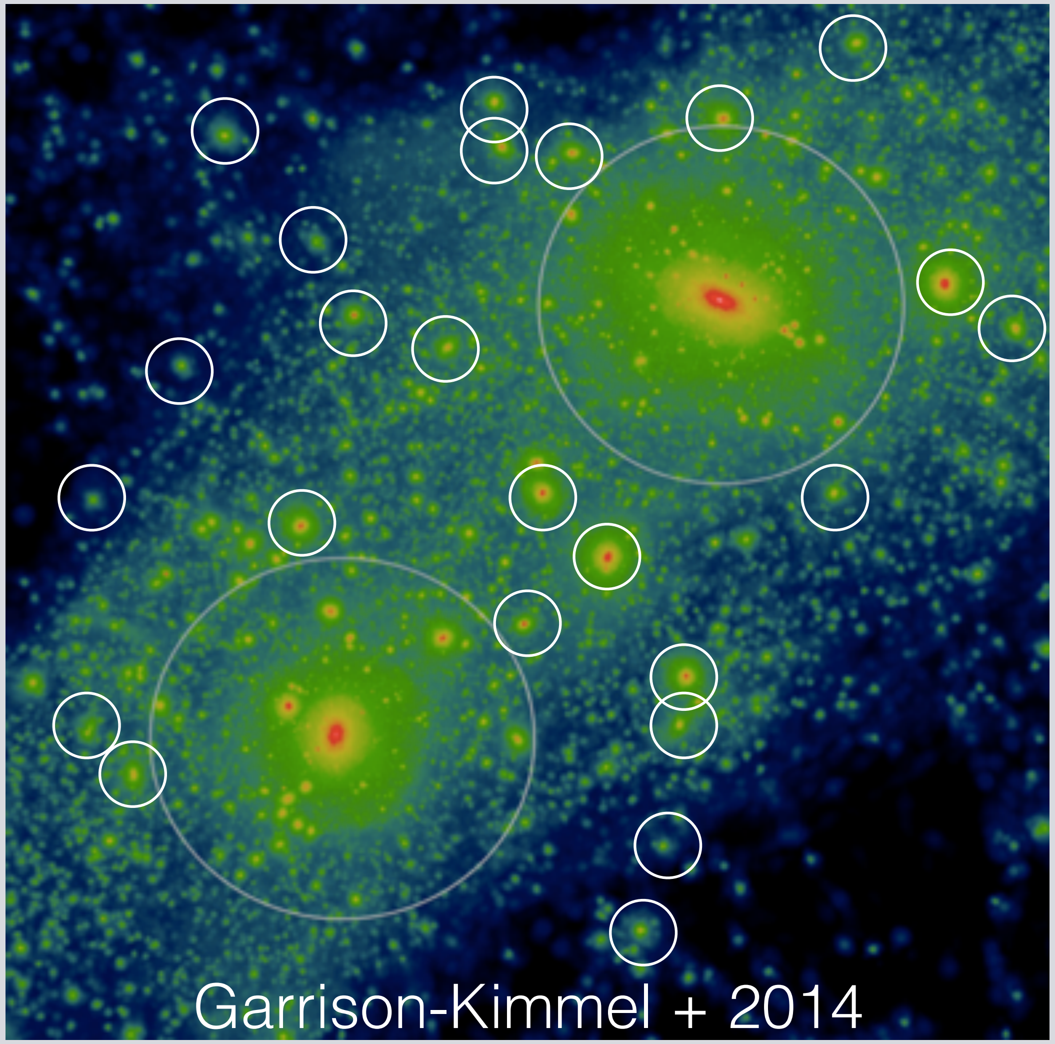


$M_{HALO} = 10^{10}\ M_{\odot}$

WHERE THINGS GET INTERESTING

$M_{HALO} = 10^{10}\ M_\odot$

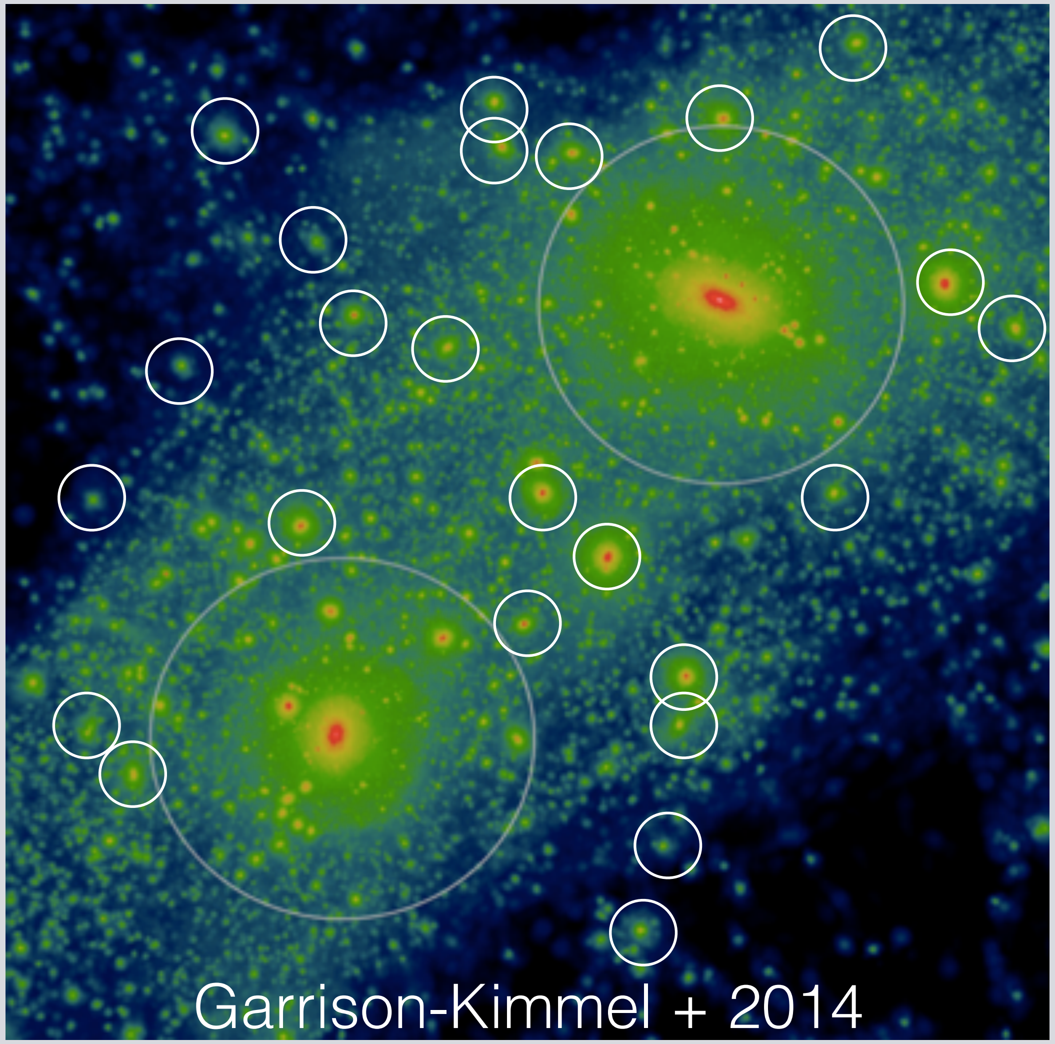
WHERE THINGS GET INTERESTING



Small enough to be abundant

$M_{HALO} = 10^{10}\ M_\odot$

WHERE THINGS GET INTERESTING



☞ Expect **10-20** halos with $M>10^{10}\ M_\odot$ within ~3Mpc of LG [excluding satellites of M31 or MW]

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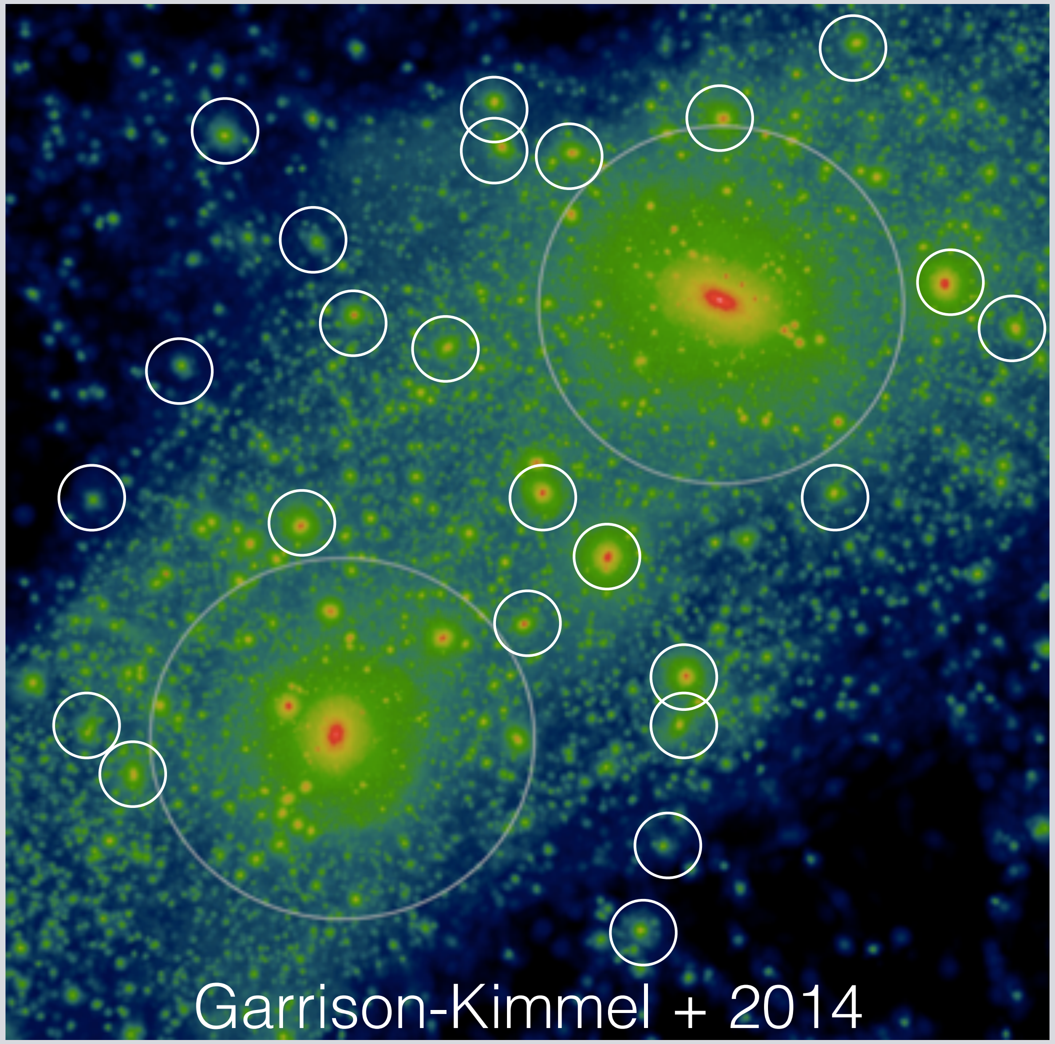


Expect **10-20** halos with $M > 10^{10}\ M_\odot$ within ~3Mpc of LG [excluding satellites of M31 or MW]

Only 4 galaxies with $M_\star > 10^7\ M_\odot$ in this volume around the LG!

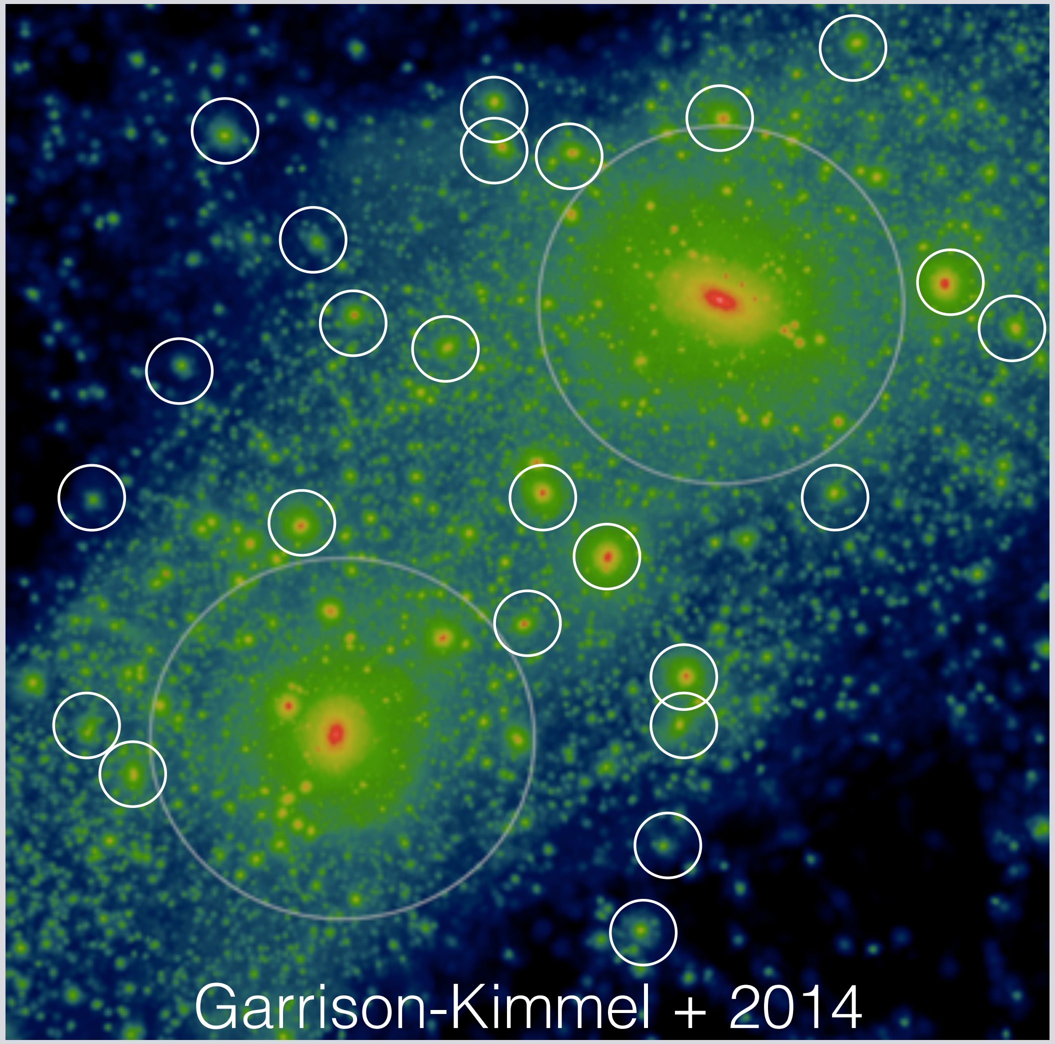
Halos at this mass scale can rarely (if ever) host galaxies as bright as Fornax.

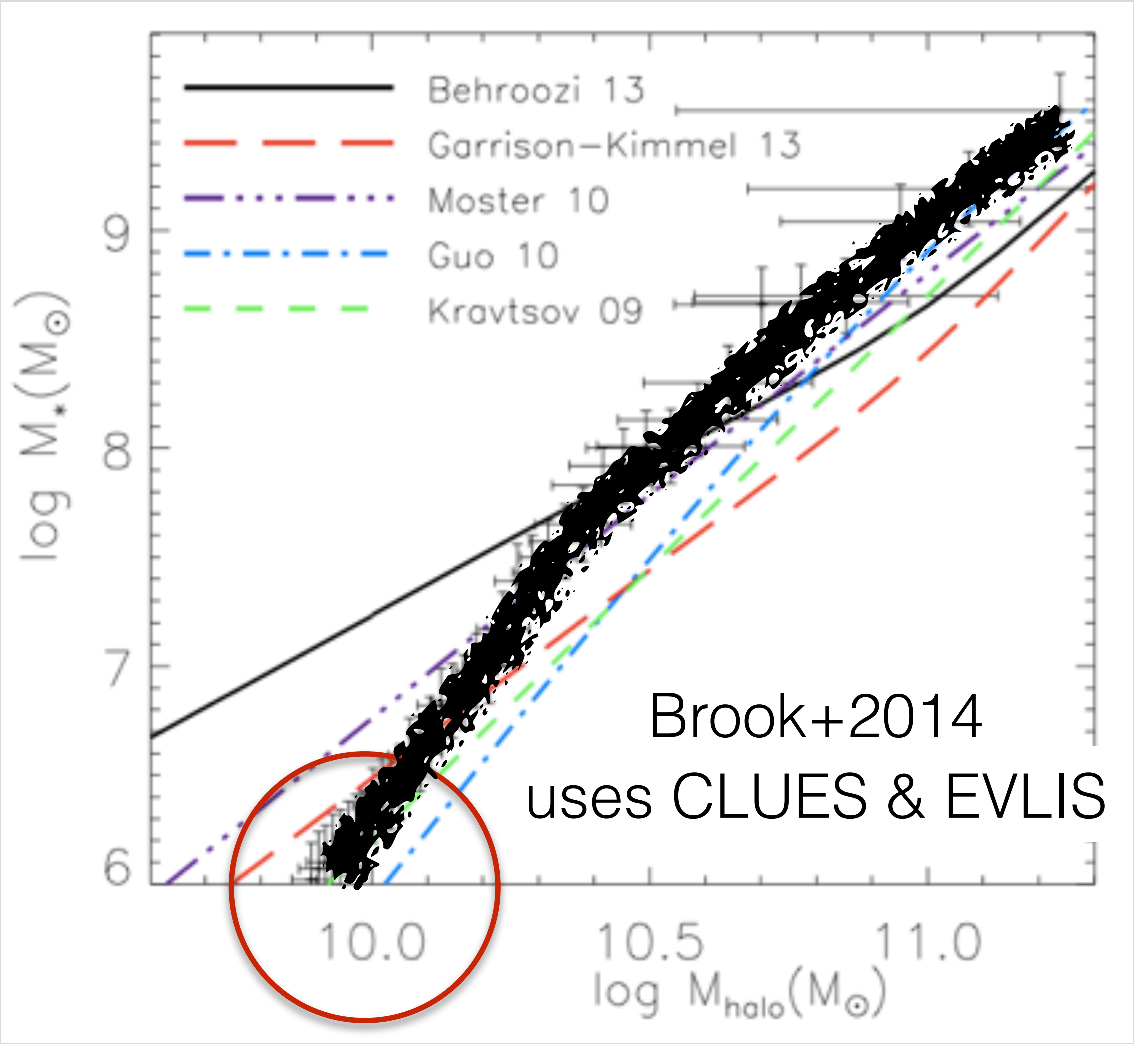
$M_{HALO} = 10^{10} M_\odot \Leftrightarrow M_\star \sim 10^6\ M_\odot$

Small enough to be abundant

$M_{HALO} = 10^{10}\ M_\odot$

WHERE THINGS GET INTERESTING





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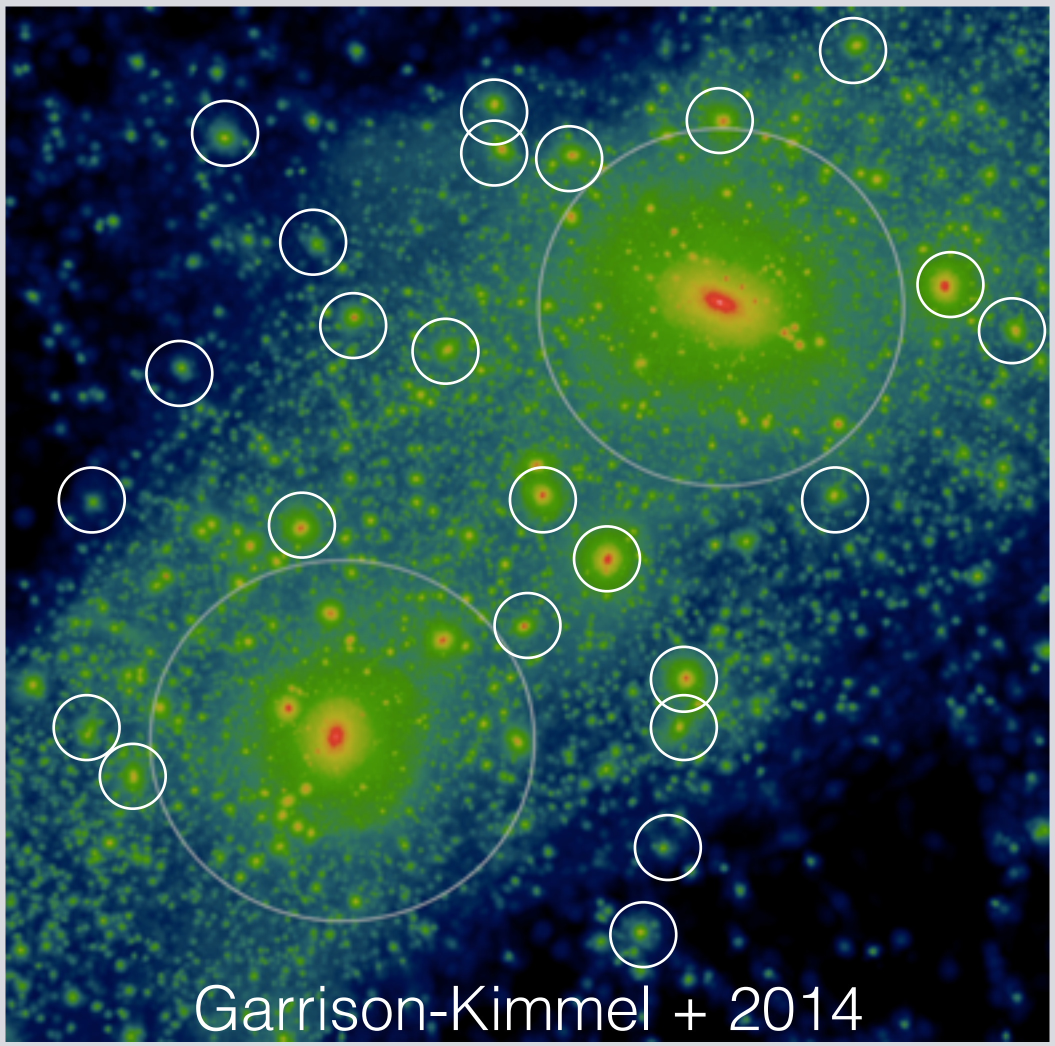
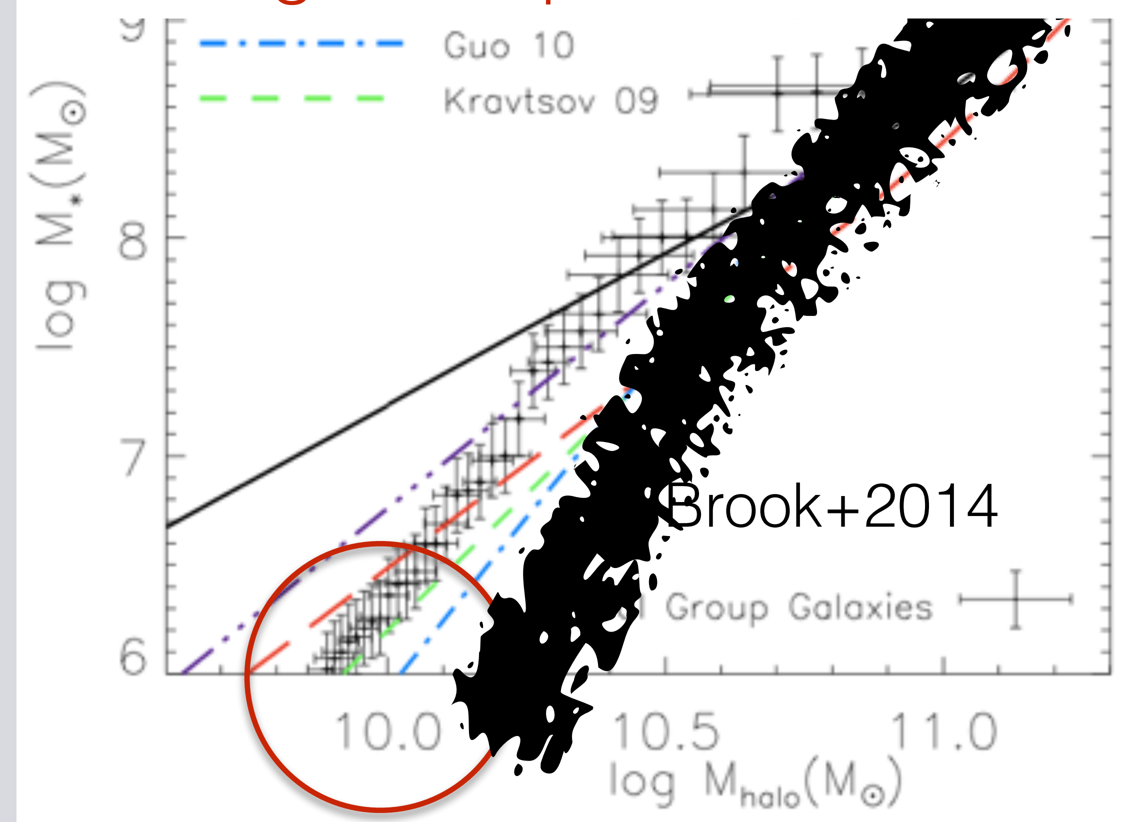


Add scatter: average relation must get steeper!



Small enough to be abundant

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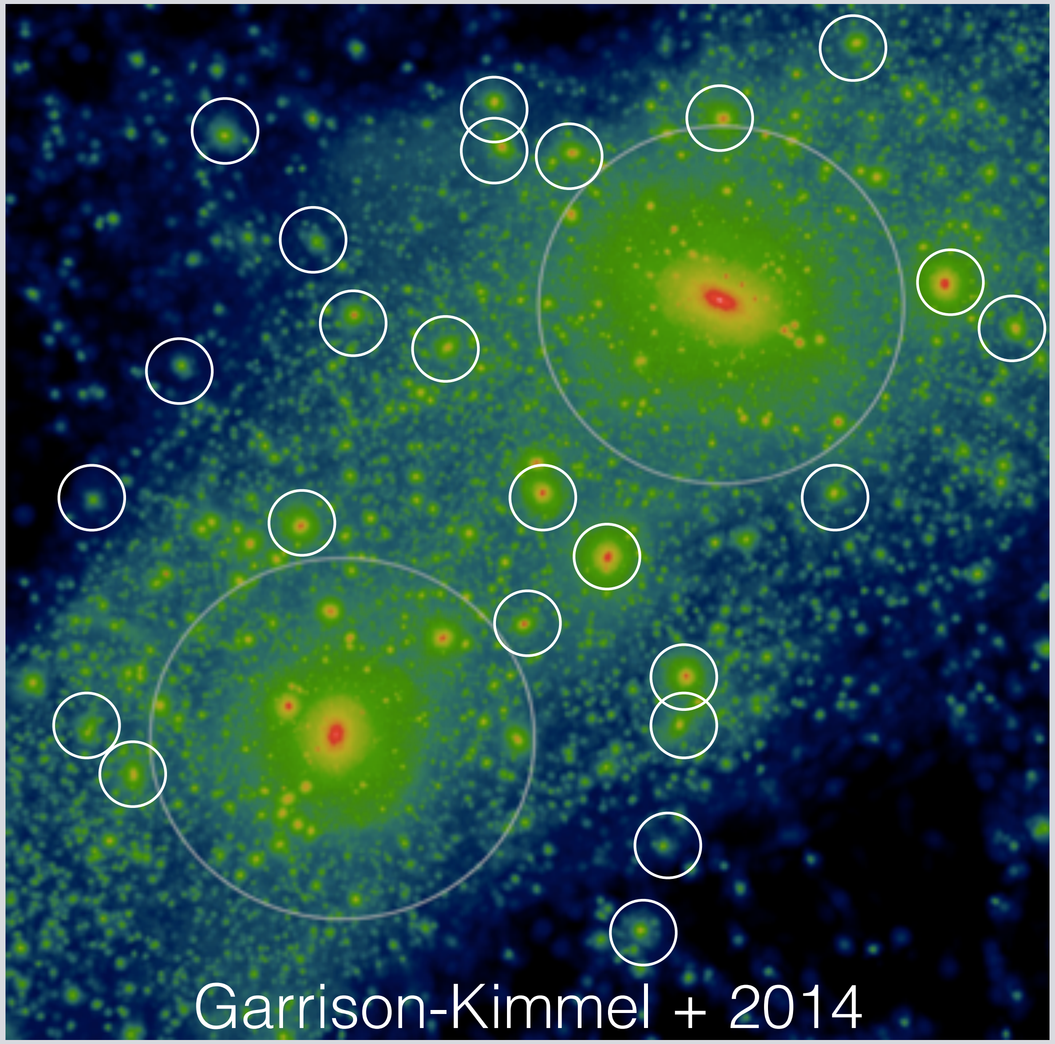

Small enough to be abundant
($M_\star \sim 10^6\ M_\odot$)

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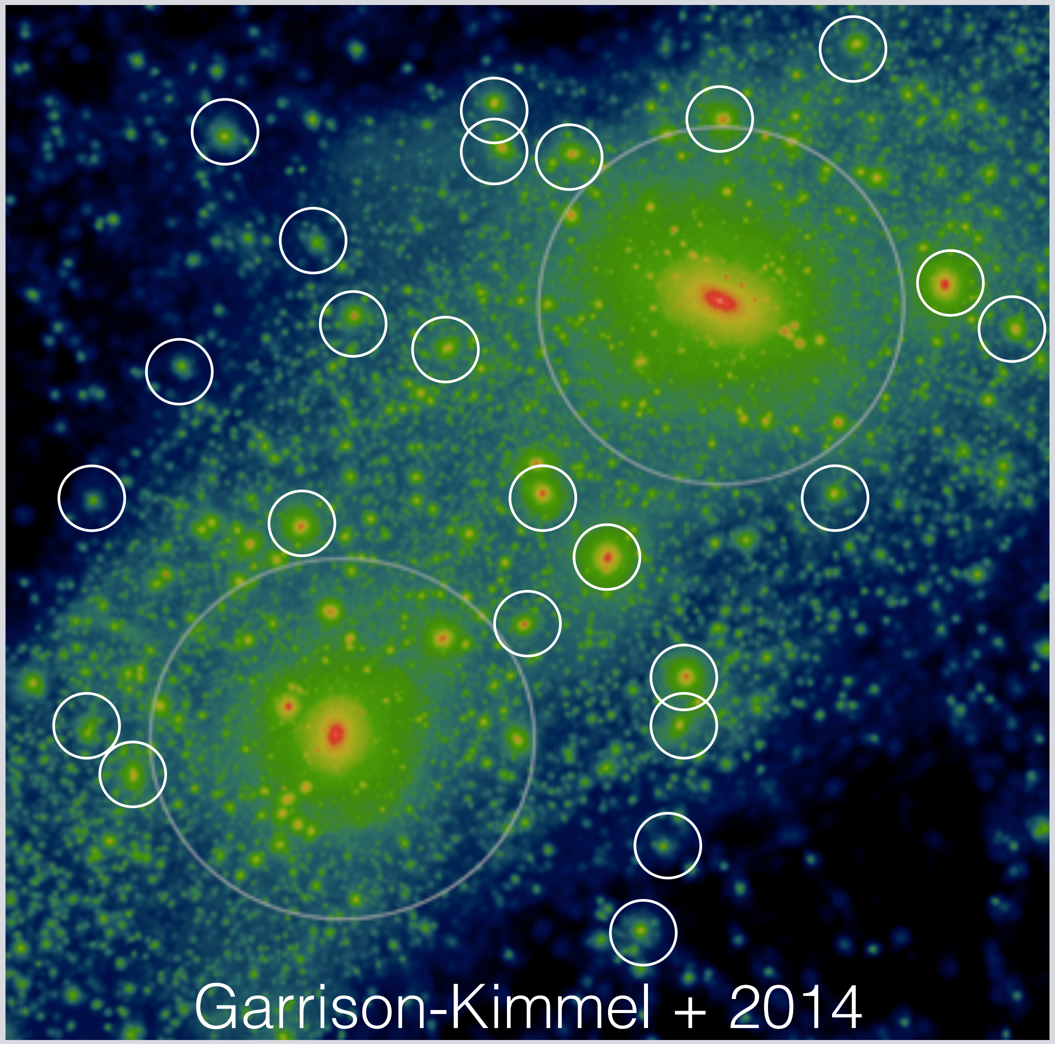
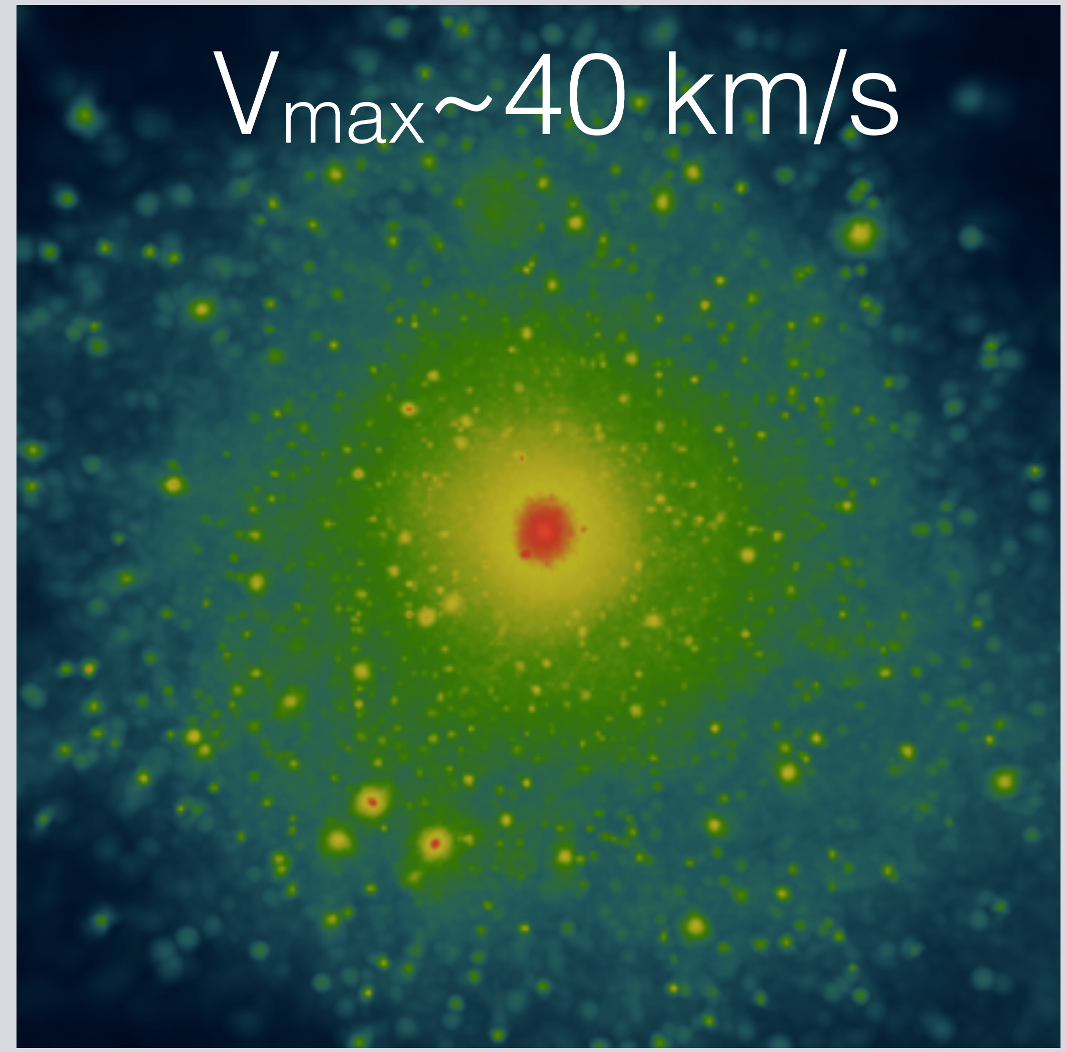
WHERE THINGS GET INTERESTING



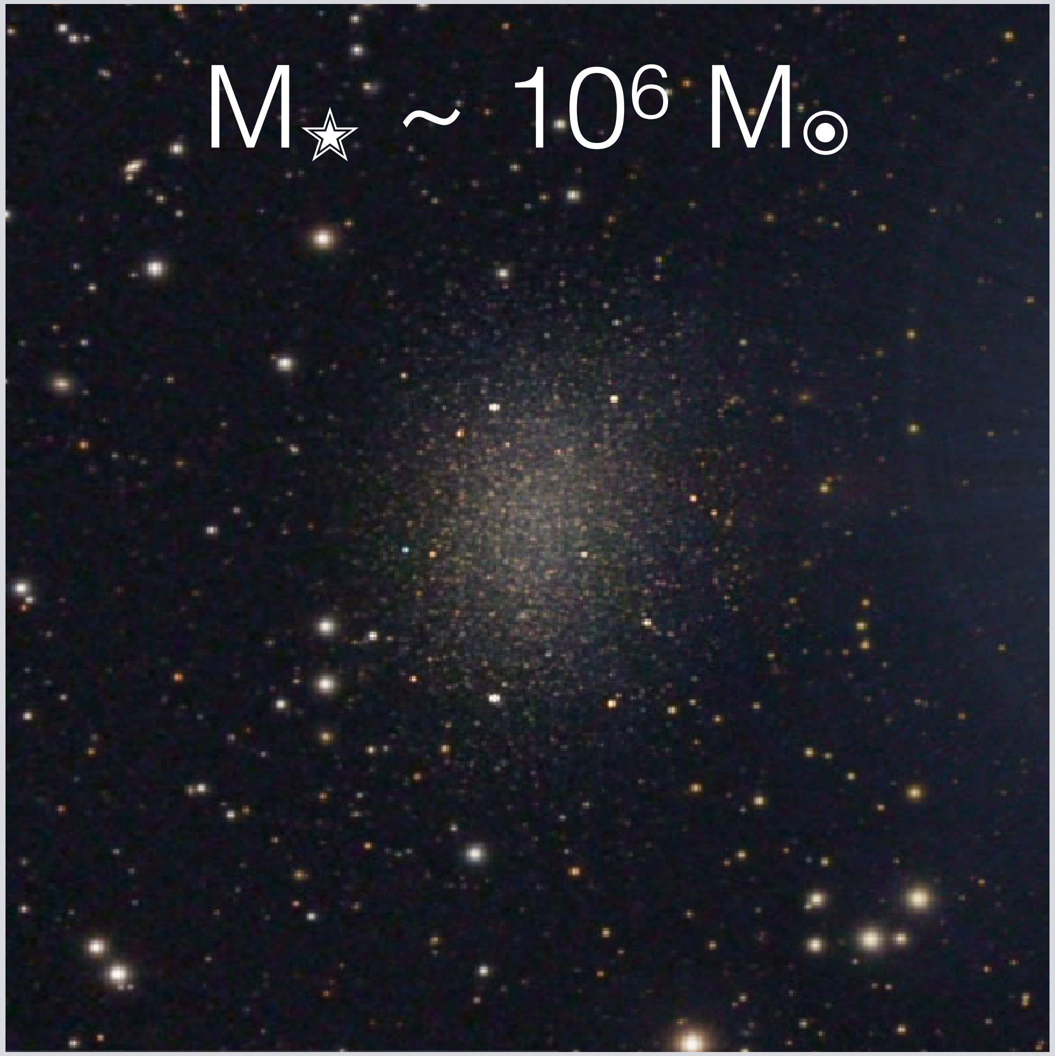


Small enough to be abundant
($M_\star \sim 10^6 M_\odot$)

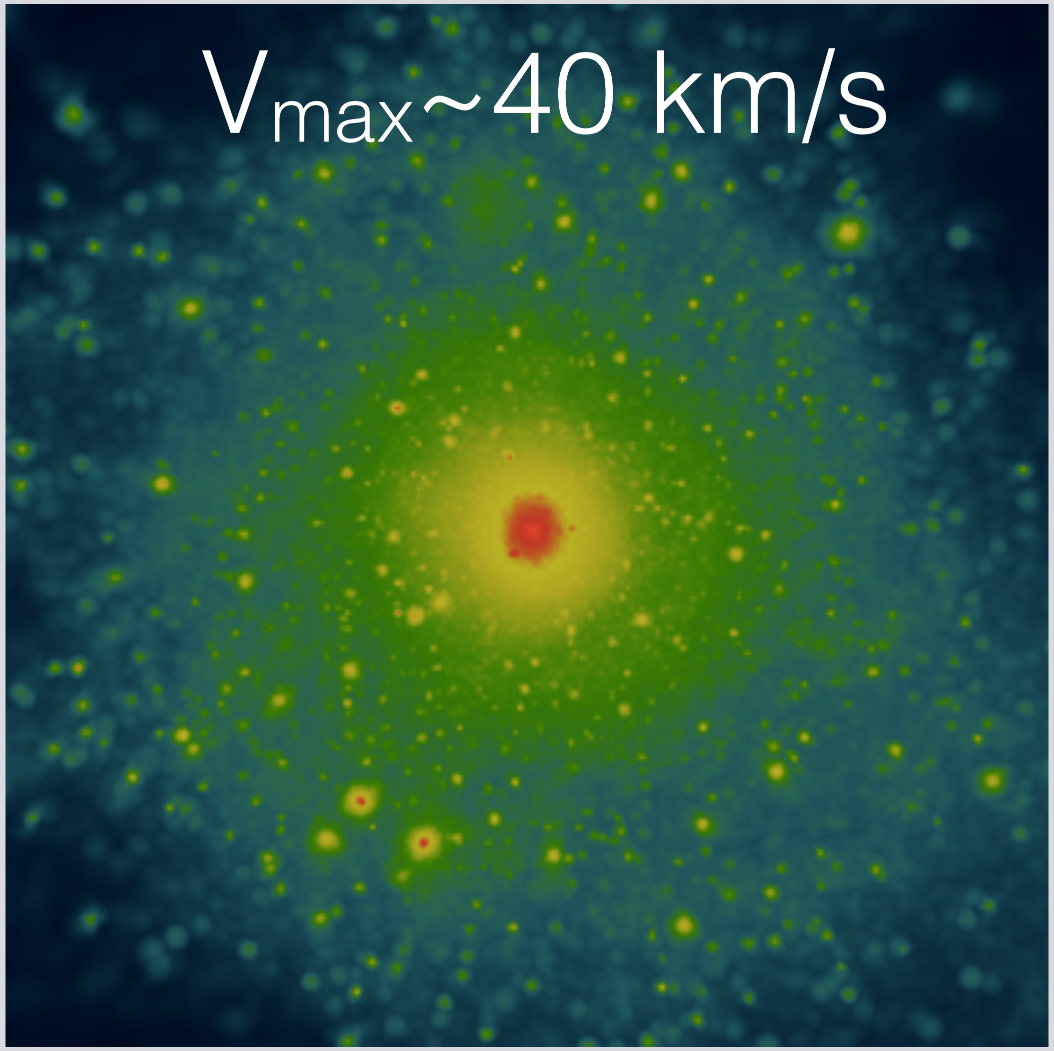
Big enough to be dense
V_{MAX} = 40 km/s

$M_{HALO} = 10^{10} M_\odot \Leftrightarrow M_\star \sim 10^6 M_\odot$

WHERE THINGS GET INTERESTING



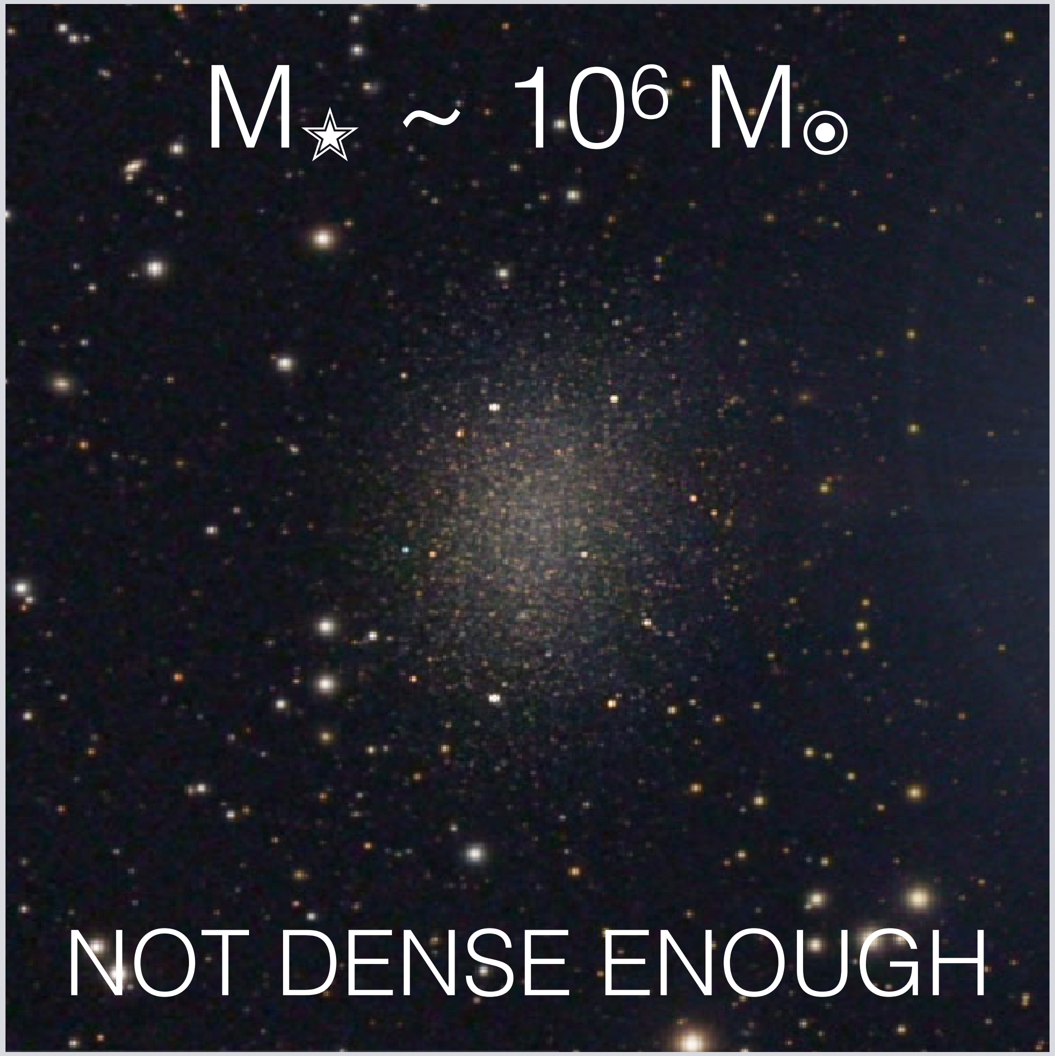
$\Leftrightarrow$



Massive enough that they should always form stars
(Too Big to Fail)

$$M_{HALO} = 10^{10} M_\odot \Leftrightarrow M_\star \sim 10^6 M_\odot$$

WHERE THINGS GET INTERESTING



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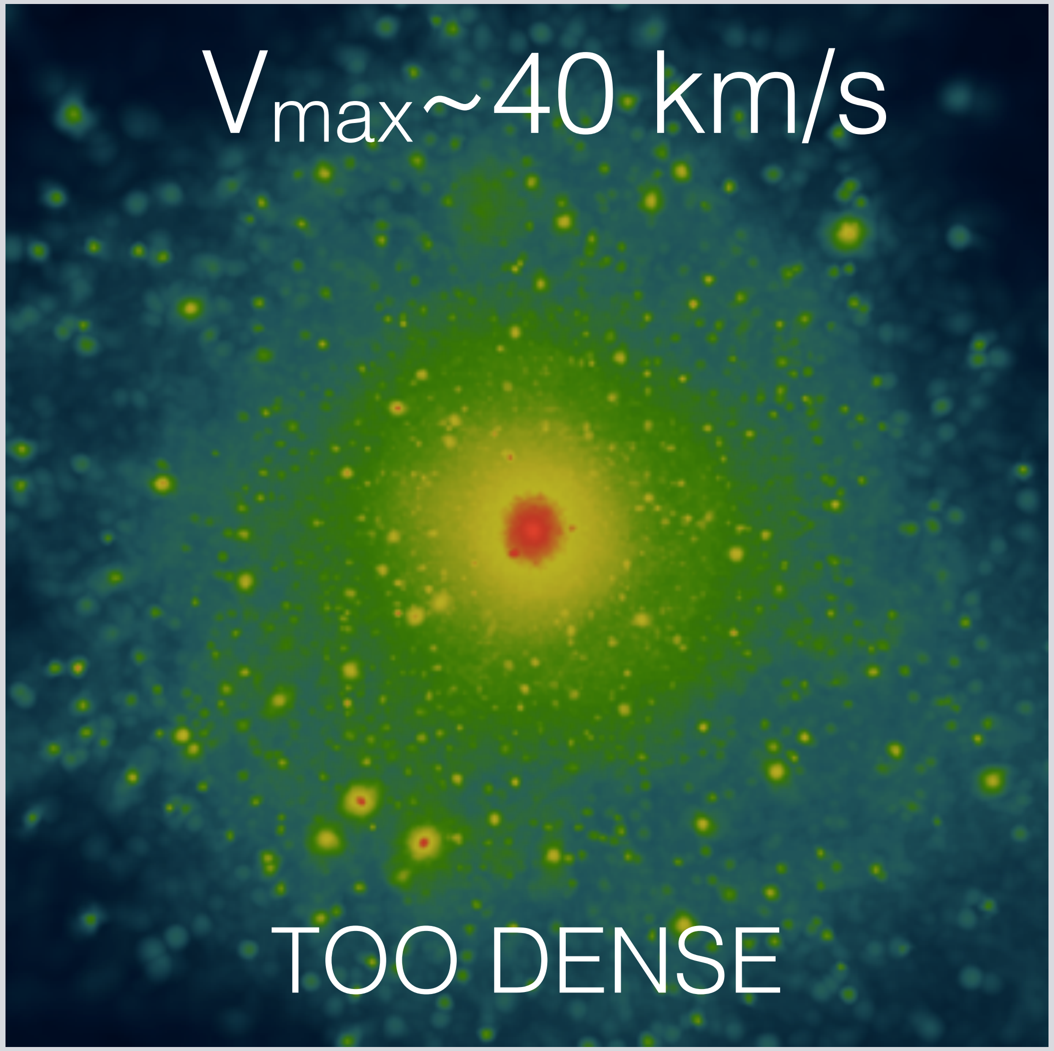

Massive enough that they should always form stars
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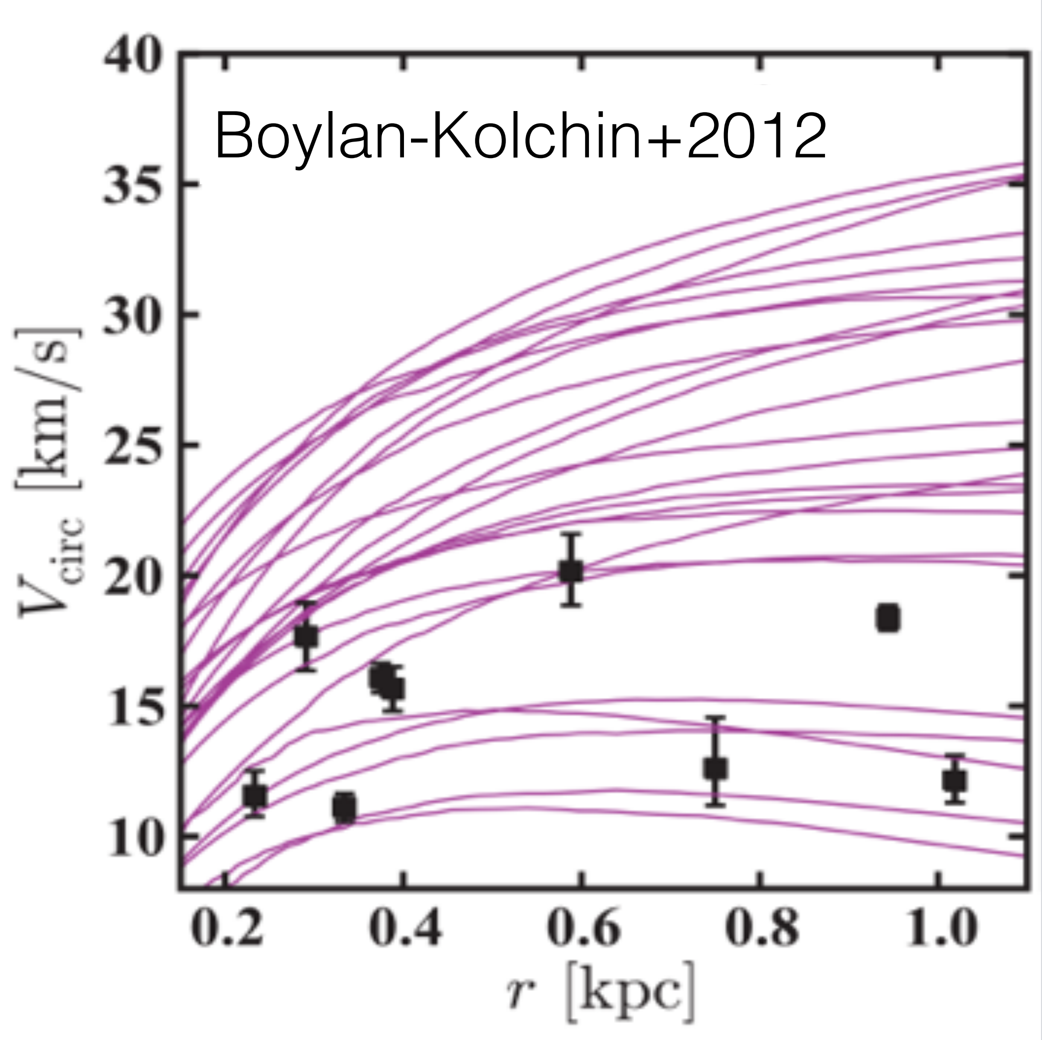
TOO BIG TO FAIL?

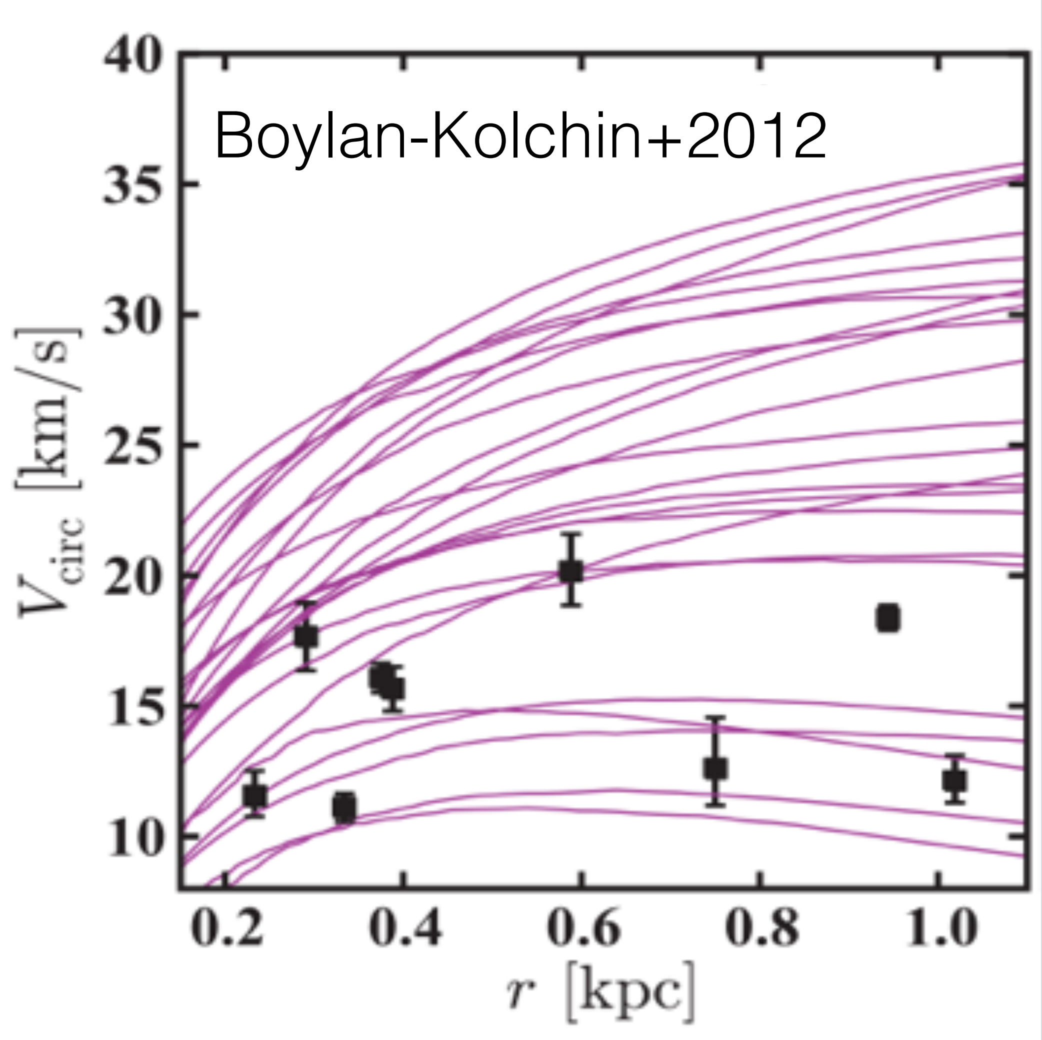
V_{MAX} ~ 40 km/s



↗ IN THE MILKY WAY

TOO BIG TO FAIL?

V_{MAX} ~ 40 km/s

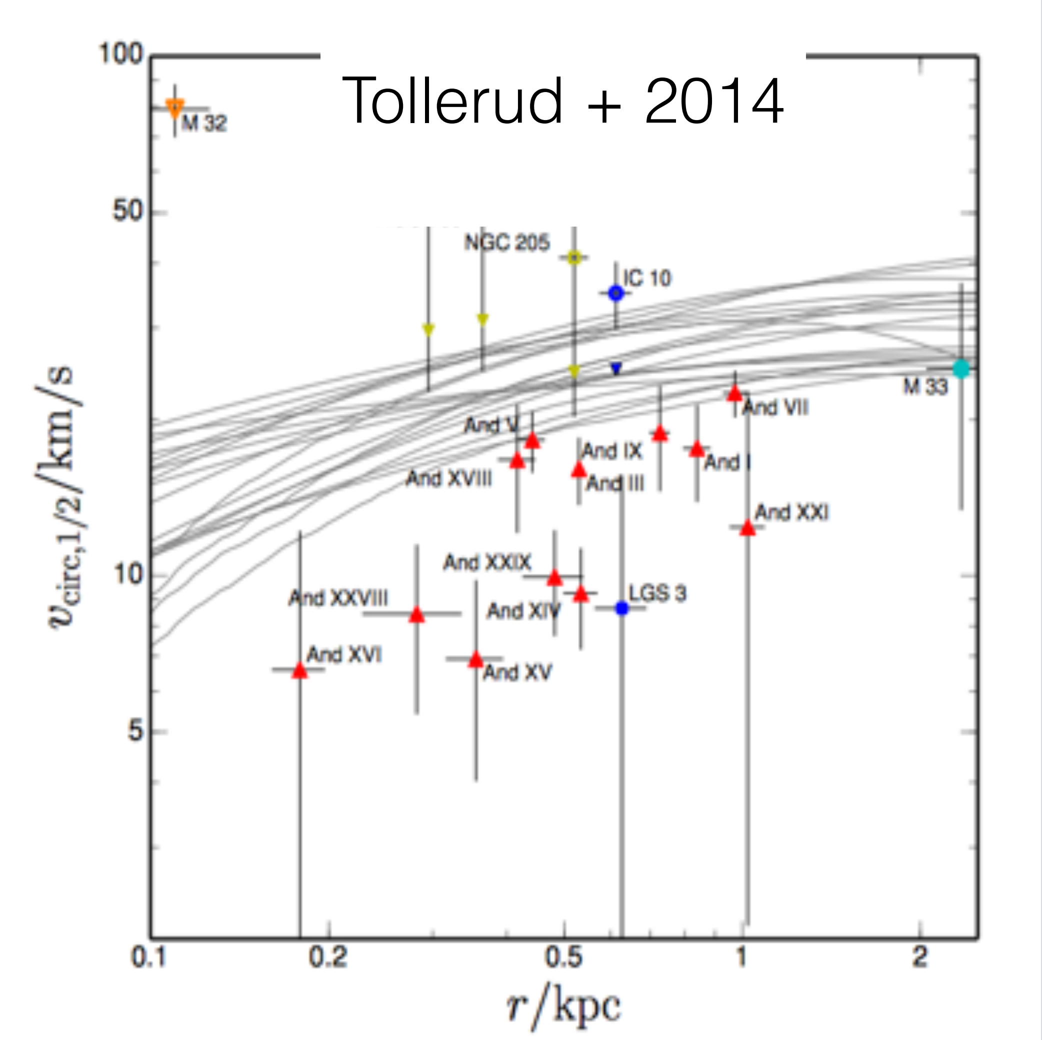


- ☜ Particle data (not fits) from Aquarius
- ☜ Even Aquarius resolution **barely** good enough to reach 500pc

↗ IN THE MILKY WAY

TOO BIG TO FAIL?

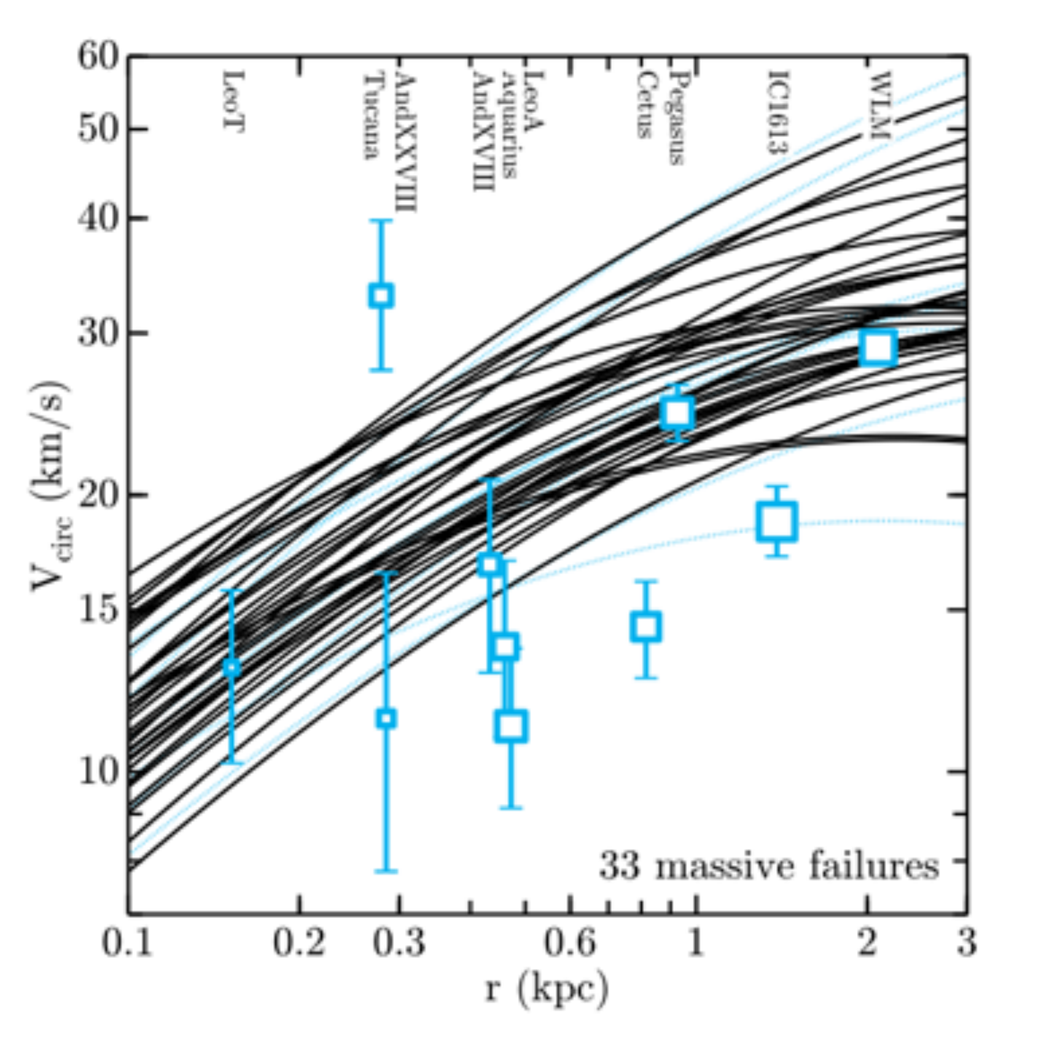
V_{MAX} ~ 40 km/s



☍ IN ANDROMEDA

TOO BIG TO FAIL?

V_{MAX} ~ 40 km/s



Garrison-Kimmel+2014

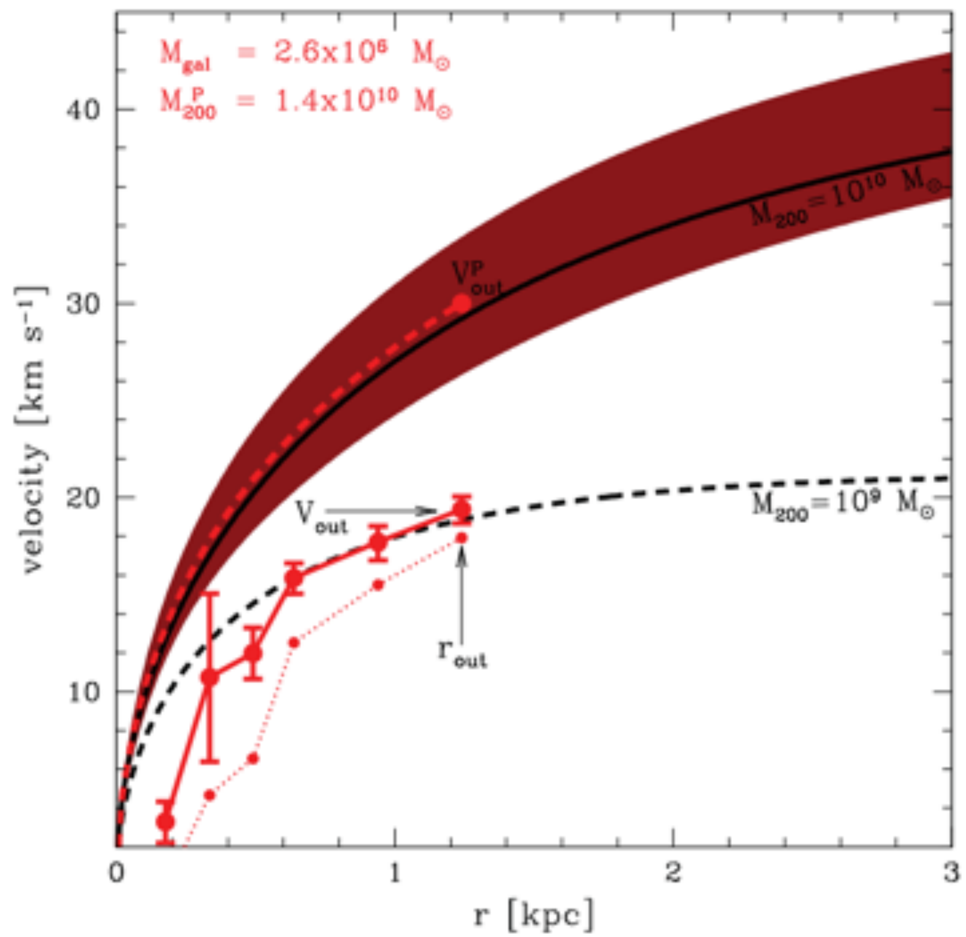
Kirby+2014

☄ IN THE OUTER LOCAL GROUP

TOO BIG TO FAIL?

$V_{MAX} \sim 40$ km/s

Ferrero + 2012

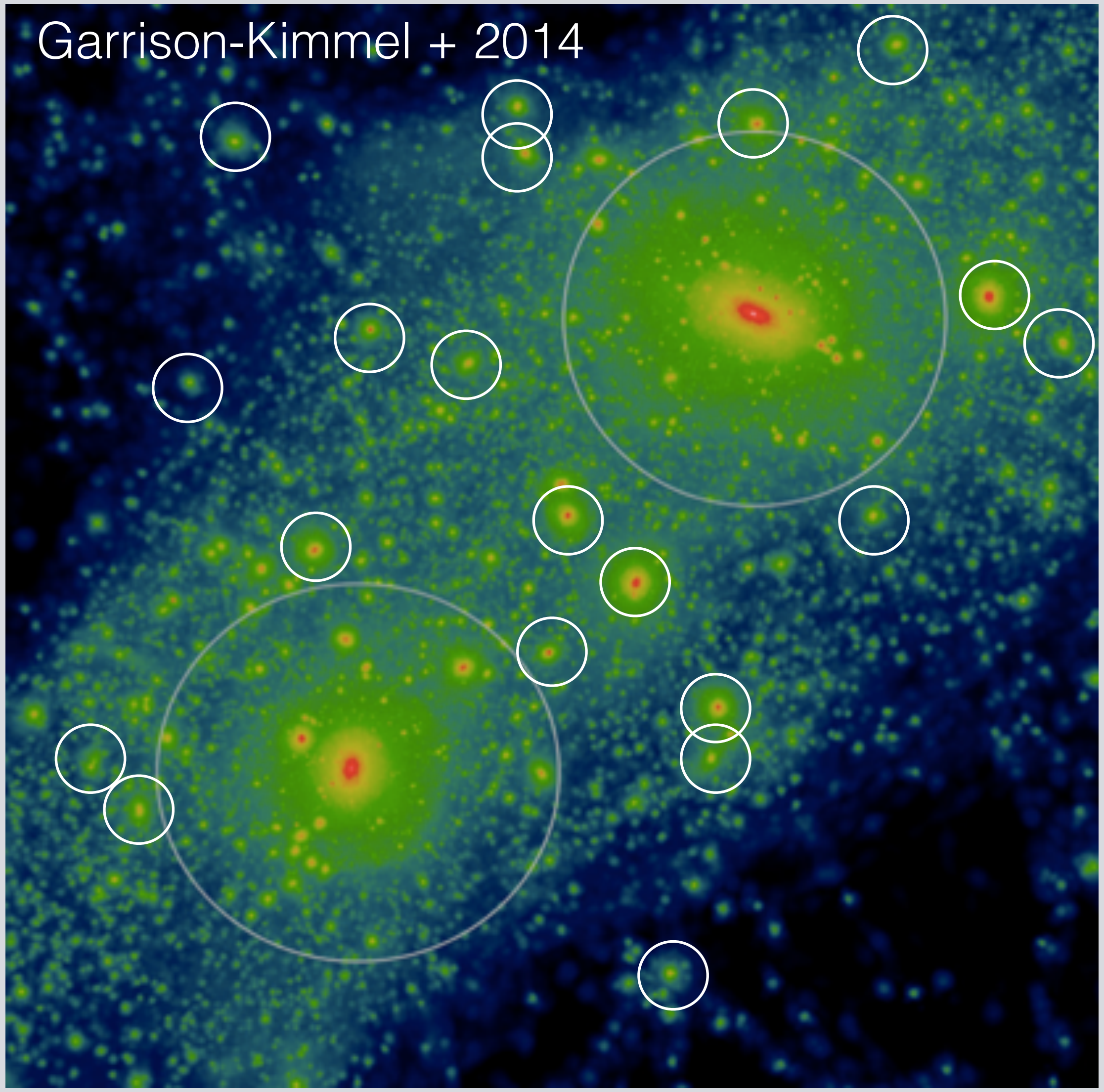


Papastergis+2014
Klypin+2014

IN THE FIELD

TOO BIG TO FAIL?

$V_{MAX} \sim 40$ km/s

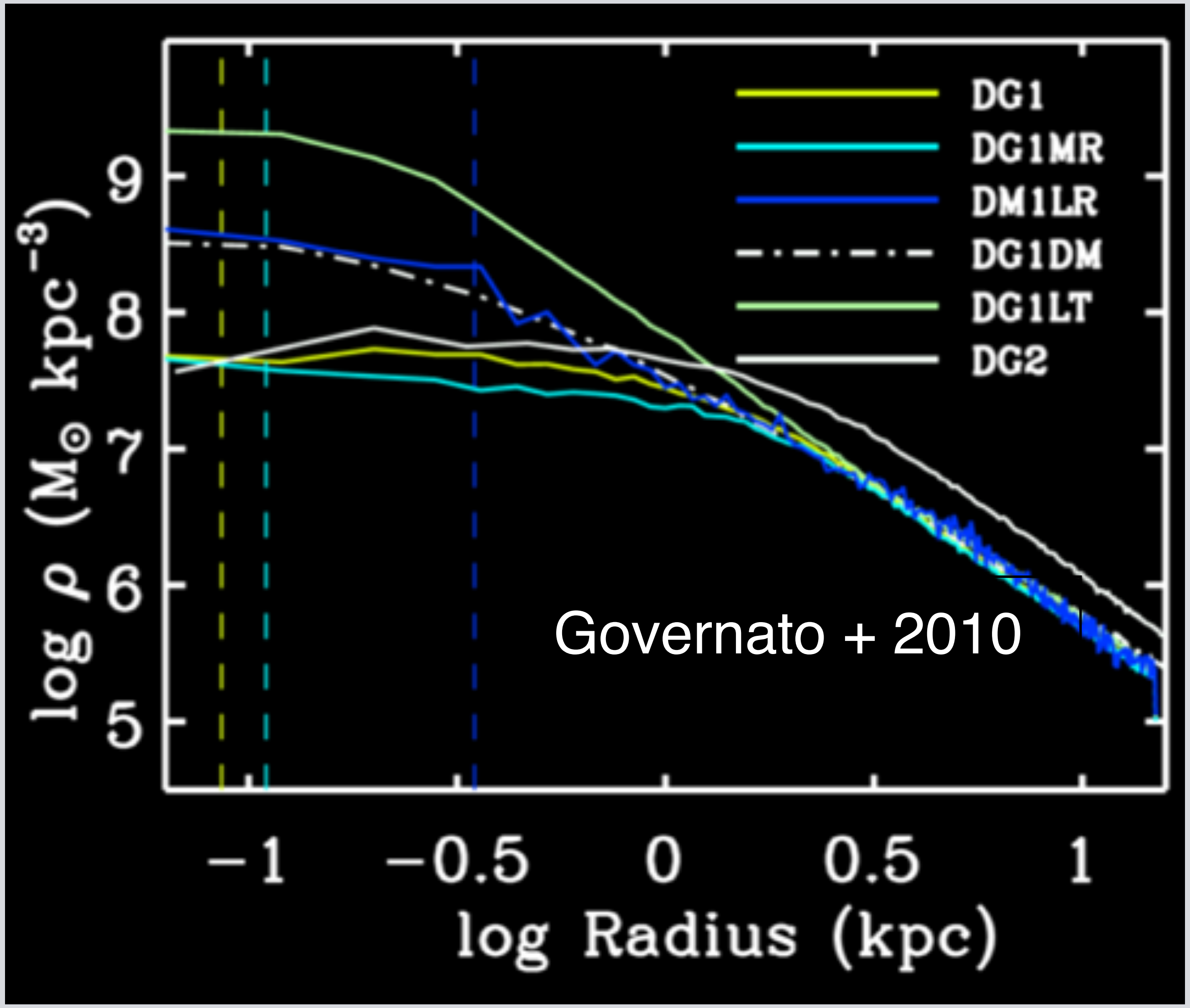


Past suggestions:
- Environment
- Statistical flukes
- Milky Way mass

All of these are unsatisfying in the face of growing ubiquity of the problem

WHAT ABOUT FEEDBACK?

NAVARRO ET AL. 1996

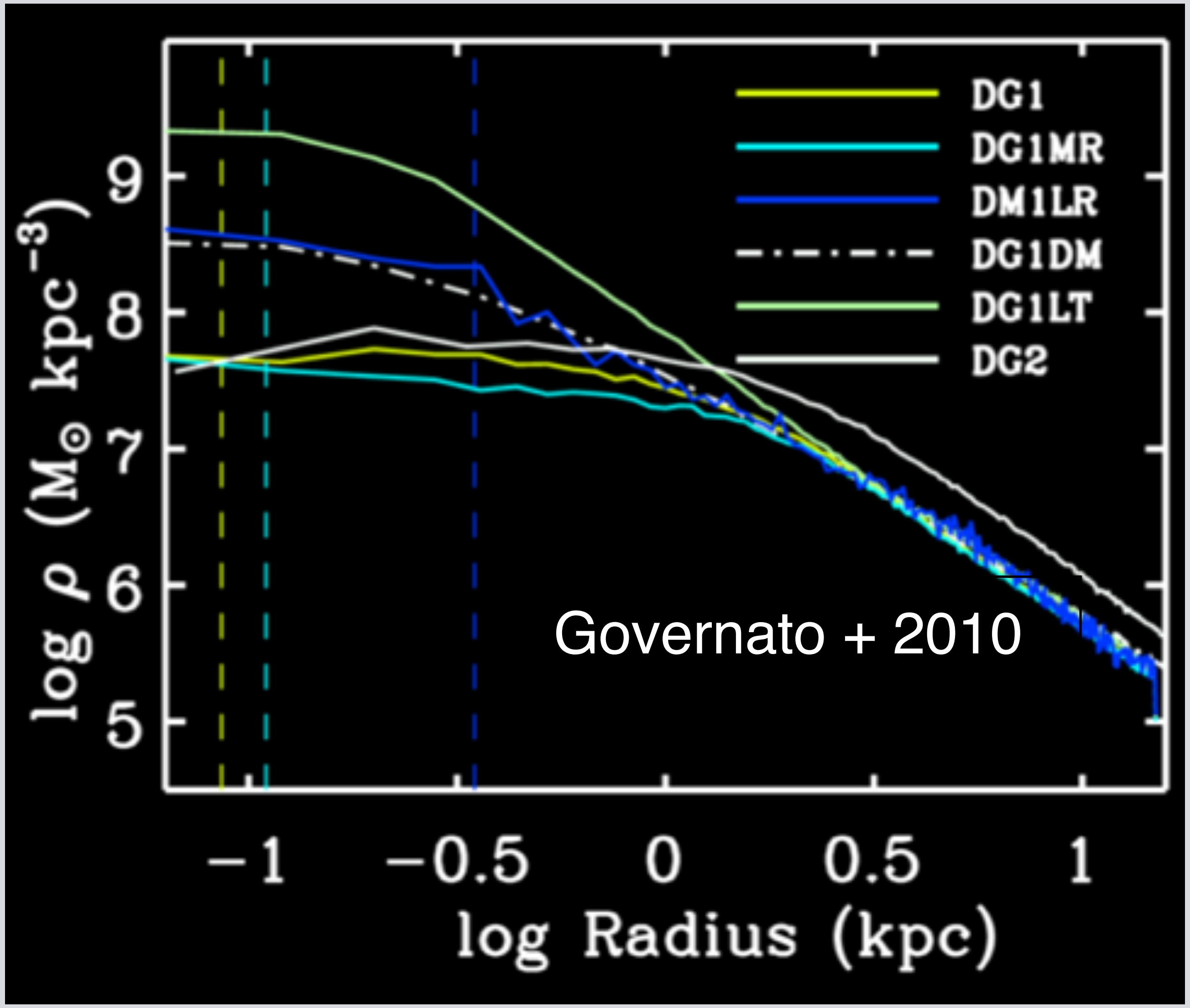


WHAT ABOUT FEEDBACK?

DO $M_\star \sim 10^6\ M_\odot$ GALAXIES HAVE ENOUGH ENERGY?

☞

Galaxies in these simulations all make $>10^7\ M_\odot$ of stars



Penarrubia+2012; Garrison-Kimmel+2013

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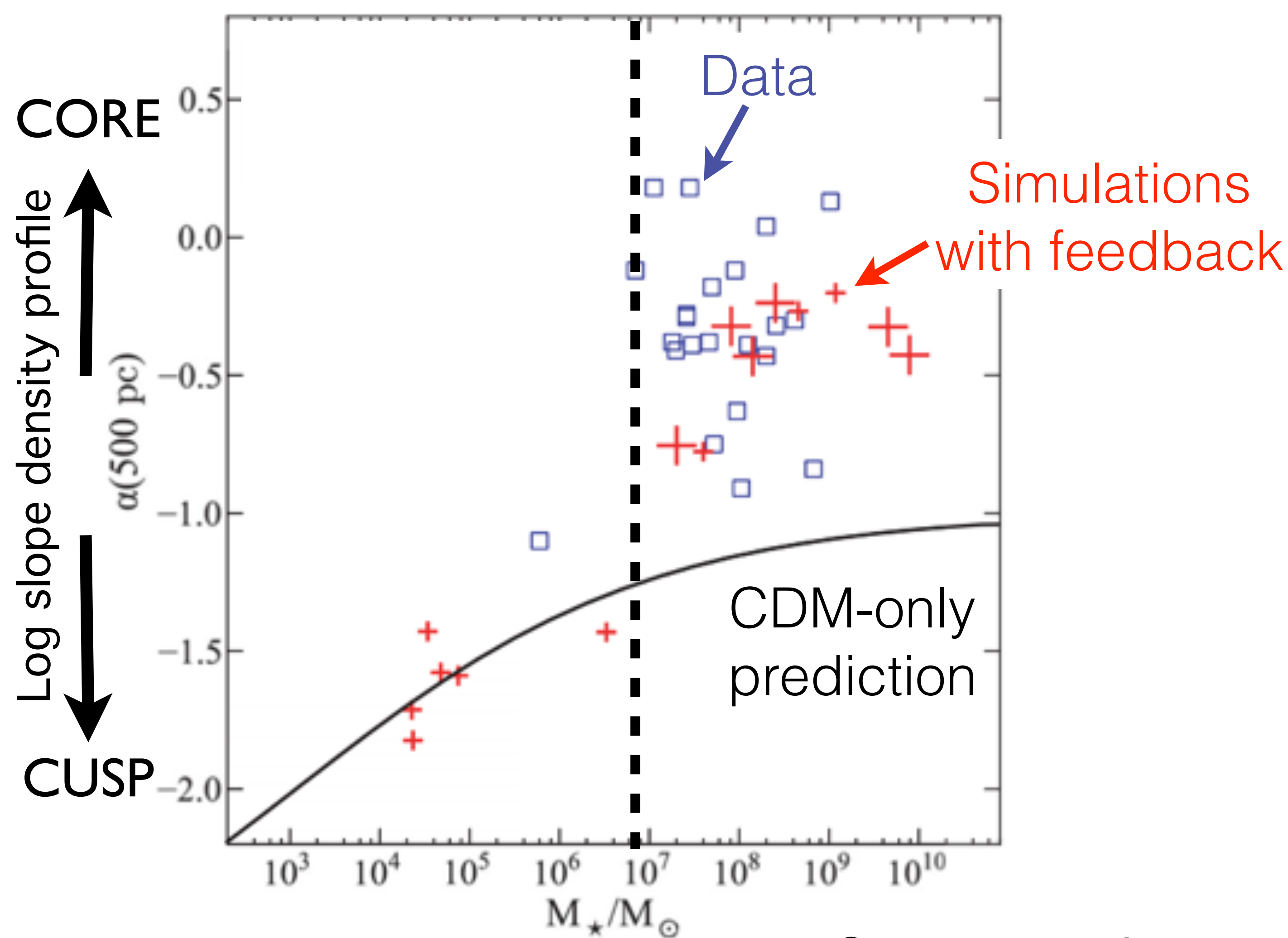

Governato et al. 2012

Penarrubia+2012; Garrison-Kimmel+2013

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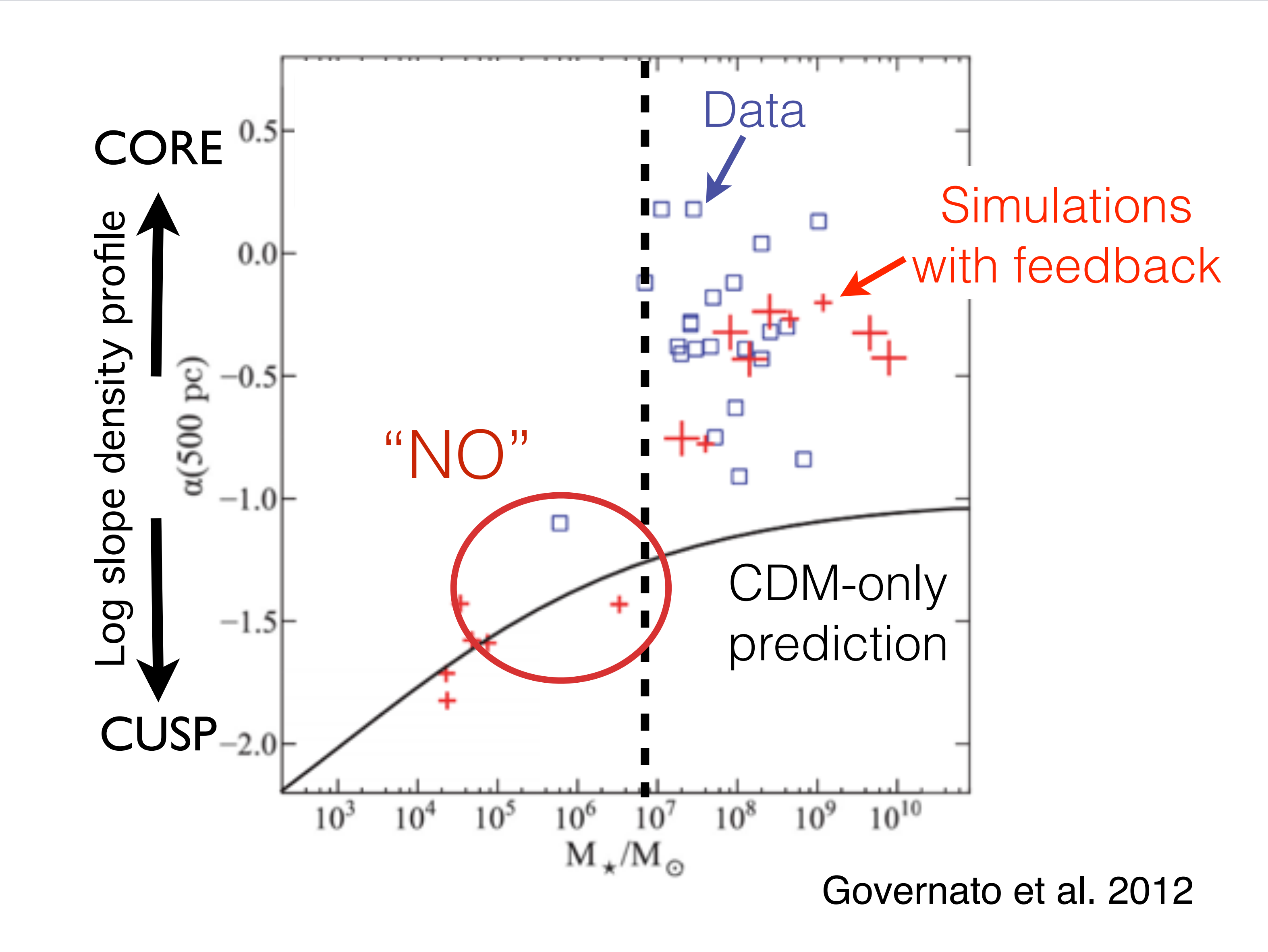

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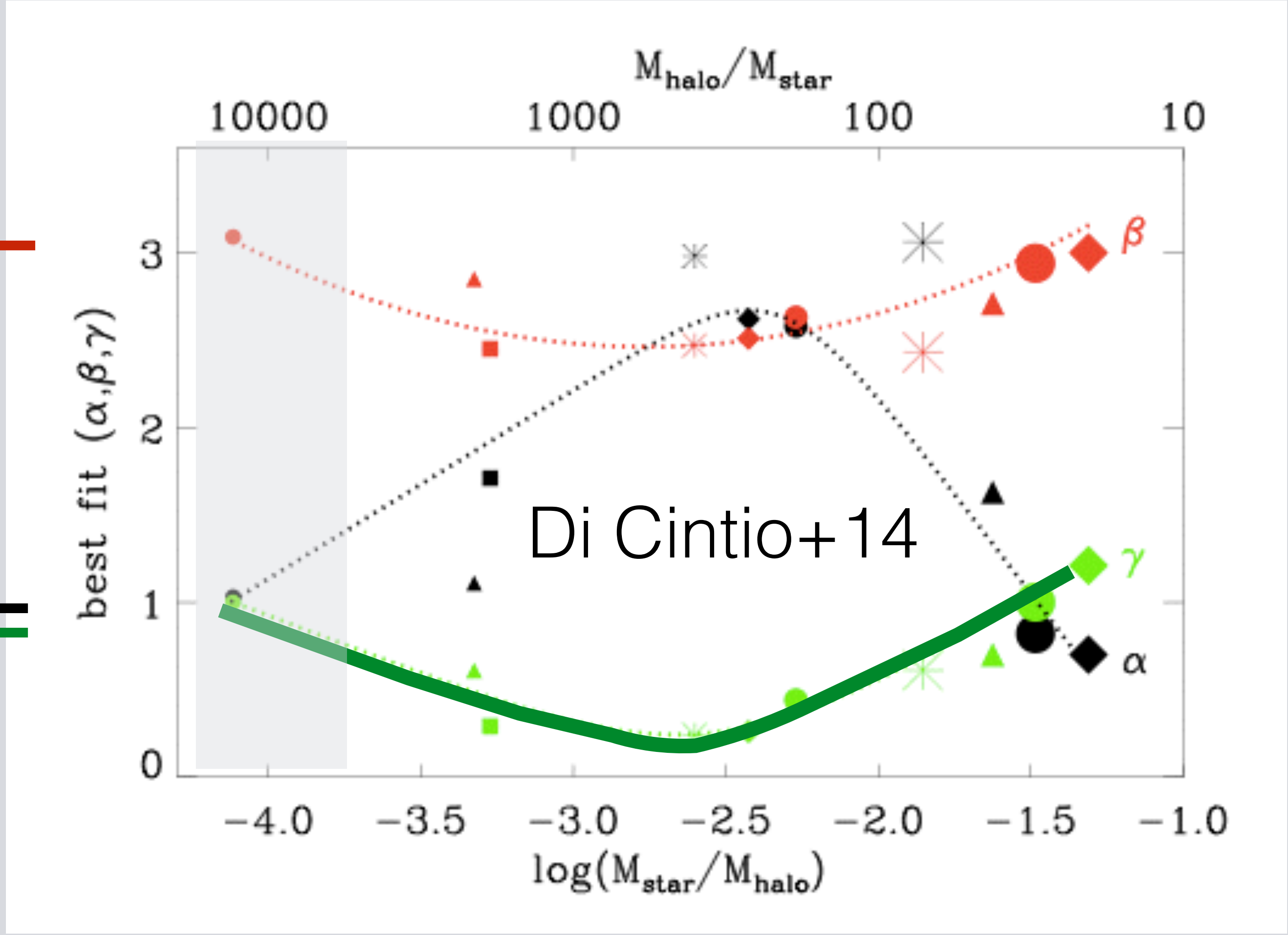
DO $M_{\star} \sim 10^6\ M_{\odot}$ GALAXIES HAVE ENOUGH ENERGY?

NFW values

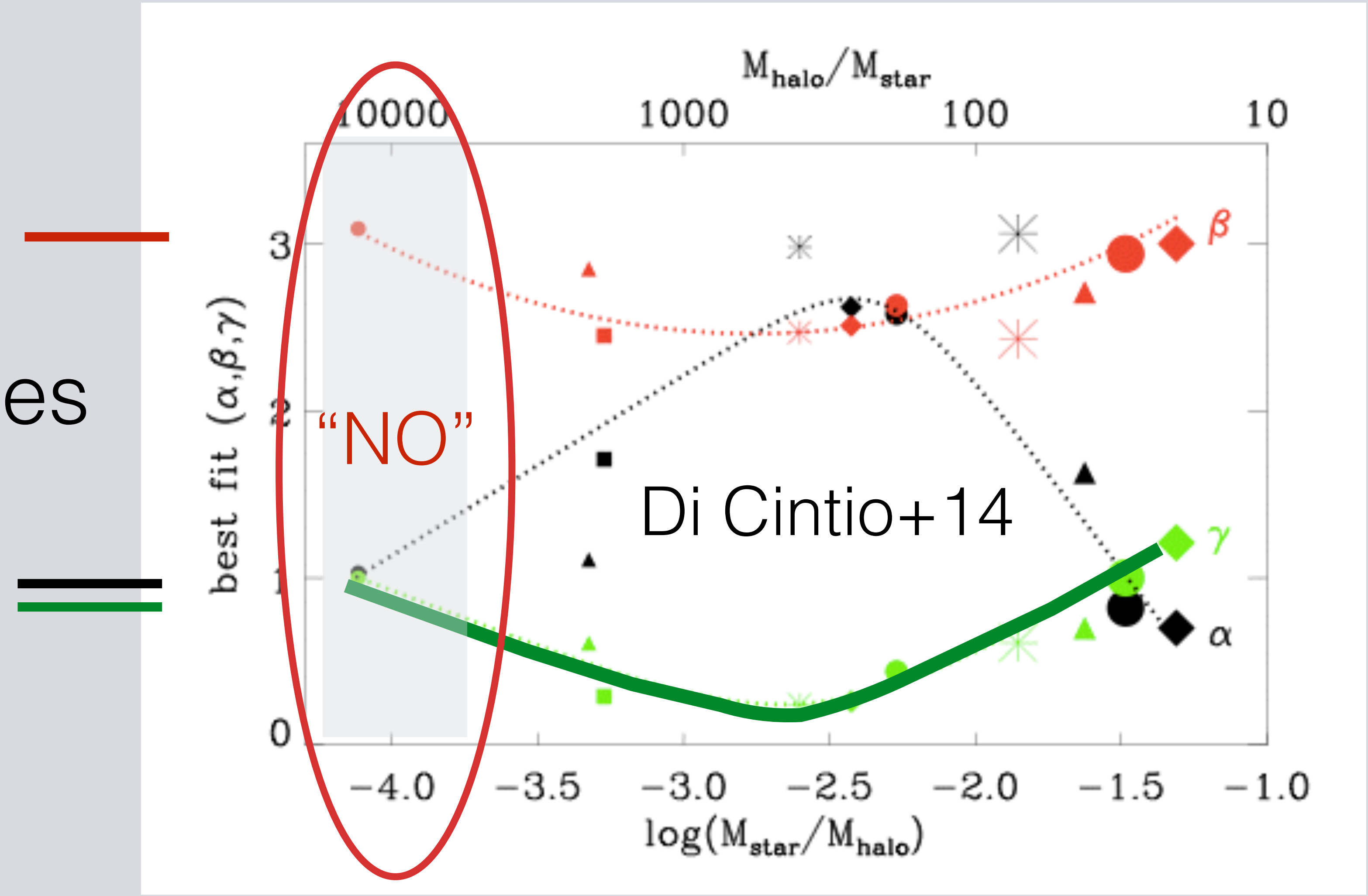


Penarrubia+2012; Garrison-Kimmel+2013

WHAT ABOUT FEEDBACK?

DO $M_{\star}$~10^6 $M_{\odot}$ GALAXIES HAVE ENOUGH ENERGY?

NFW values



$M_{HALO}=10^{10}M_{\odot}$ ⟺ $M_{\star}$ ~ 10^6 $M_{\odot}$

Penarrubia+2012; Garrison-Kimmel+2013

Jose Oñorbe

DWARF GALAXIES ON FIRE

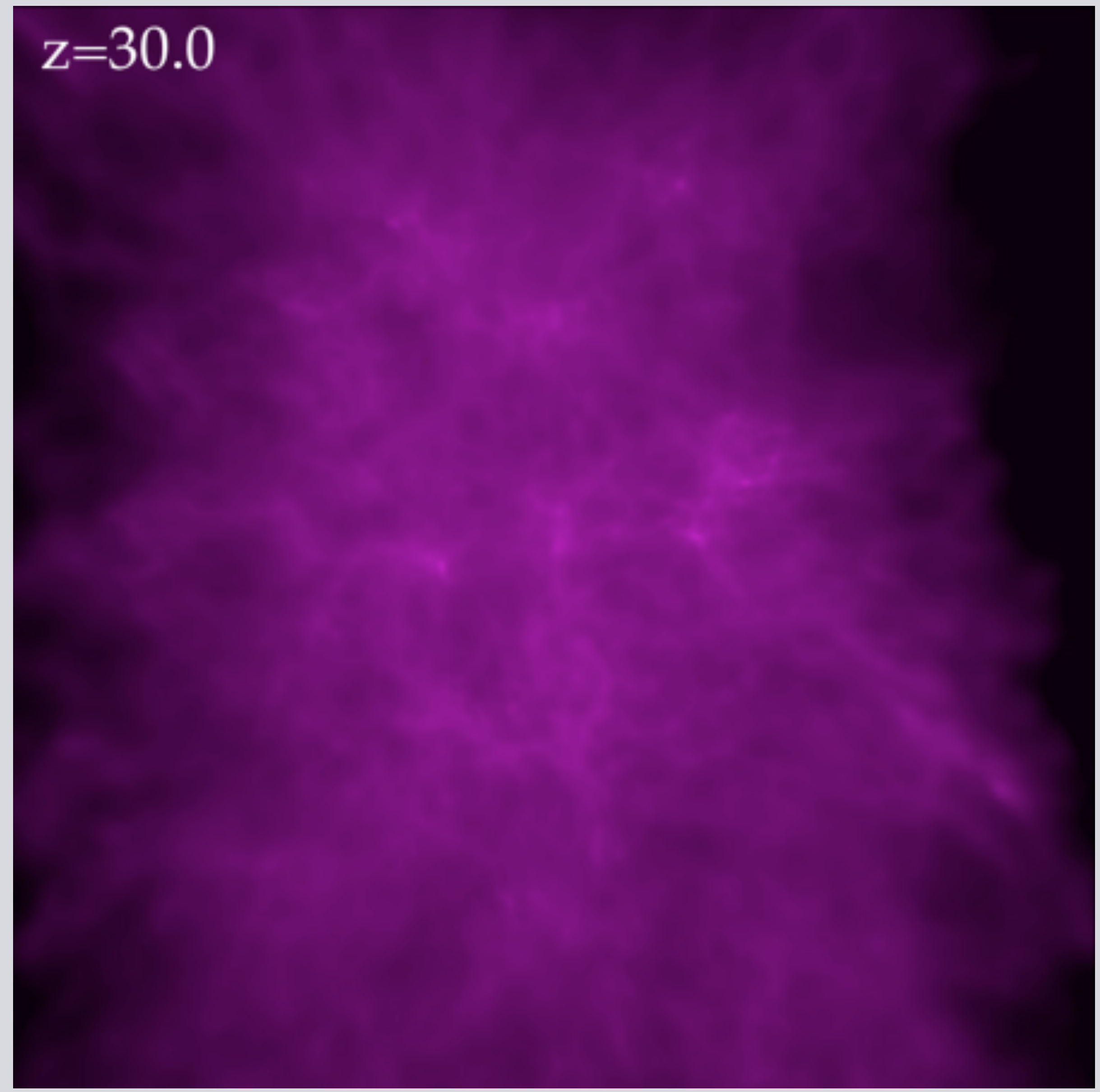
OÑORBE, BOYLAN-KOLCHIN, JSB, HOPKINS, KERES

$m_{dm} \sim 1000\ M_\odot$
$m_{gas} \sim 250\ M_\odot$
$f_{res} \sim 25pc$

$\Rrightarrow$ as **required** to resolve dynamics @300pc

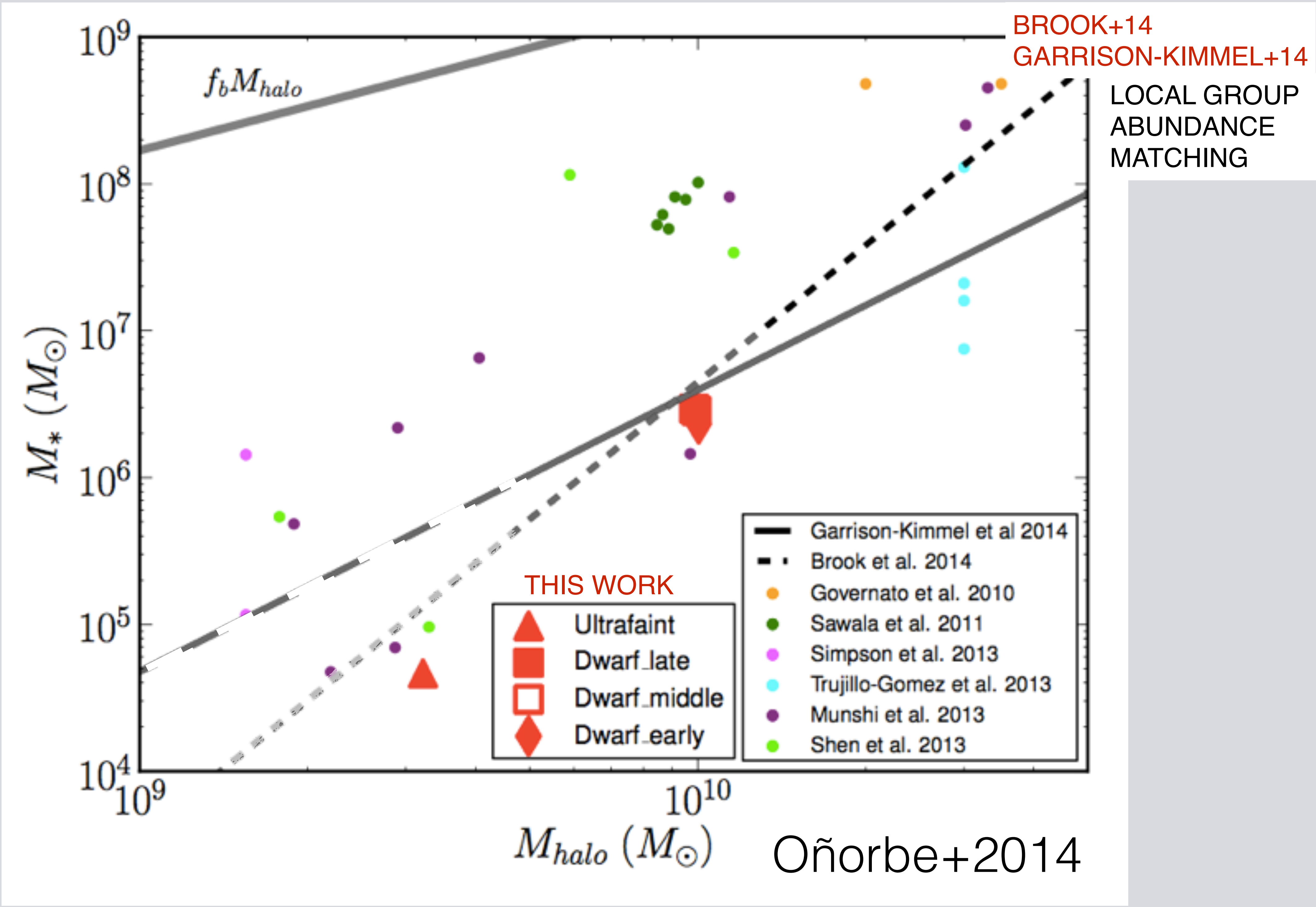
<u>3 Dwarf Runs</u>:
- $M_{HALO}=10^{10}\ M_\odot$
- Identical ICs
- Small changes to subgrid energy injection method
- All form $M_\star \sim 10^6\ M_\odot$

1 <u>Ultrafaint Dwarf Run</u>:
- $M_{HALO}=3.10^9\ M_\odot$
- forms $M_\star \sim 10^4\ M_\odot$

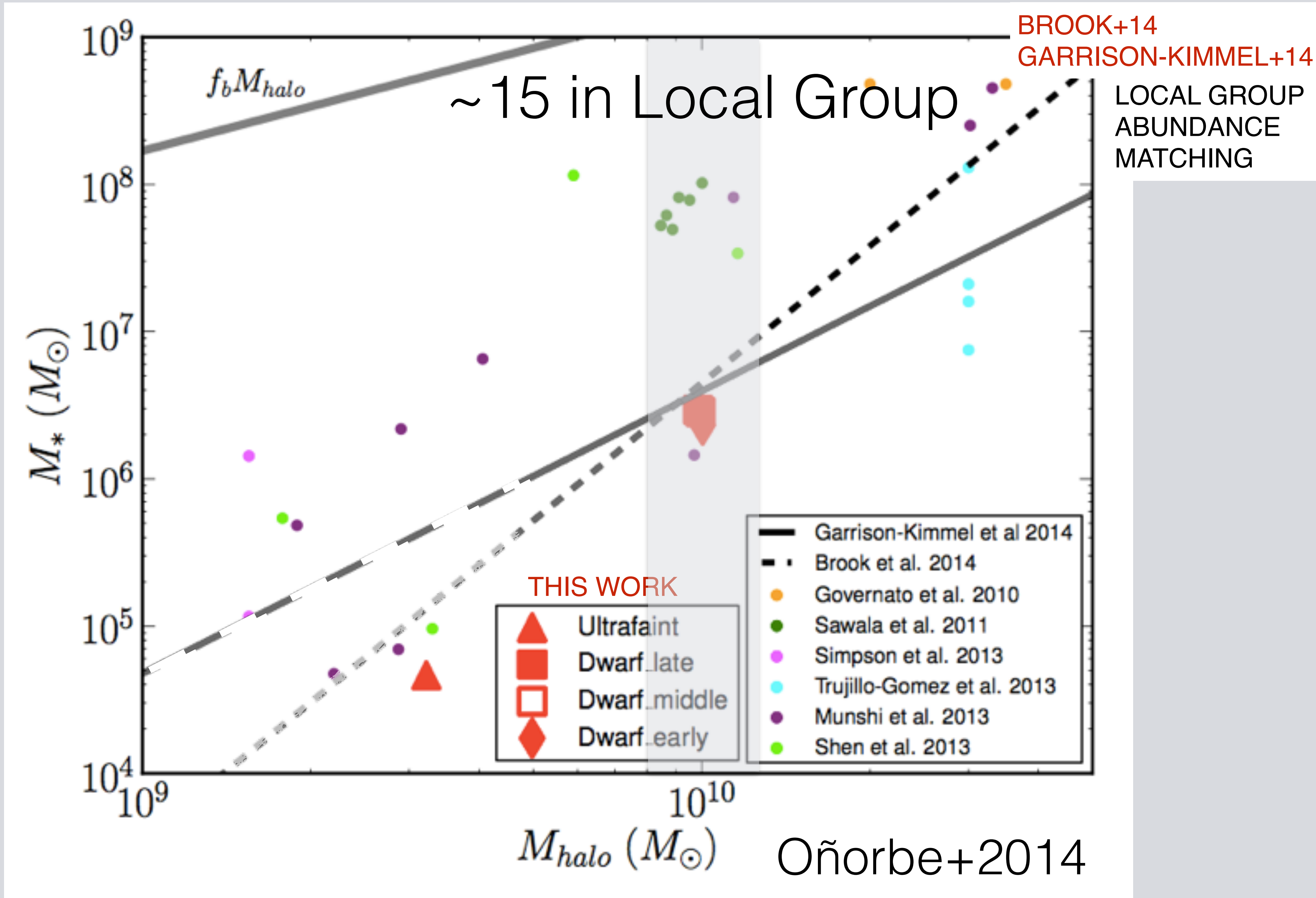


HOPKINS

M★ VS. MHALO


BROOK+14
GARRISON-KIMMEL+14
LOCAL GROUP
ABUNDANCE
MATCHING
$f_b M_{halo}$
$M_*\ (M_\odot)$
$M_{halo}\ (M_\odot)$
10^4
10^5
10^6
10^7
10^8
10^9
10^{10}
THIS WORK
Ultrafaint
Dwarf_late
Dwarf_middle
Dwarf_early
Garrison-Kimmel et al 2014
Brook et al. 2014
Governato et al. 2010
Sawala et al. 2011
Simpson et al. 2013
Trujillo-Gomez et al. 2013
Munshi et al. 2013
Shen et al. 2013
Oñorbe+2014

M⋆ vs. MHALO



BROOK+14
GARRISON-KIMMEL+14
LOCAL GROUP
ABUNDANCE
MATCHING
~15 in Local Group
$f_b M_{halo}$
M_* ($M_\odot$)
M_{halo} ($M_\odot$)
THIS WORK
Ultrafaint
Dwarf_late
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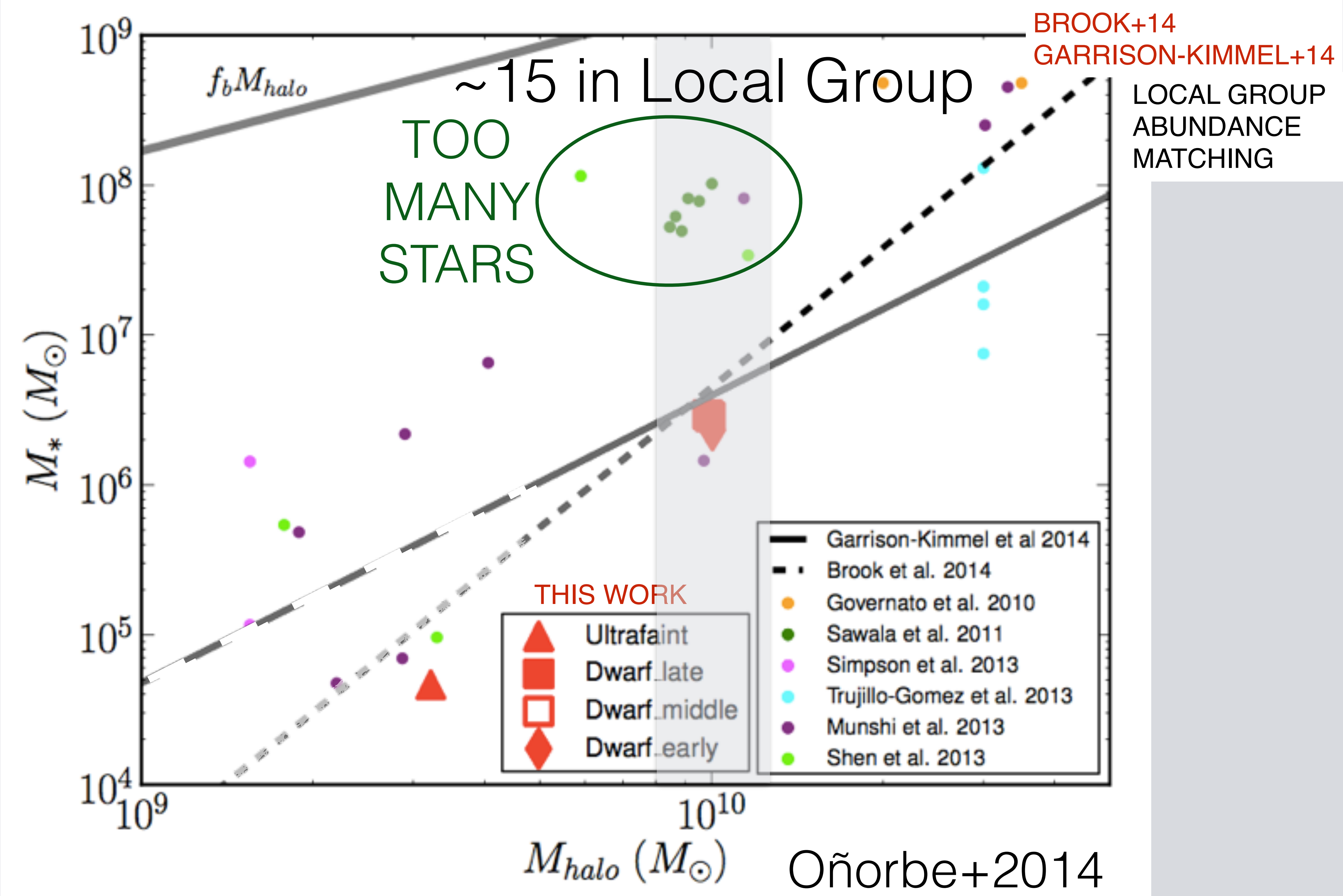
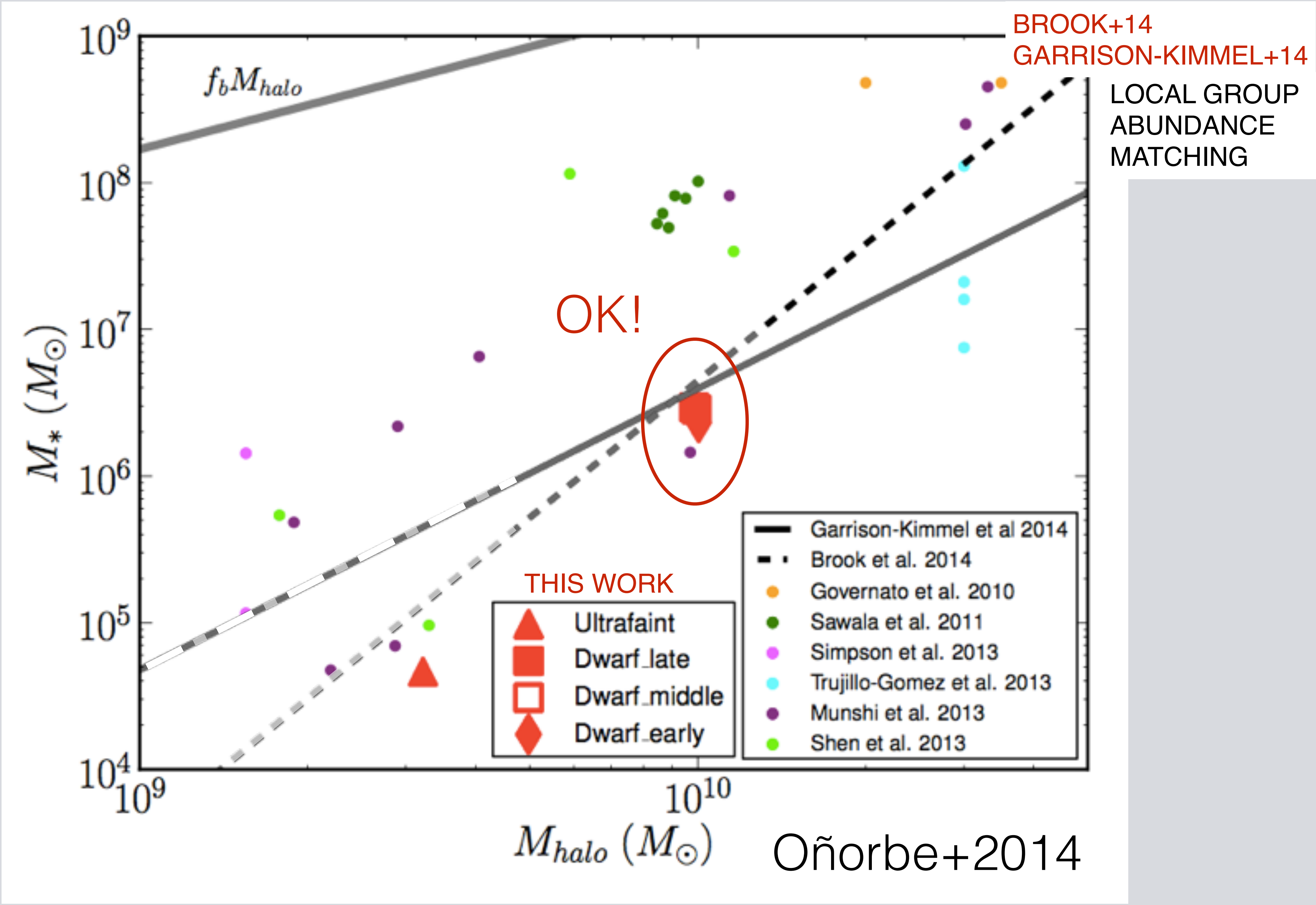
Oñorbe+2014

$M_\star$ vs. M_{HALO}



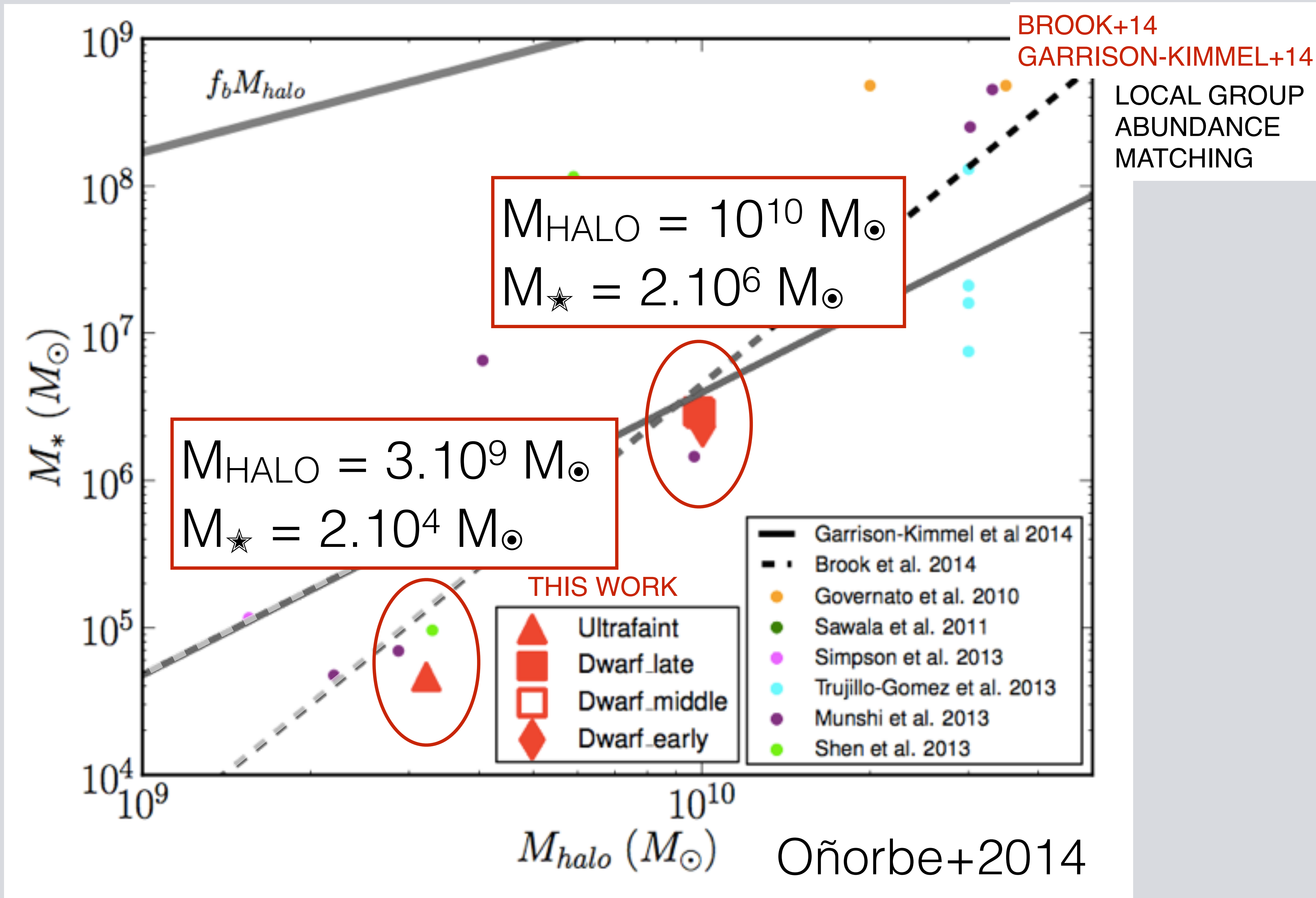
Oñorbe+2014

M★ vs. MHALO

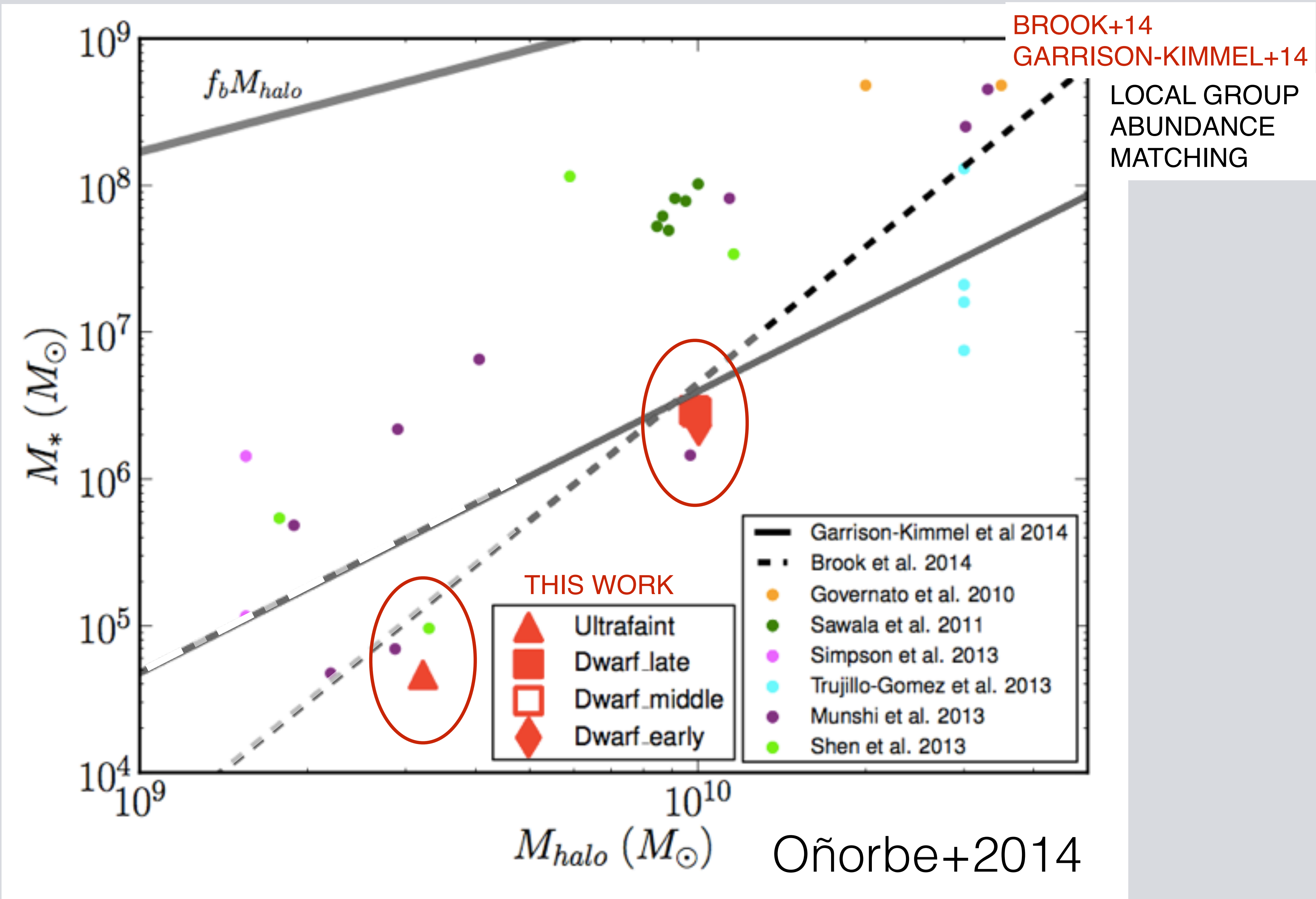


$f_b M_{halo}$
OK!
THIS WORK
Ultrafaint
Dwarf_late
Dwarf_middle
Dwarf_early
Garrison-Kimmel et al 2014
Brook et al. 2014
Governato et al. 2010
Sawala et al. 2011
Simpson et al. 2013
Trujillo-Gomez et al. 2013
Munshi et al. 2013
Shen et al. 2013
$M_* (M_\odot)$
$M_{halo} (M_\odot)$
10^4
10^5
10^6
10^7
10^8
10^9
10^{10}
BROOK+14
GARRISON-KIMMEL+14
LOCAL GROUP ABUNDANCE MATCHING
Oñorbe+2014

$M_\star$ vs. M_{HALO}



M★ VS. MHALO



BROOK+14
GARRISON-KIMMEL+14
LOCAL GROUP
ABUNDANCE
MATCHING
$f_b M_{halo}$
$M_* \ (M_\odot)$
$M_{halo} \ (M_\odot)$
10^9
10^8
10^7
10^6
10^5
10^4
10^9
10^{10}
THIS WORK
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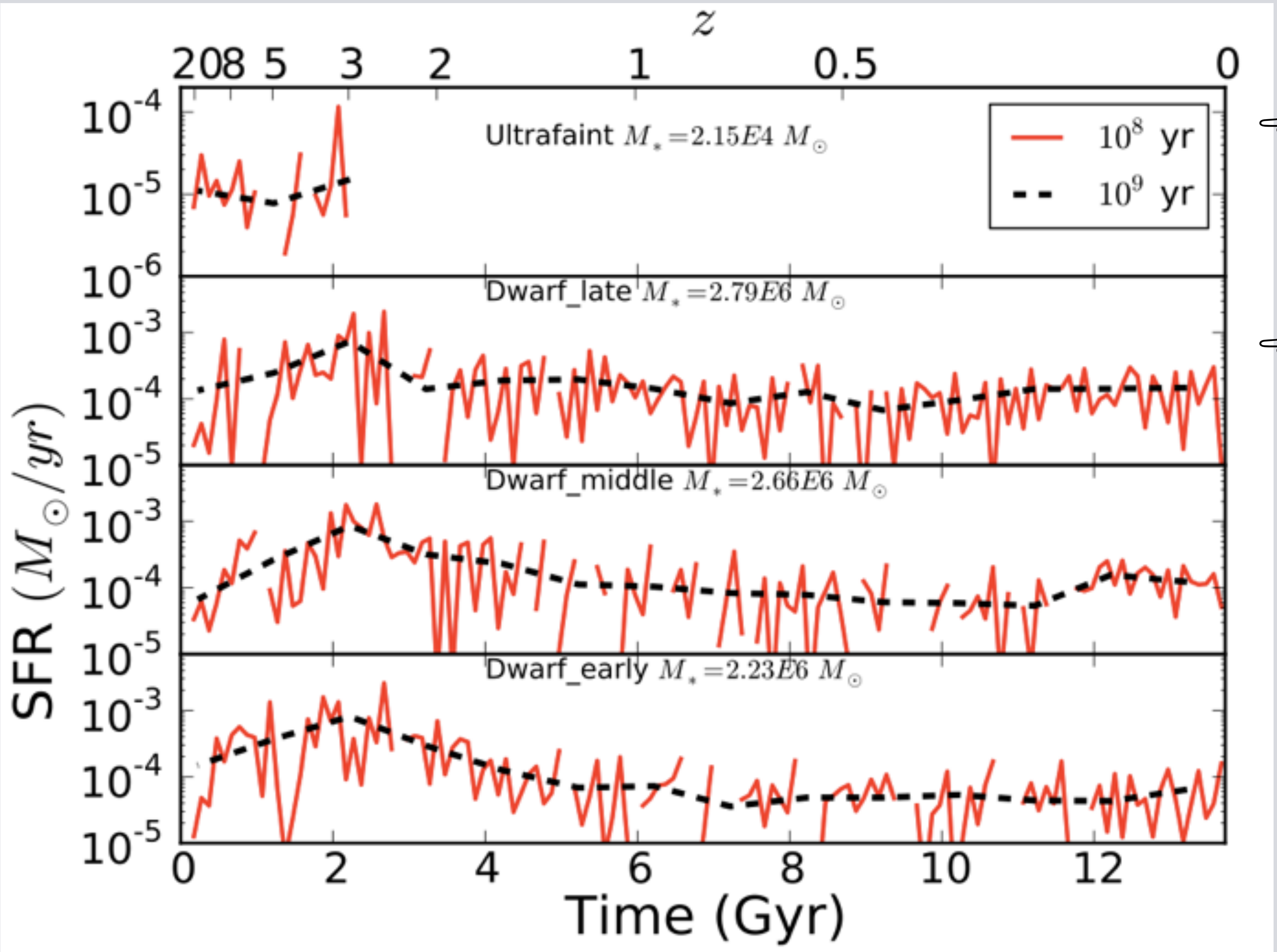
Munshi et al. 2013
Shen et al. 2013
Oñorbe+2014

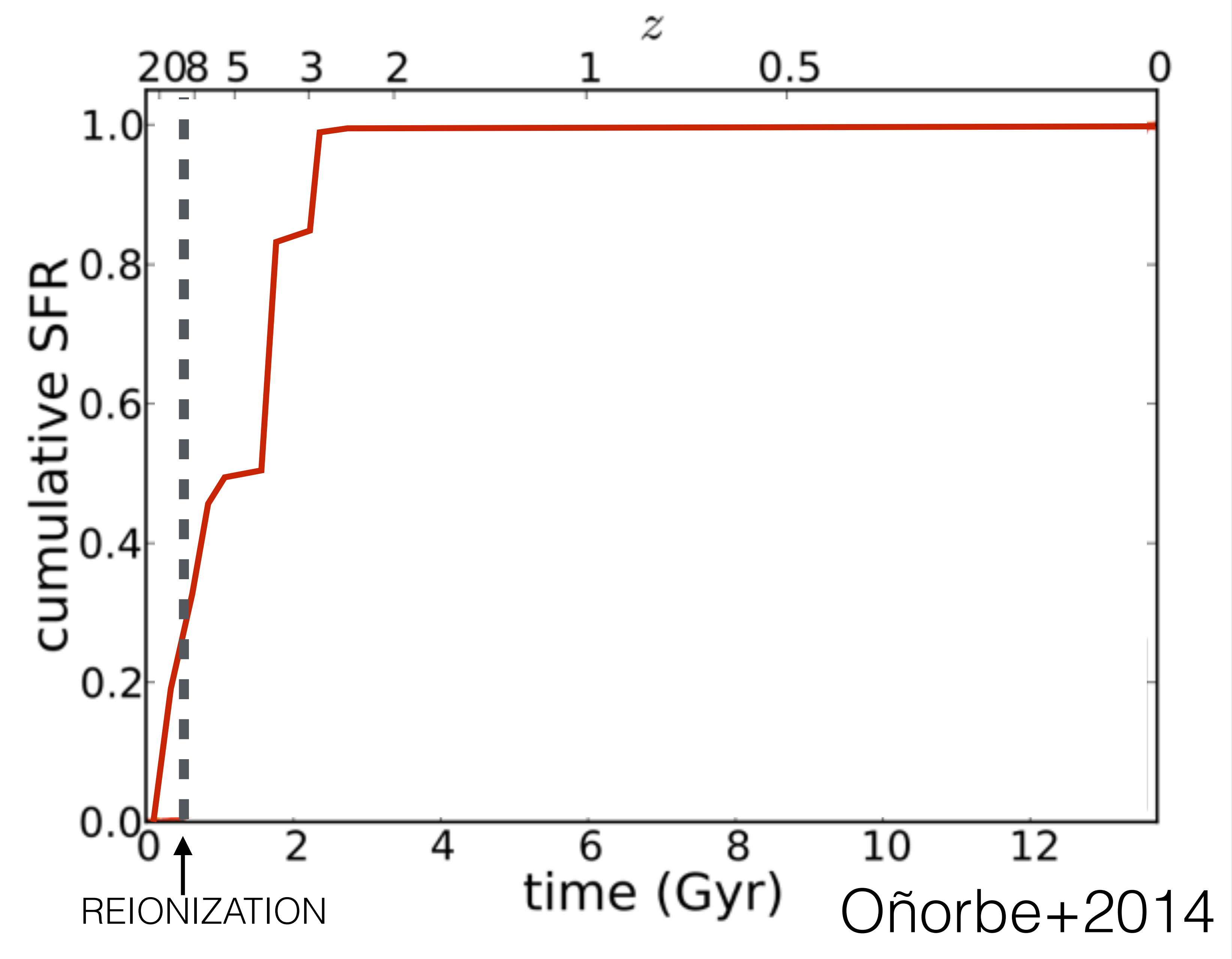
SFH: all are bursty



- *field* ultrafaint is quenched
- All of the “larger” field dwarfs continue to form stars until z=0

ULTRA-FAINT SFH

$M_{HALO}=3.10^9\ M_\odot$ $M_\star=2.10^4\ M_\odot$



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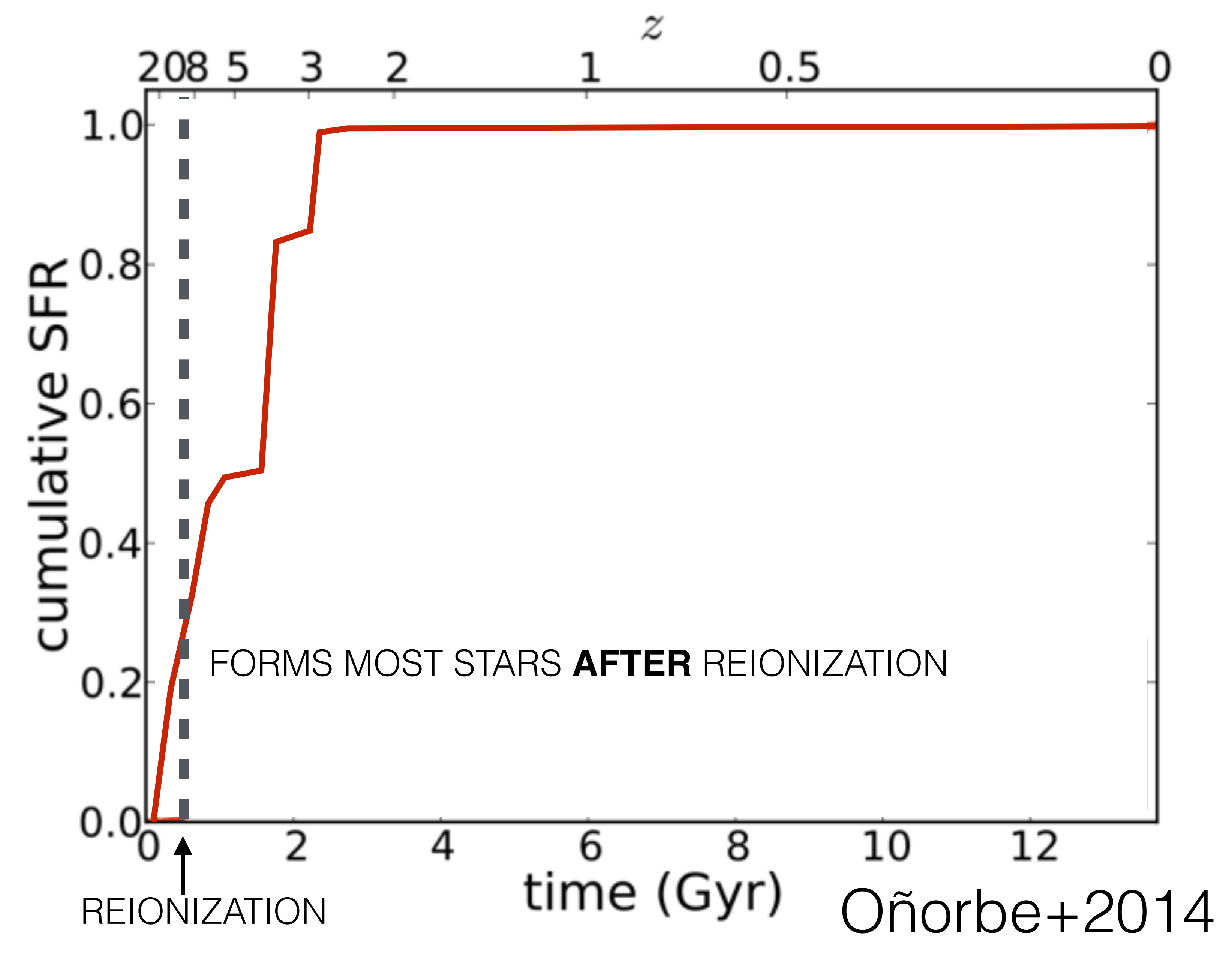

ULTRA-FAINT SFH

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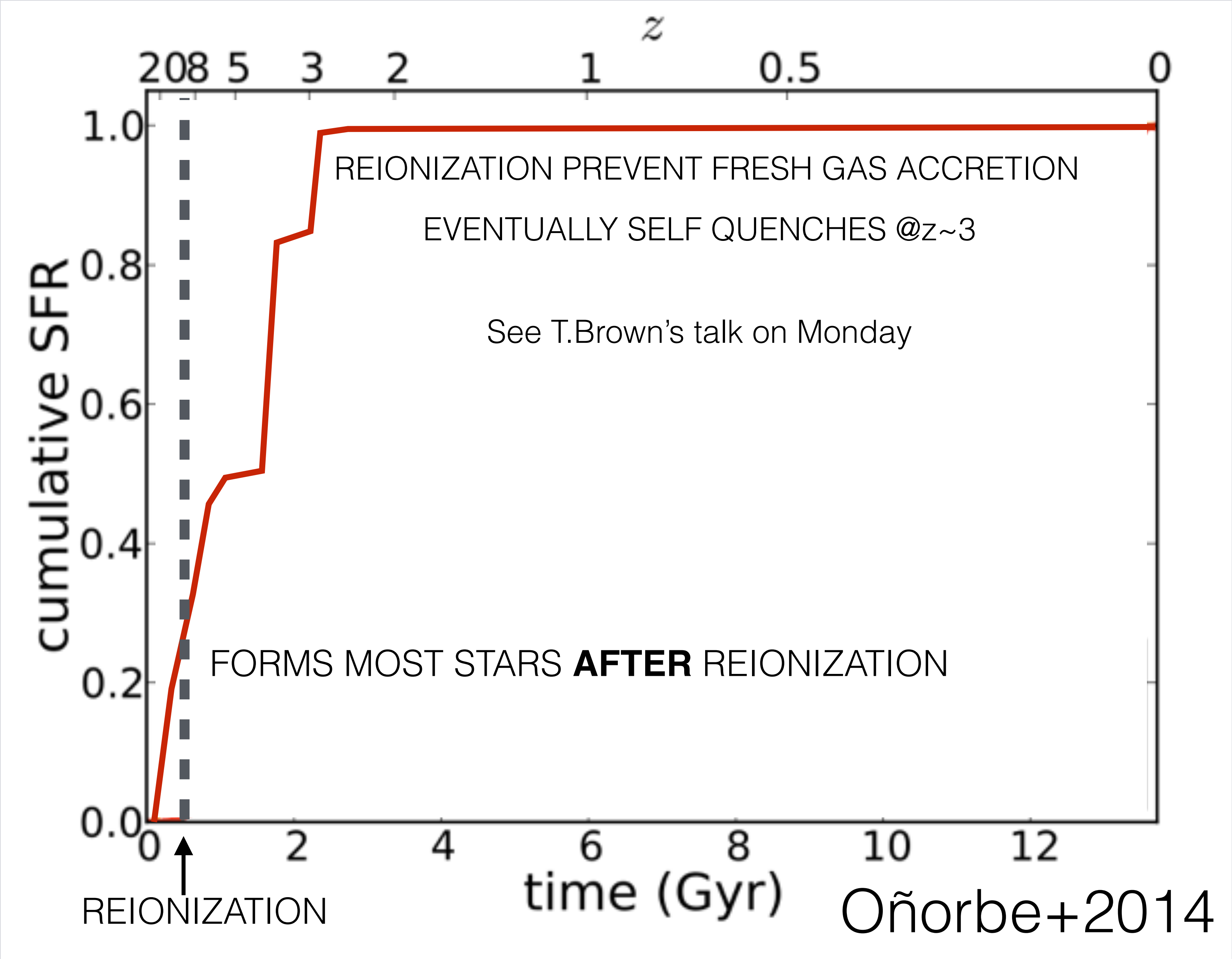
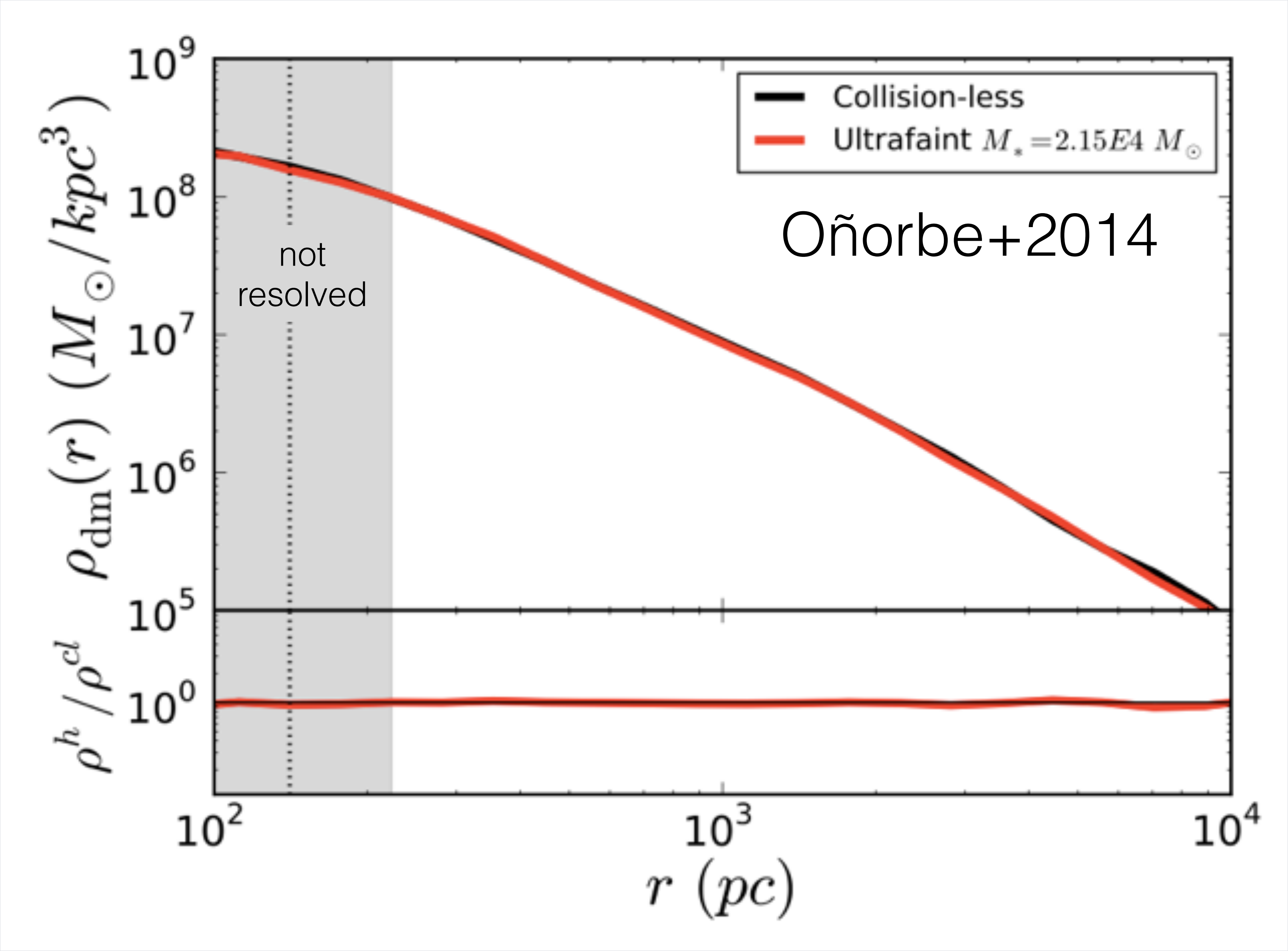


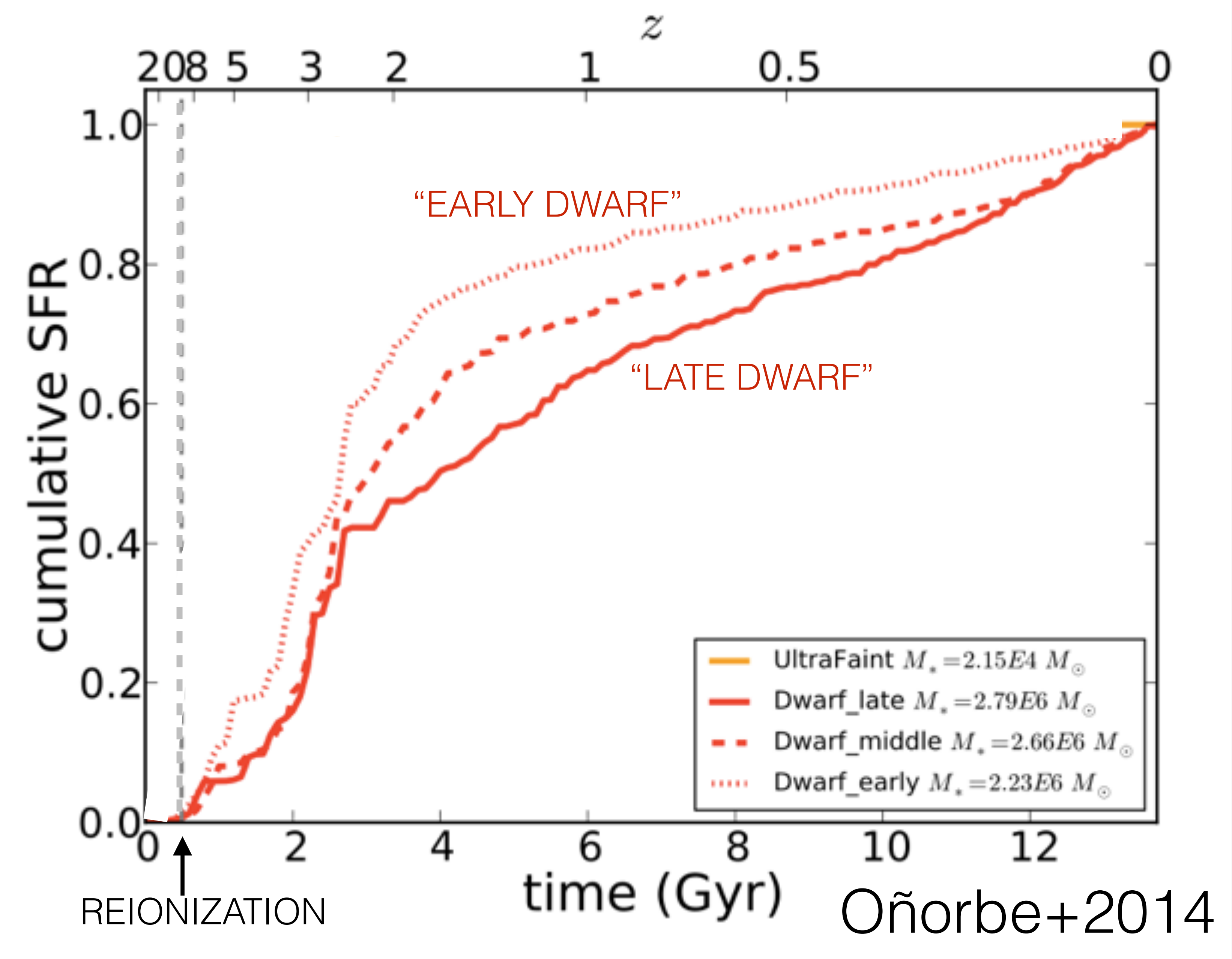
ULTRA-FAINT: DM HALO SAME AS N-BODY

$M_{HALO}=3.10^9\ M_\odot$ $M_\star=2.10^4\ M_\odot$



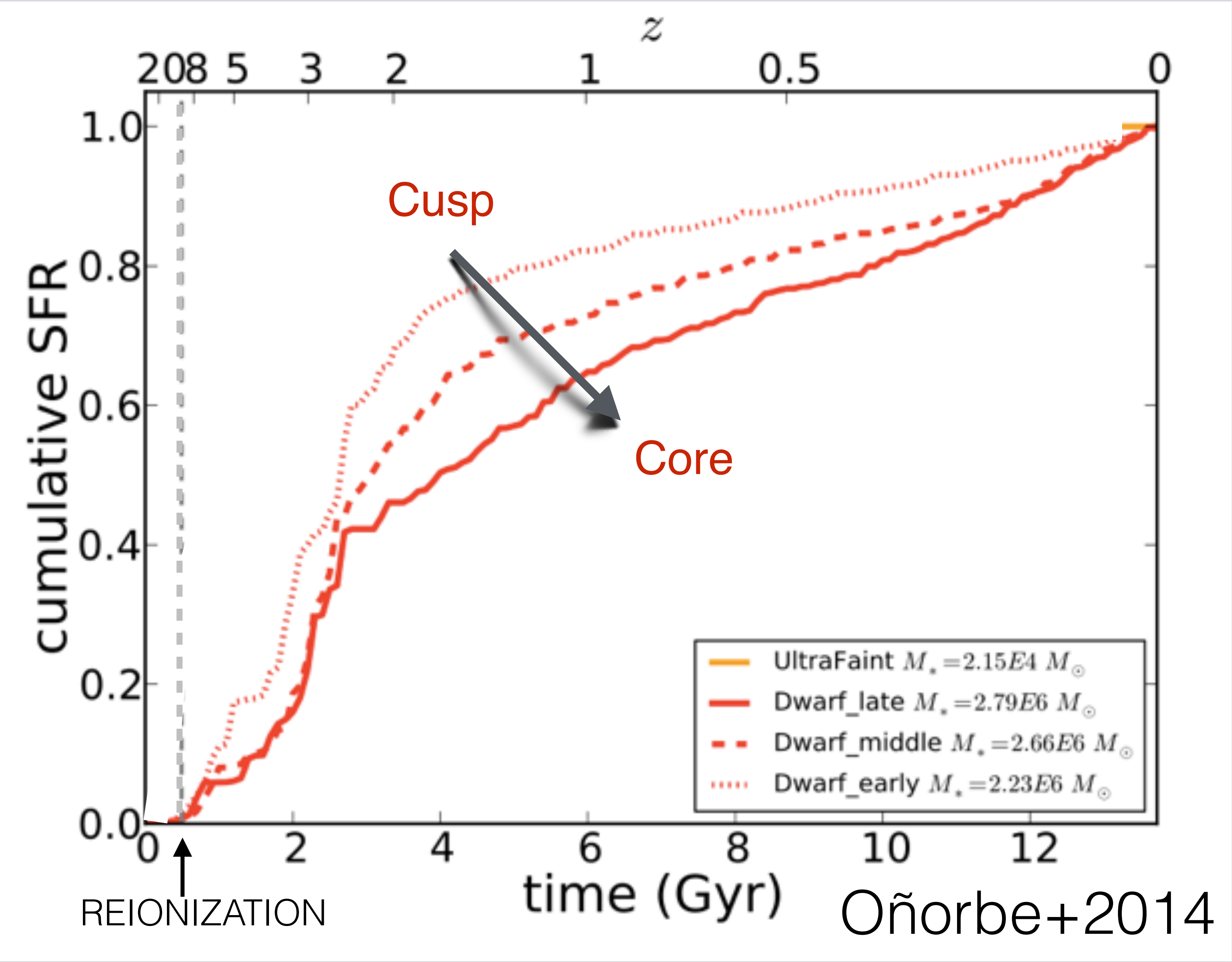
DWARF SFHs

$M_{HALO}=10^{10}\ M_\odot$ $M_\star=(2.2\text{-}2.8)\times10^6\ M_\odot$



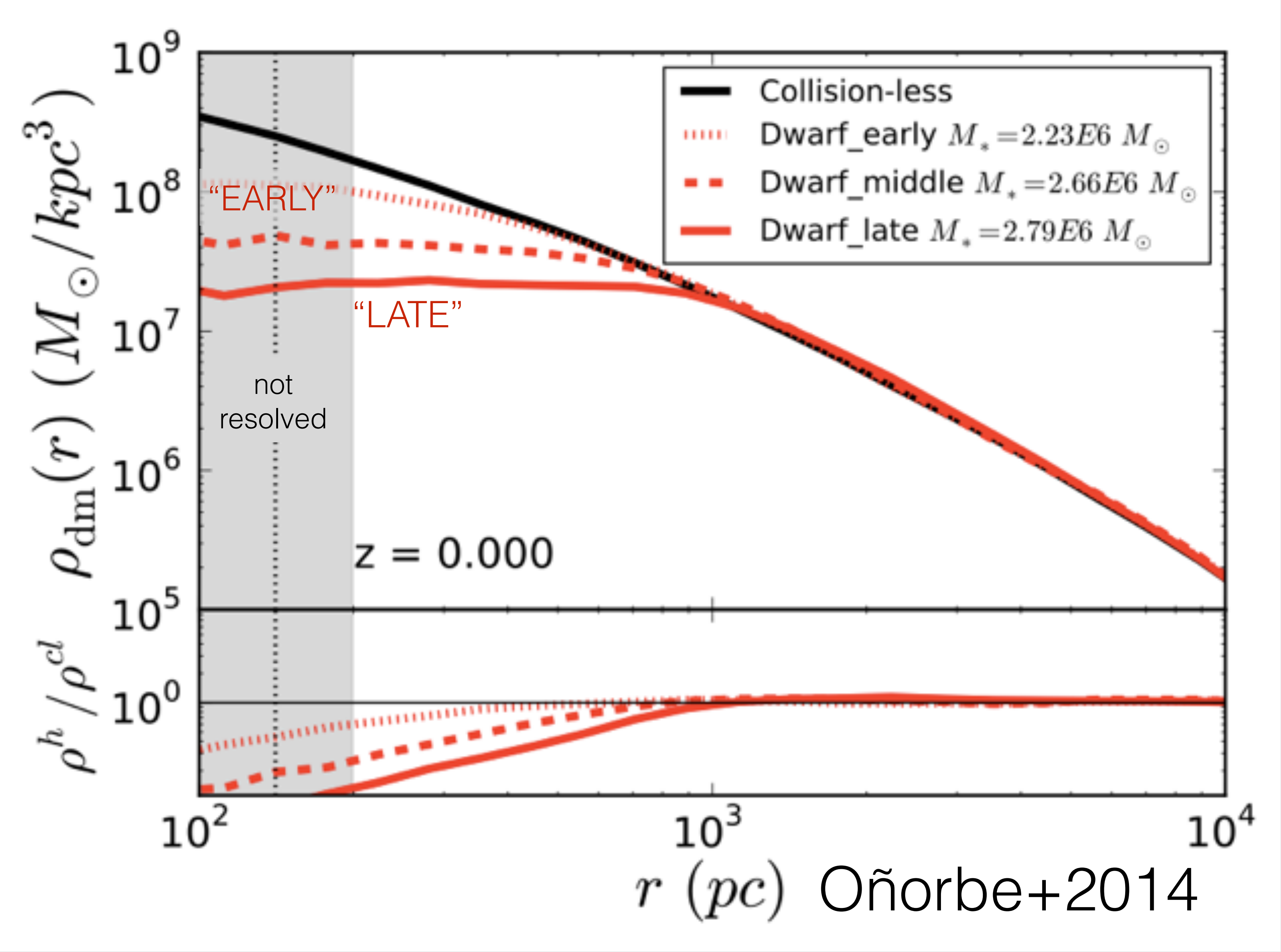
DWARF SFHs

$M_{HALO}=10^{10}\ M_\odot \quad M_\star=(2.2\text{-}2.8)\times10^6\ M_\odot$



DWARF DARK MATTER DENSITIES

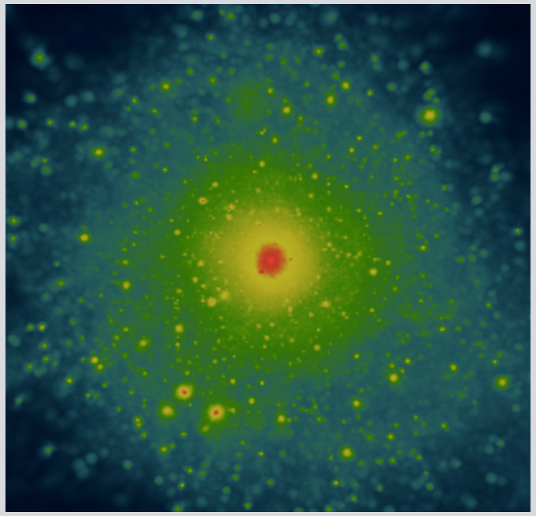
$M_{HALO}=10^{10}\ M_{\odot}$ $M_{\star}=(2.2\text{-}2.8)\times10^{6}\ M_{\odot}$



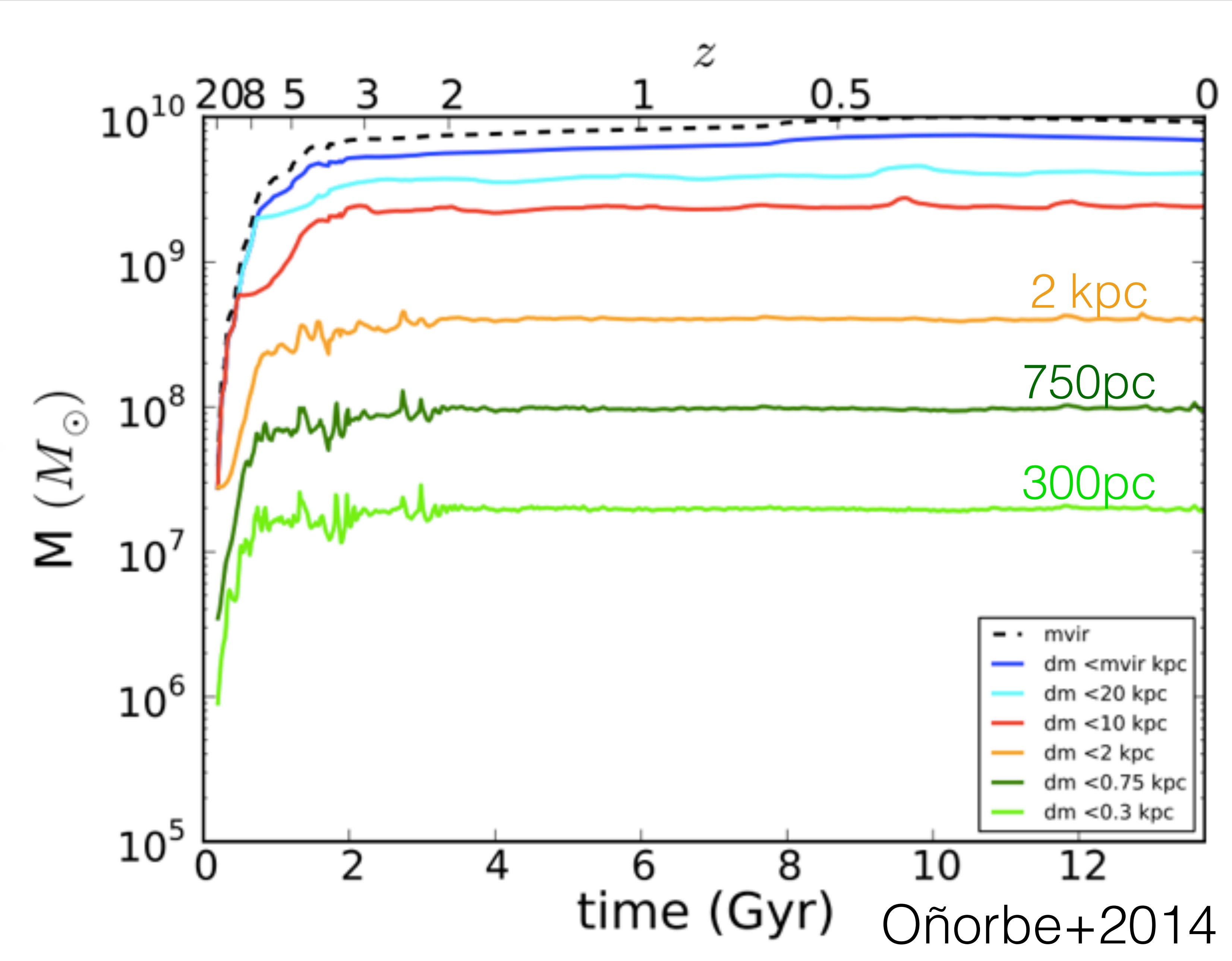
Oñorbe+2014

HOW DO HALOS GET THEIR CUSPS?

N-BODY: CUSPS FORM (AND REFORM) AT z>2



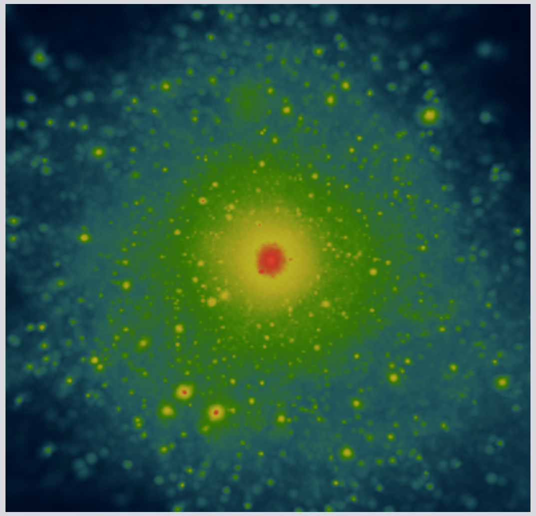
DM-only ➲



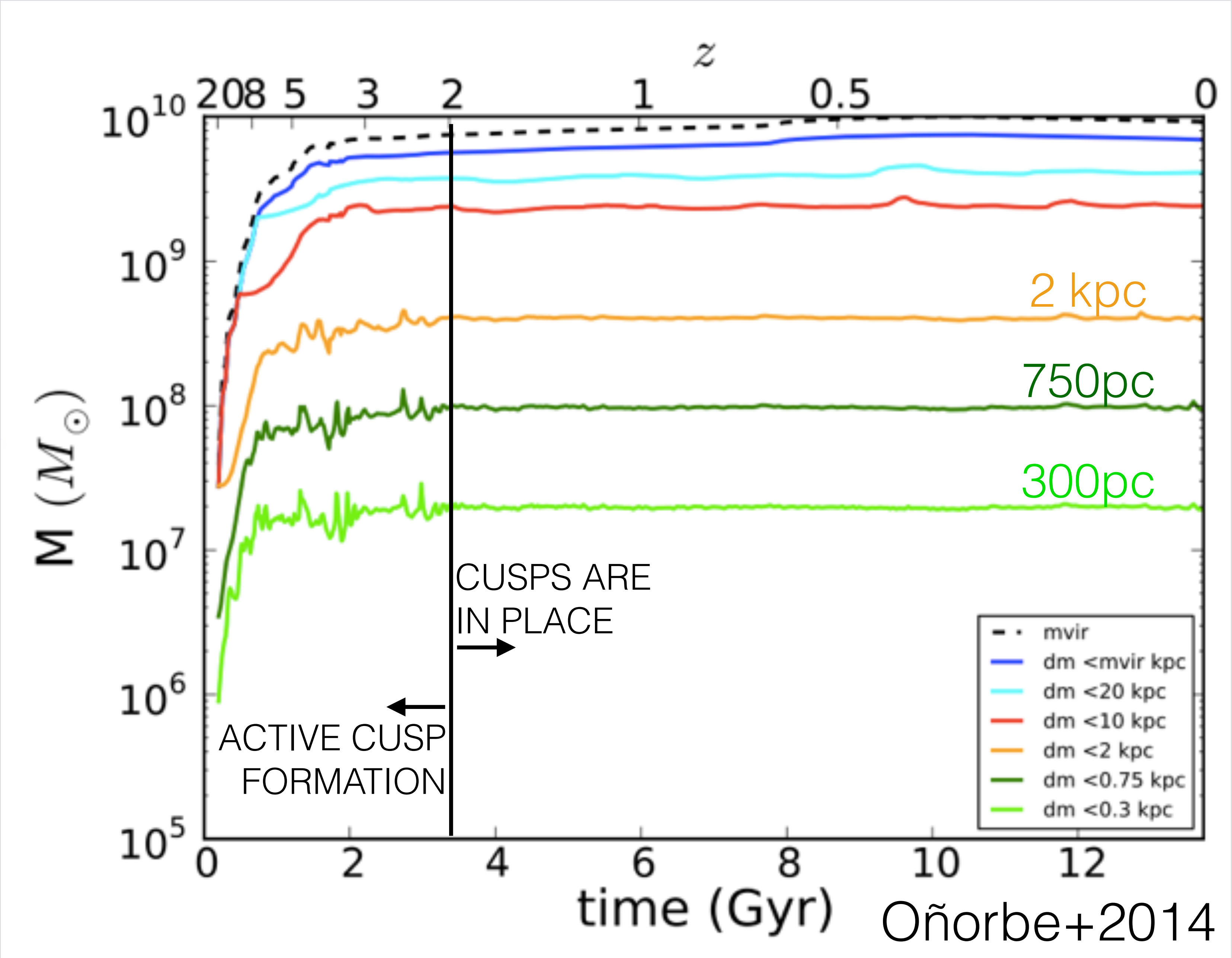
Oñorbe+2014

HOW DO HALOS GET THEIR CUSPS?

N-BODY: CUSPS FORM (AND REFORM) AT z>2

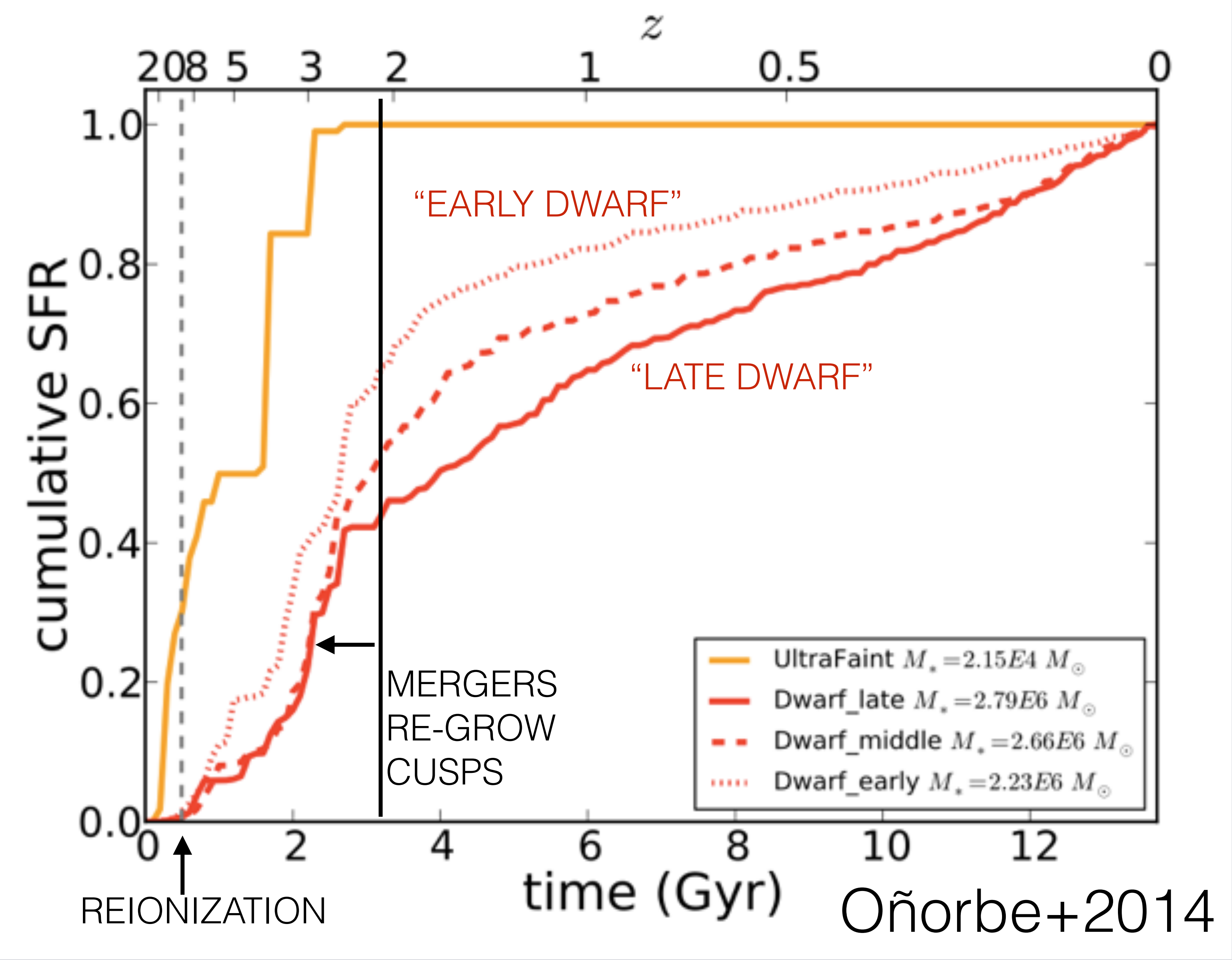


DM-only ➲



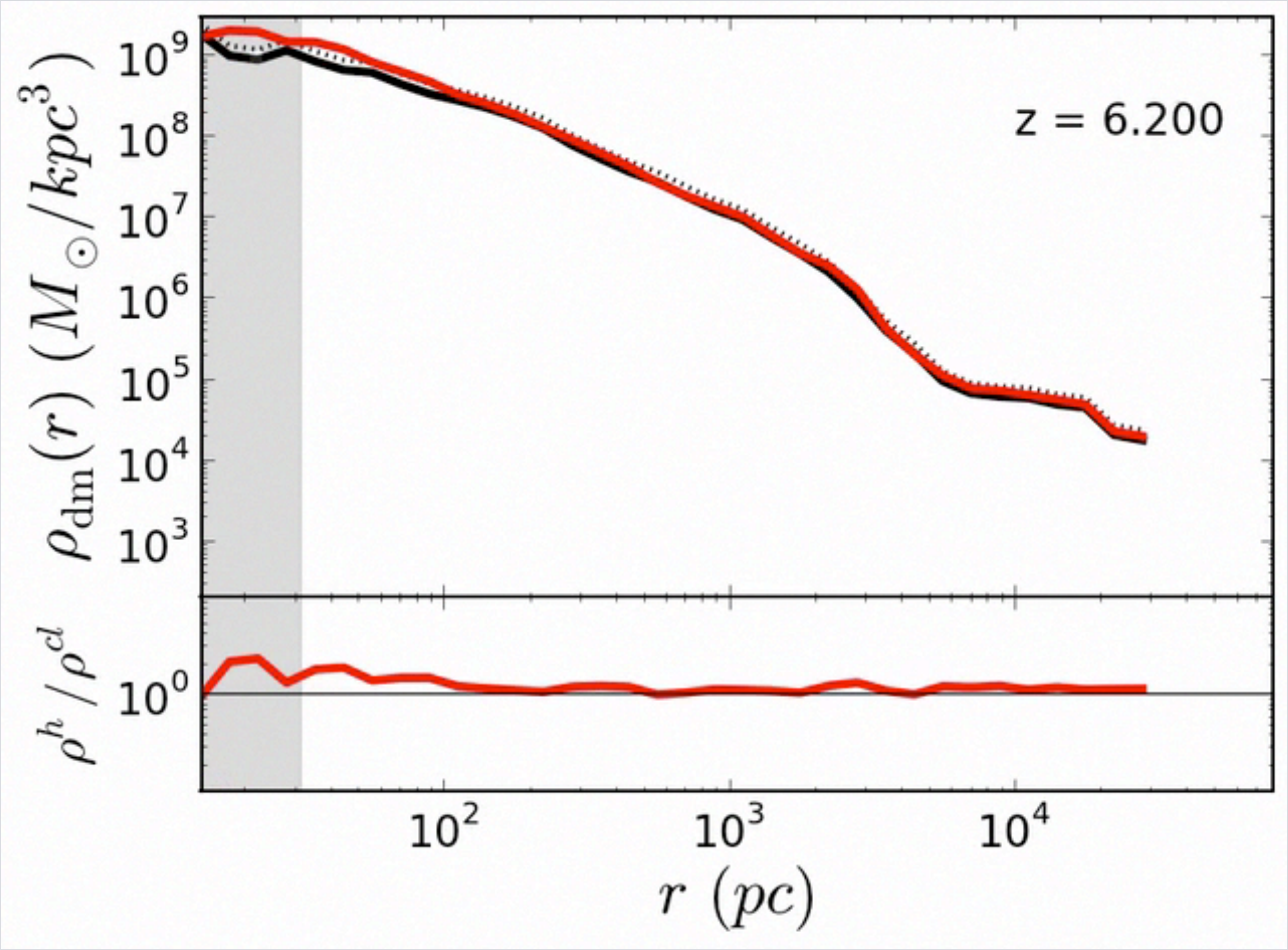
DWARF SFHs

$M_{HALO}=10^{10}\ M_\odot \quad M_\star=(2.2\text{-}2.8)\times10^{6}\ M_\odot$



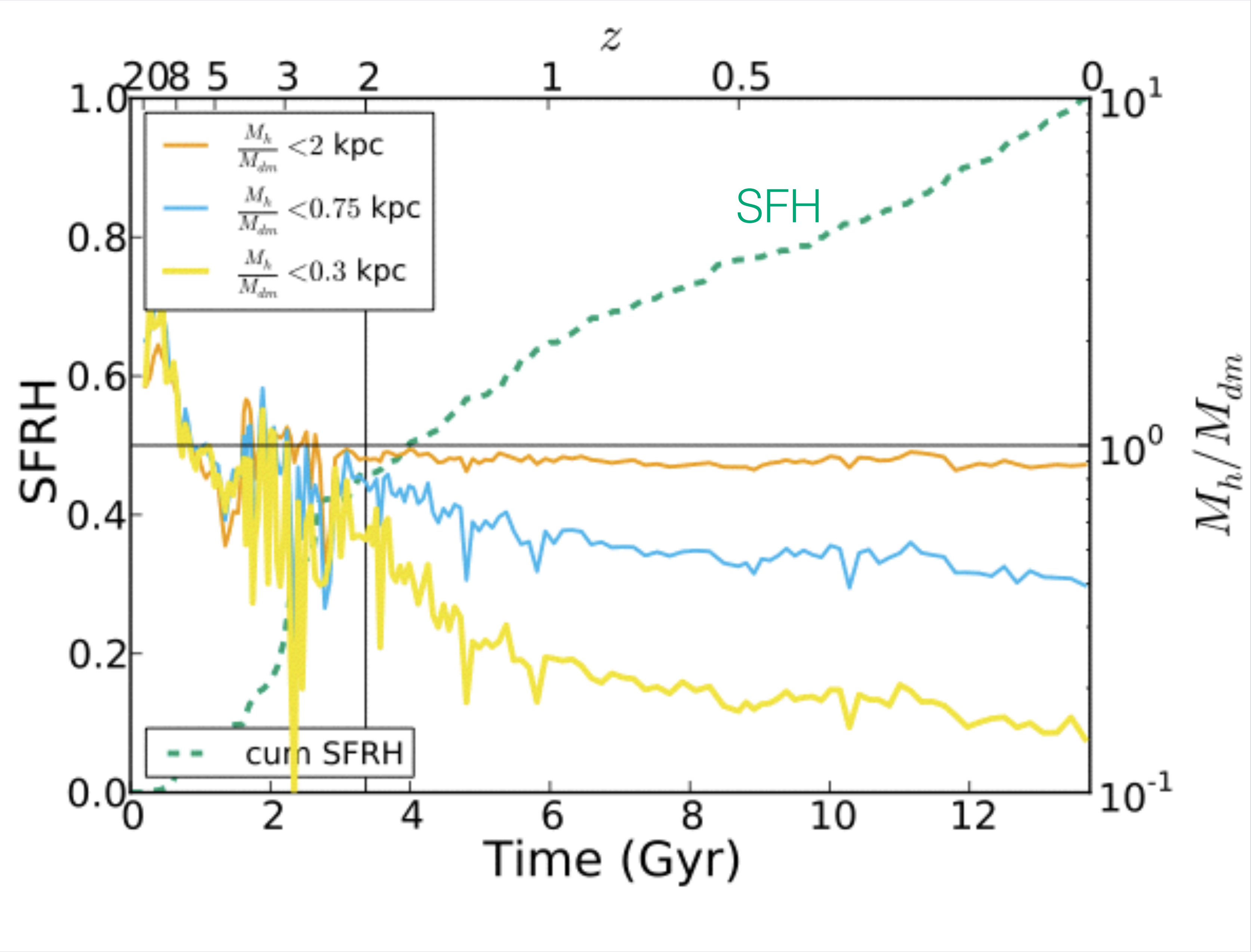
Oñorbe+2014

THE CUSP/CORE CYCLE



LATE STAR FORMATION

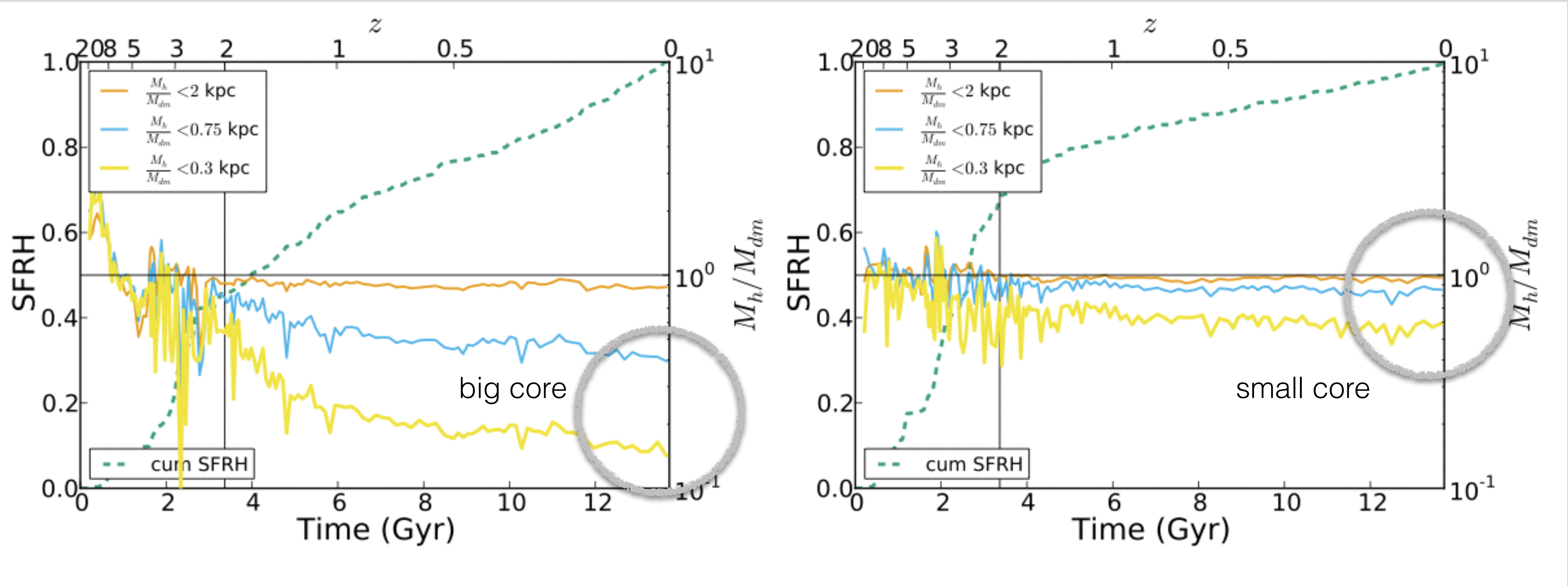
ESSENTIAL FOR SURVIVAL OF DM CORES



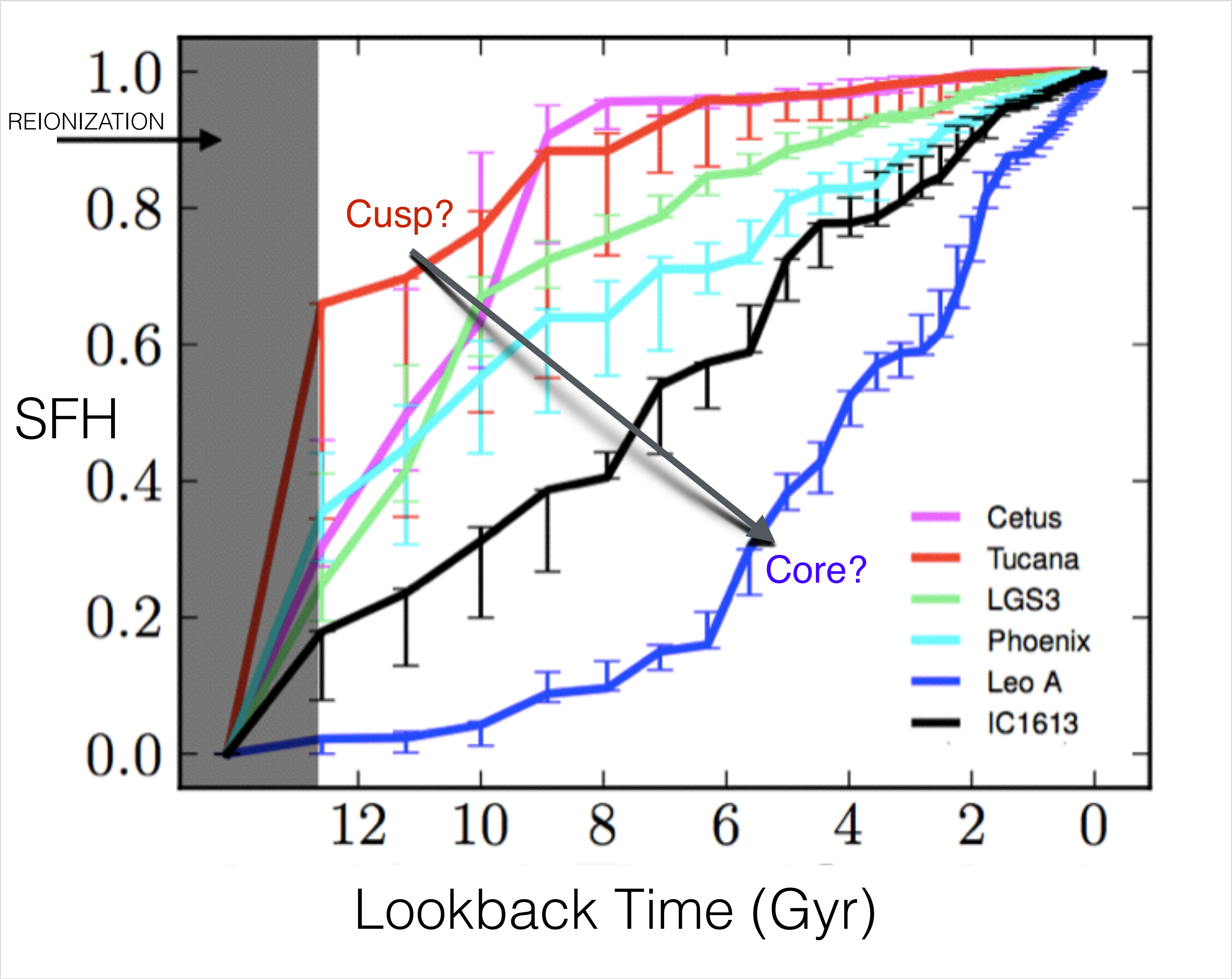
LATE STAR FORMATION

ESSENTIAL FOR SURVIVAL OF DM CORES

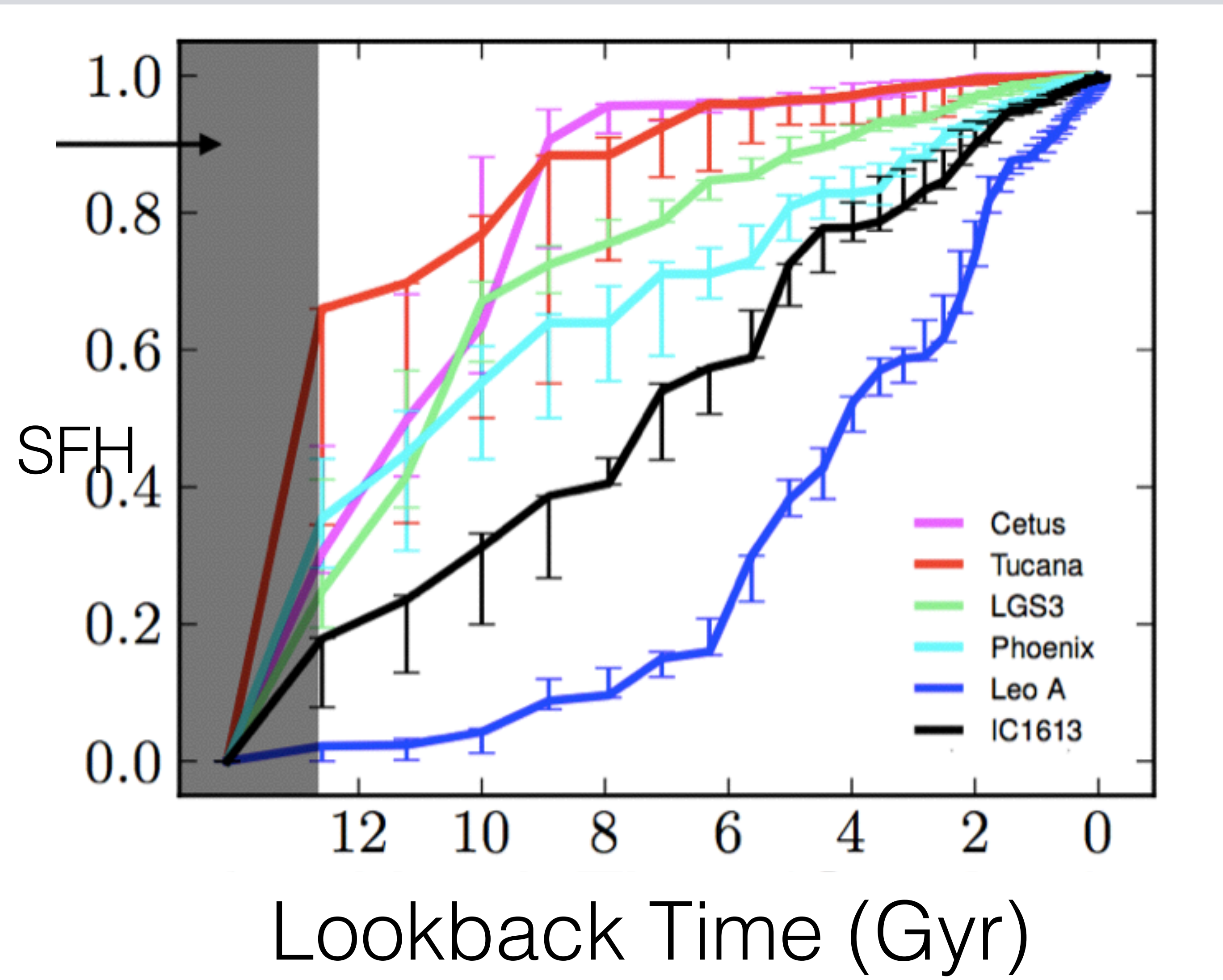
“LATE DWARF” “EARLY DWARF”



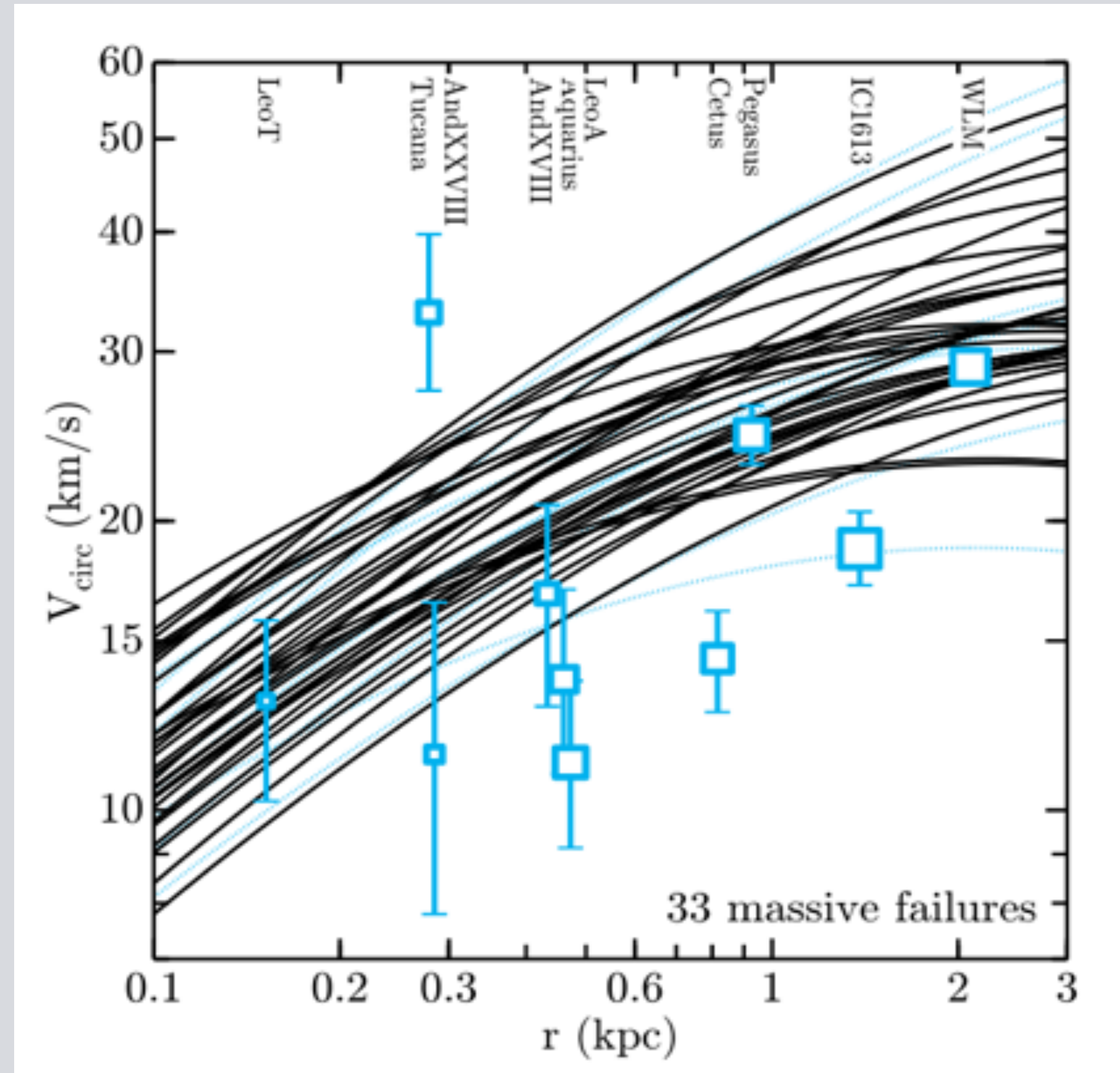
Skillman et al. 2014 (ACS LCID project); Weisz et al. 2014



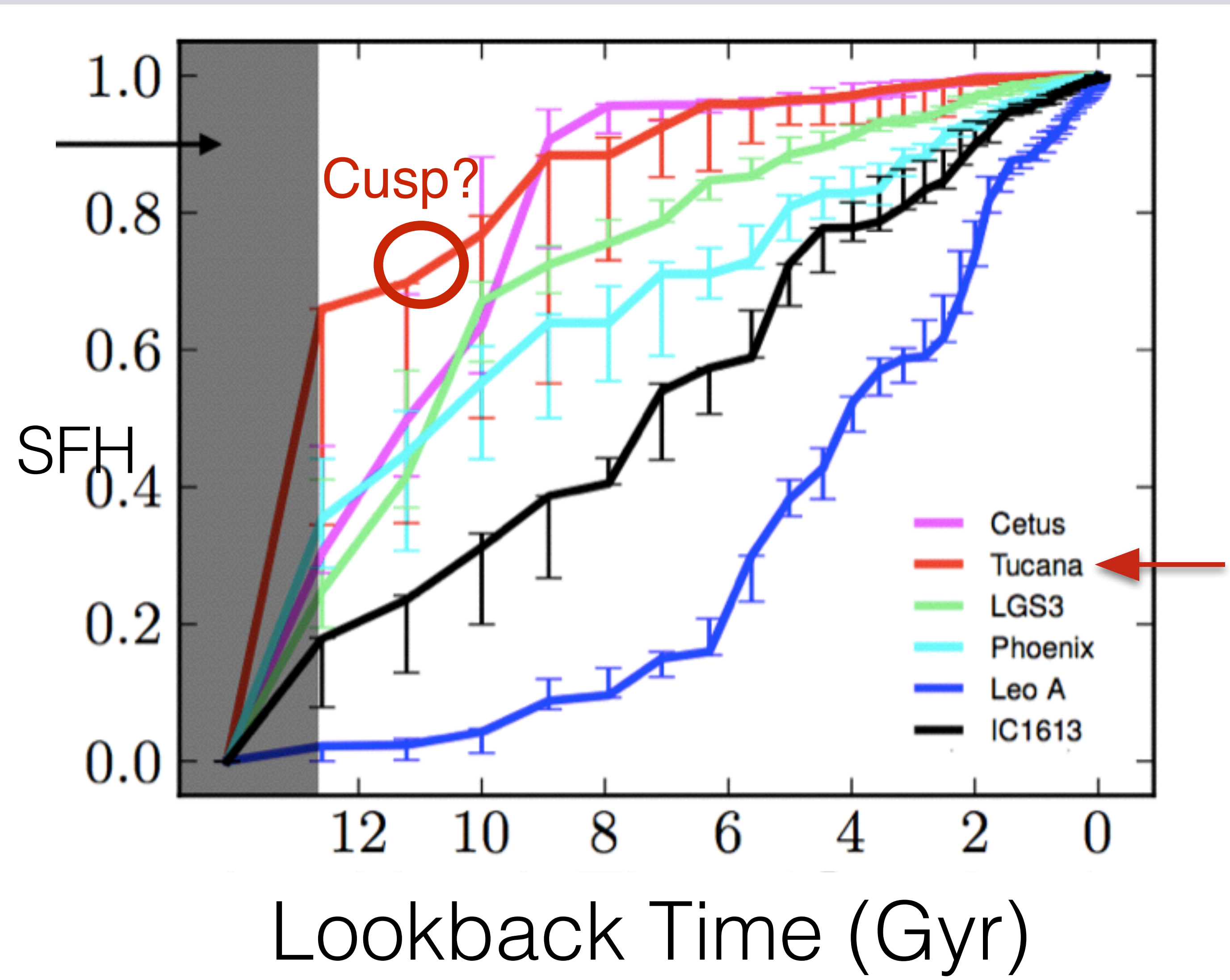
Skillman + 2014



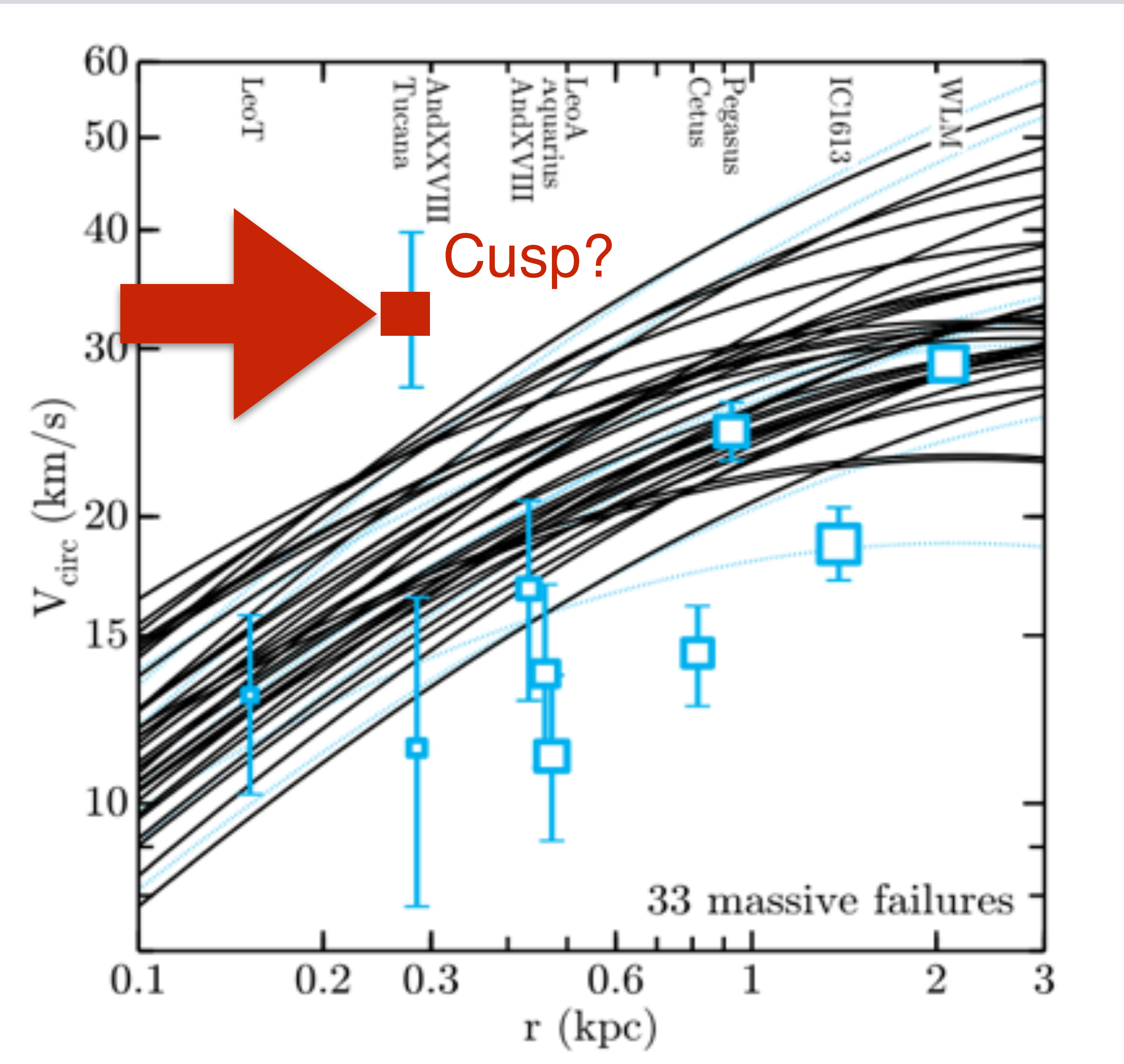
Garrison-Kimmel + 2014



Skillman + 2014

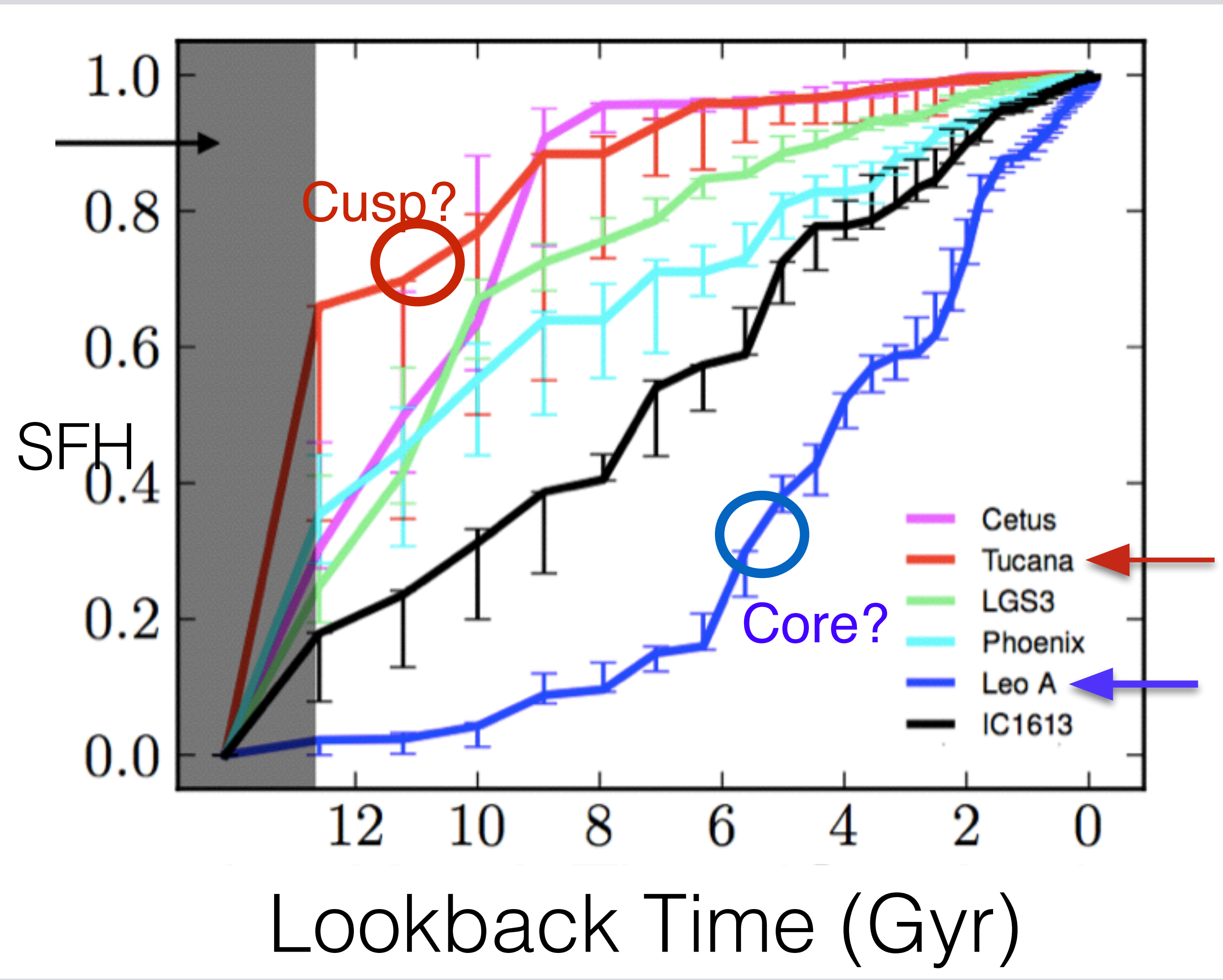


Garrison-Kimmel + 2014

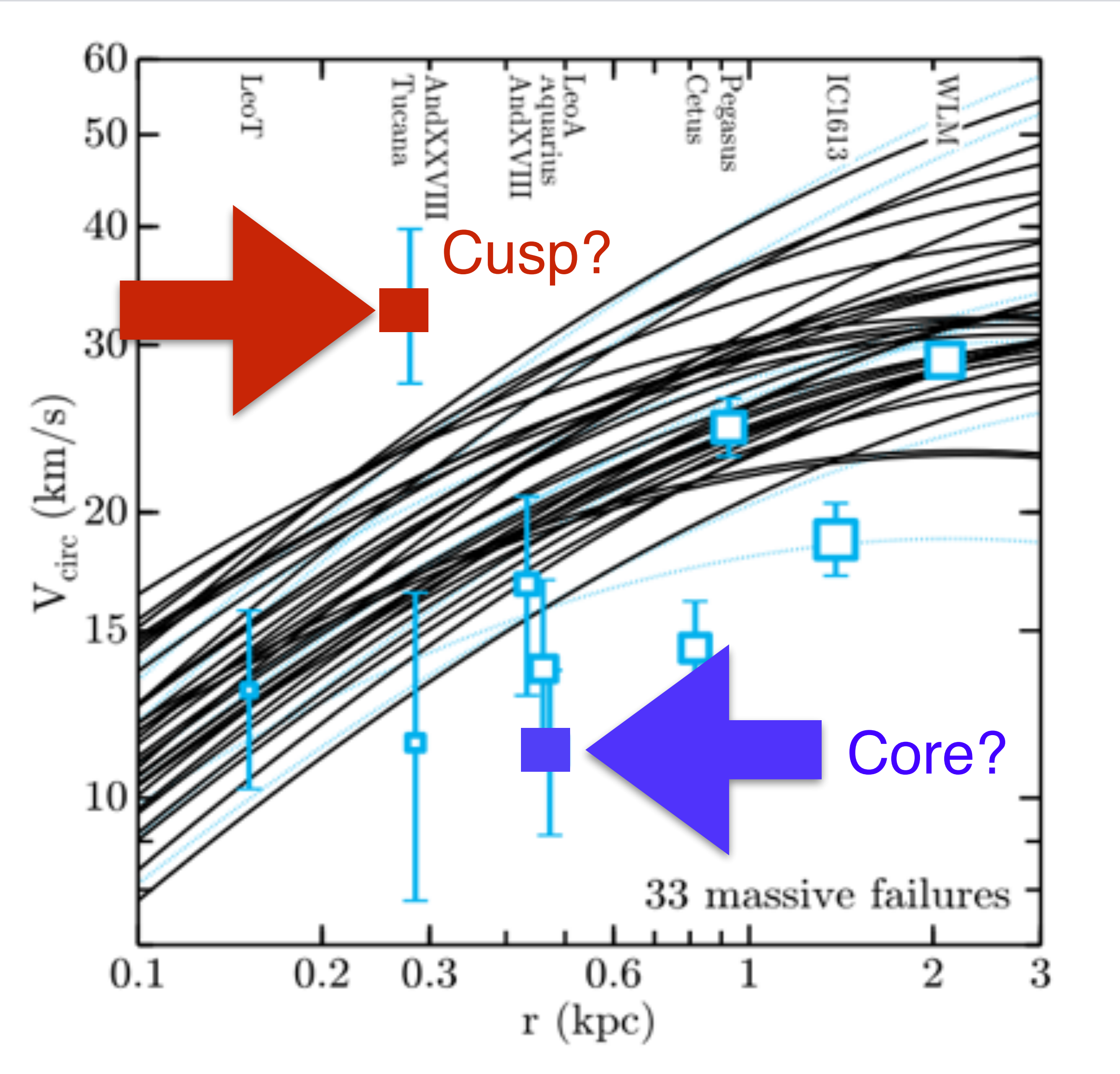


$M_{\star} = 6.e5 M_{\odot}$

Skillman + 2014



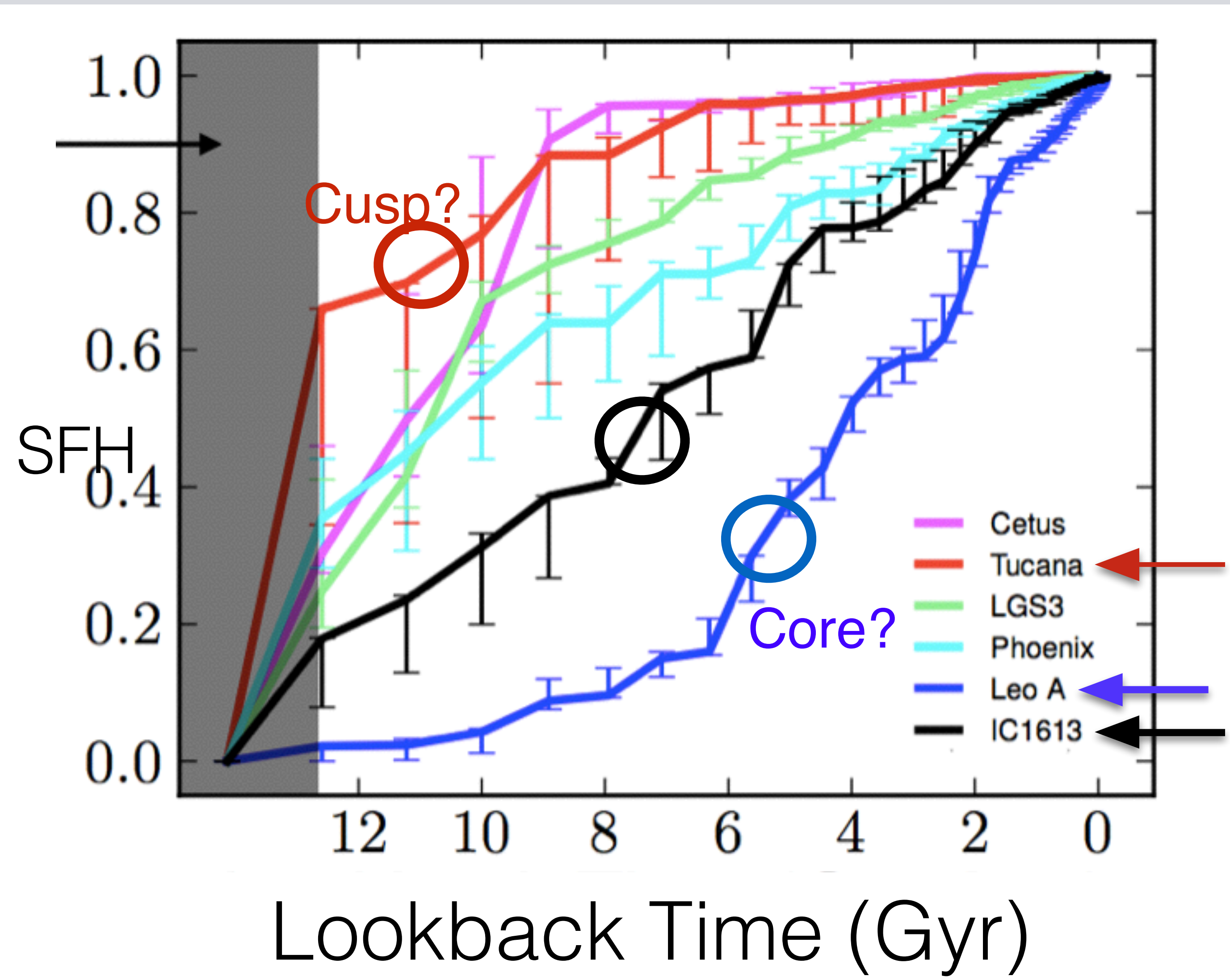
Garrison-Kimmel + 2014



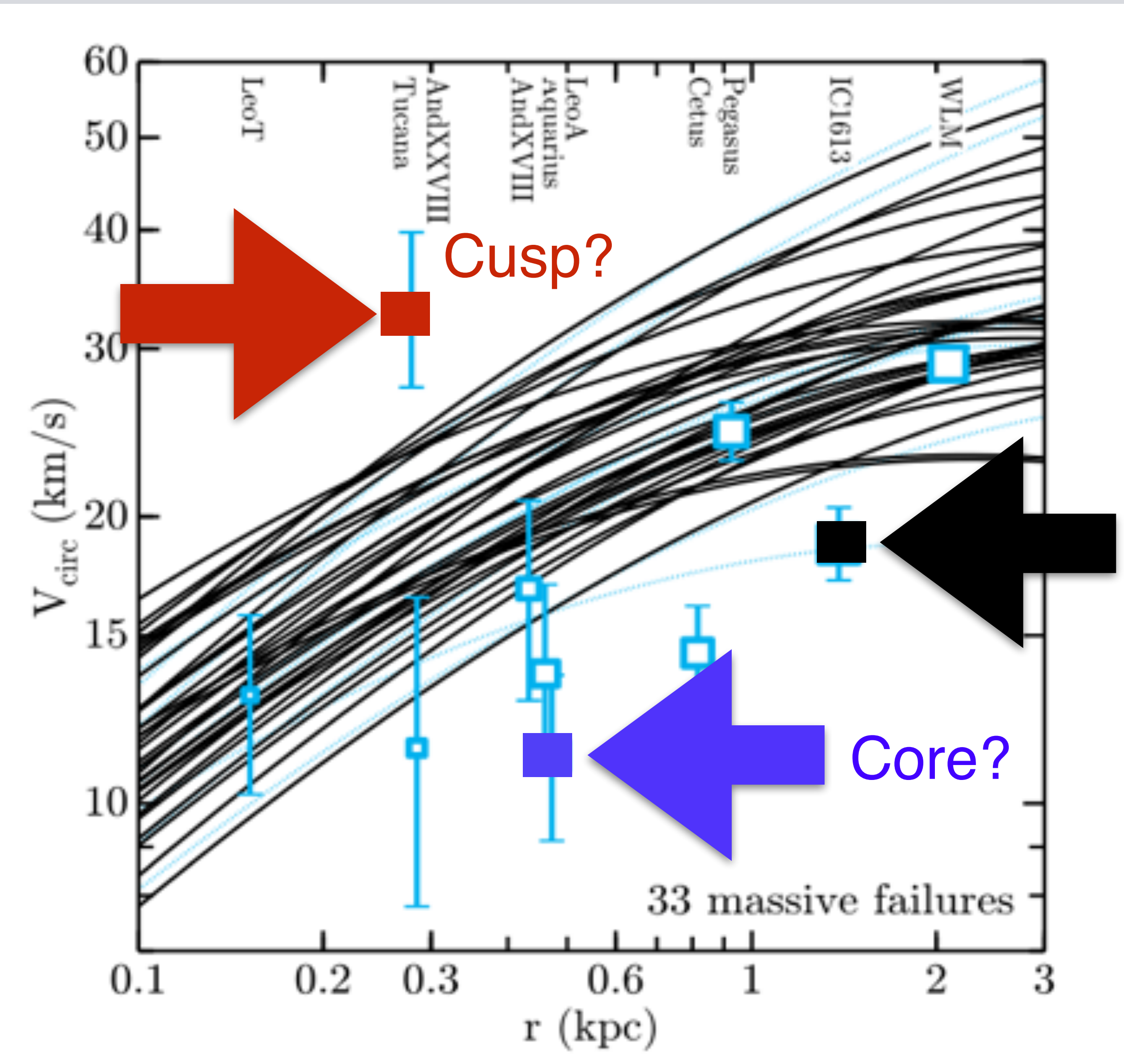
$M_\star$ = 6.e5$M_\odot$

$M_\star$ = 6.e6$M_\odot$

Skillman + 2014



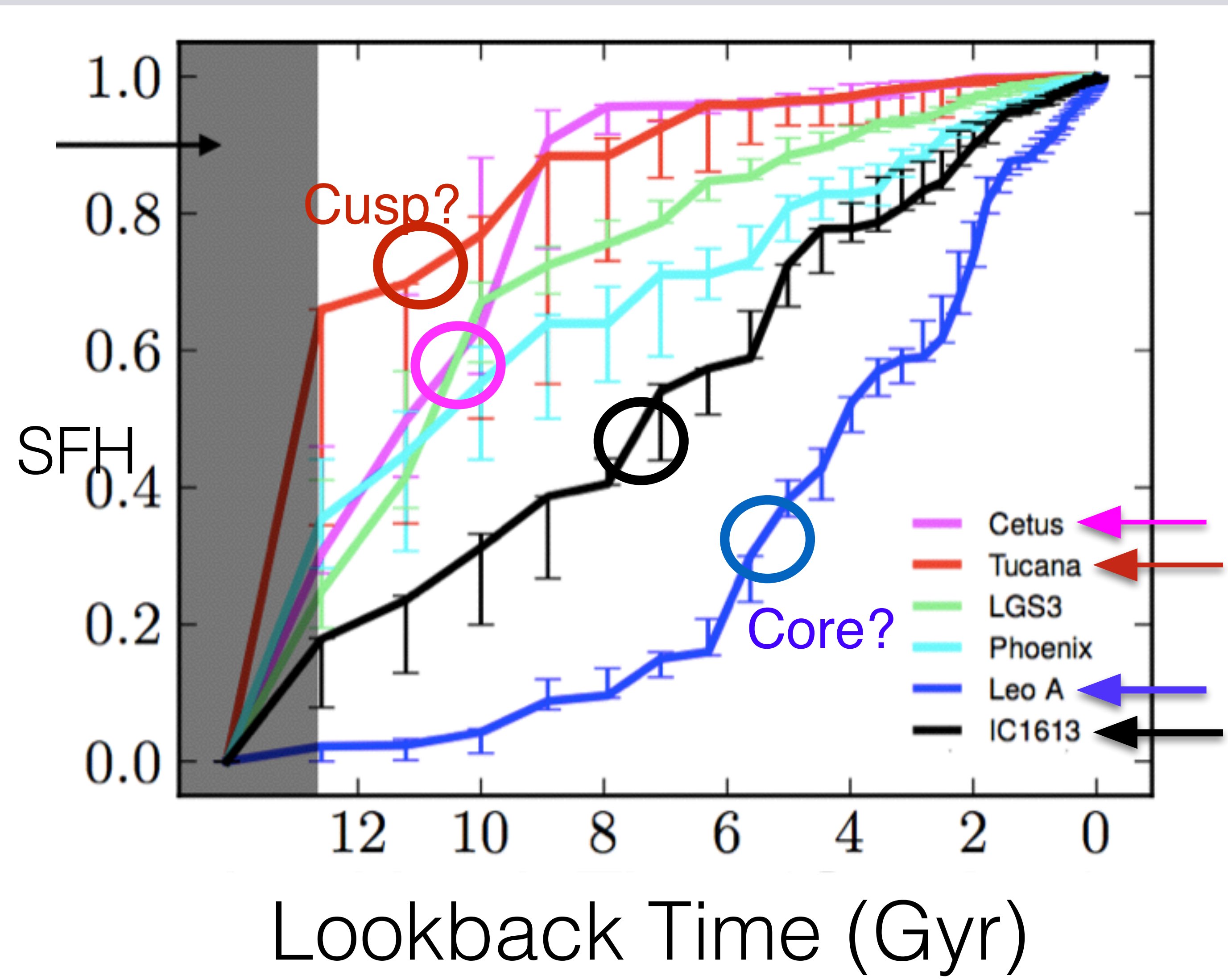
Garrison-Kimmel + 2014



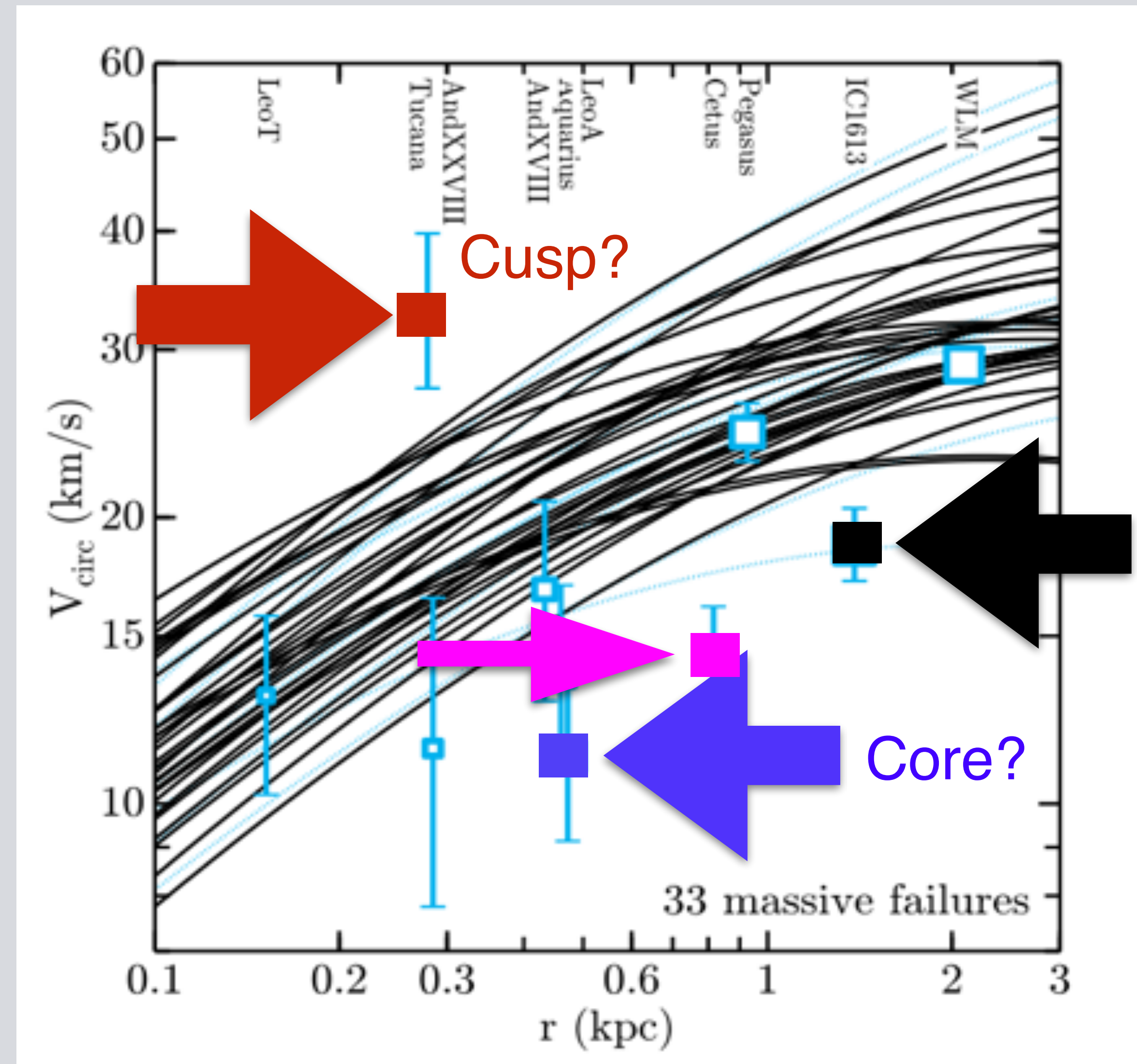
$M_{\star}$ = 6.e5$M_{\odot}$ $M_{\star}$ = 1.e8$M_{\odot}$ $M_{\star}$ = 6.e6$M_{\odot}$

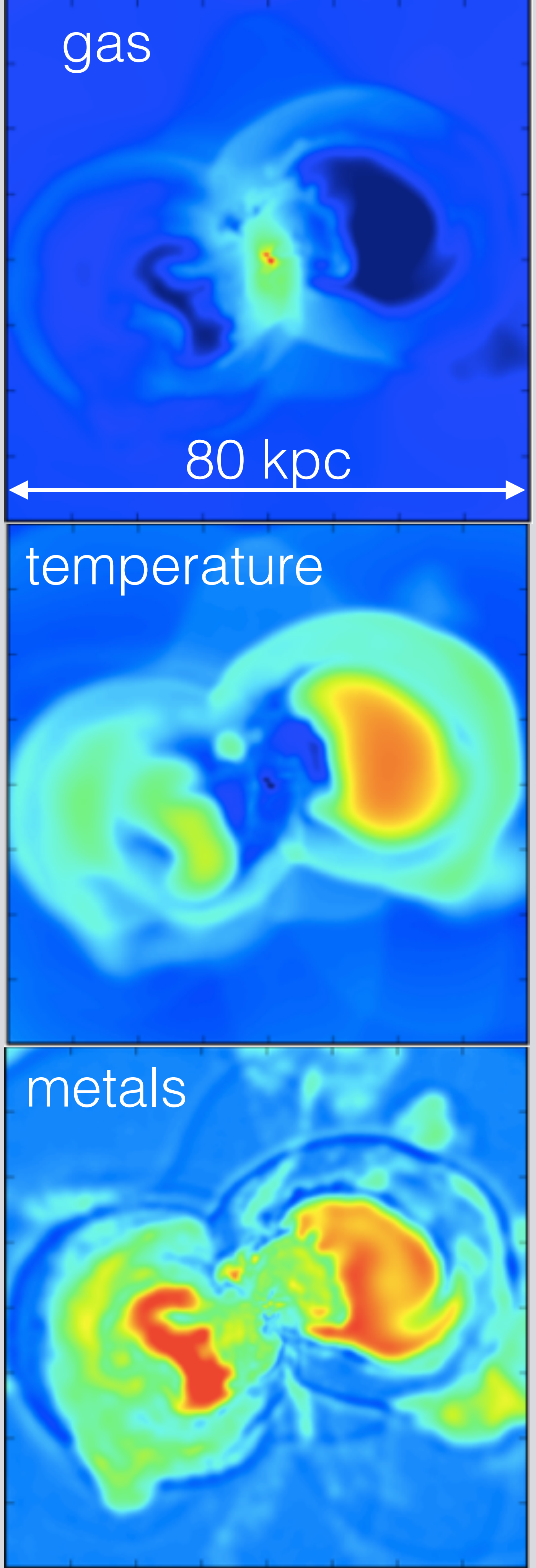
Damn you Cetus!

Skillman + 2014



Garrison-Kimmel + 2014





z=0 properties

$M_\star \sim (2\text{-}3)\times10^6\ M_\odot$ ✓ $M_{vir}=10^{10}\ M_\odot$

$[Fe/H] \sim -2$ ✓ (a little low)

$M_{HI}\sim(2\text{-}4)\times10^6\ M_\odot$ ✓

$r_{1/2} \sim 0.5\text{-}1$kpc ✓ (a little high?)

$(M_{dm}/M_{baryon})_{r_{1/2}}\sim1$ ✗ (too low…)

Summary in Tweets!

Summary in Tweets!

Mike BK @MBKplus · Aug 26

I really wish @jbprime would shut up about too-big-to fail already. Enough. #dwarfs2014.

Potsdam, Potsdam

Marcel S. Pawlowski @8minutesold · Aug 26

Who gave this guy a talk? #embarrassing #dwarfs2014.

Potsdam, Potsdam

Coral Wheeler @coralrosew · Aug 26

You think this is bad, try attending one of @jbprime's group meetings. Shoot me. #dwarfs2014.

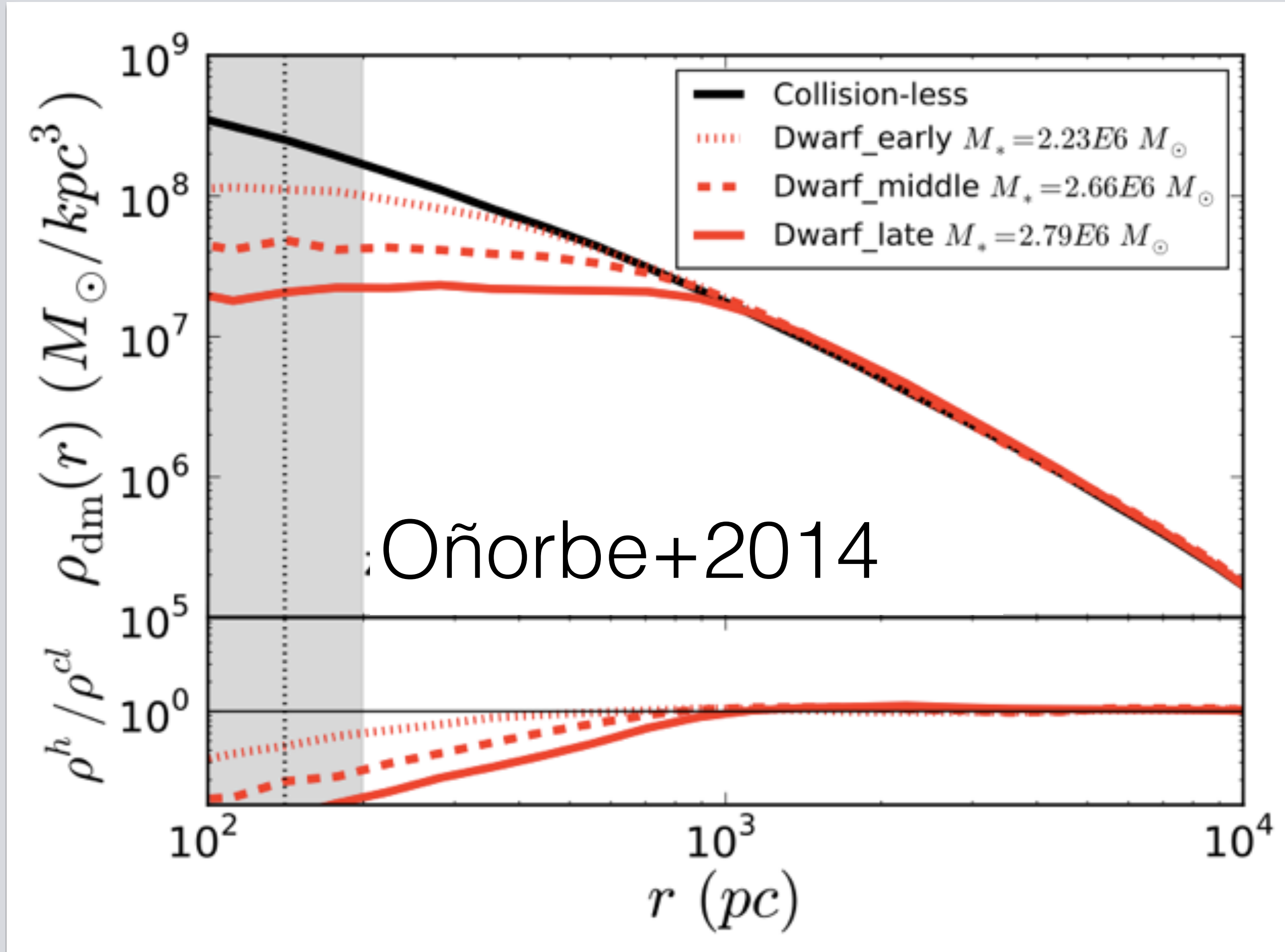
Potsdam, Potsdam

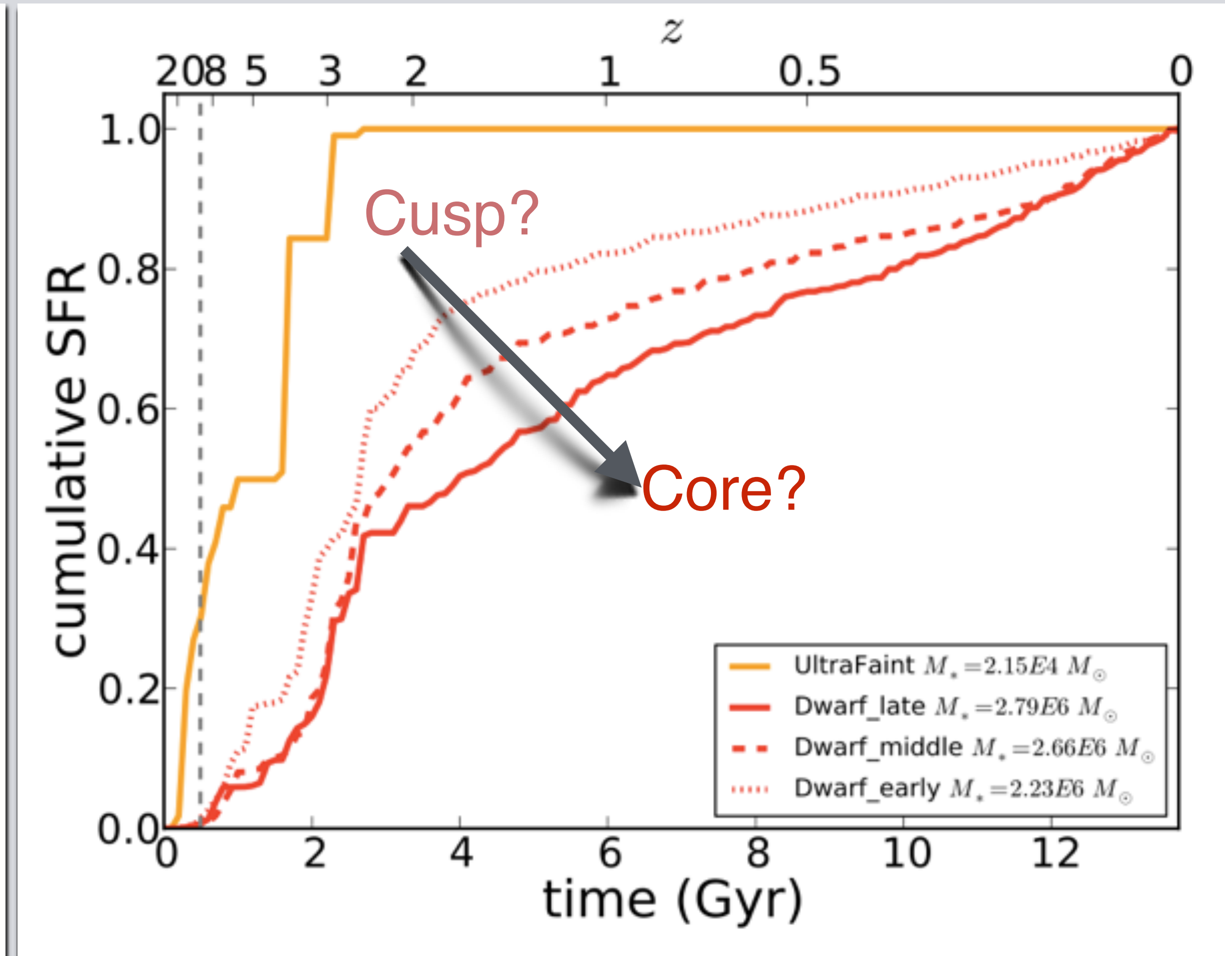
Nicolas Martin @nfmartin1980 · Aug 26

Sleeping during @jbprime's talk. Suddenly he's cursing at sea monsters What happened? Anybody paying attention? #dwarfs2014.

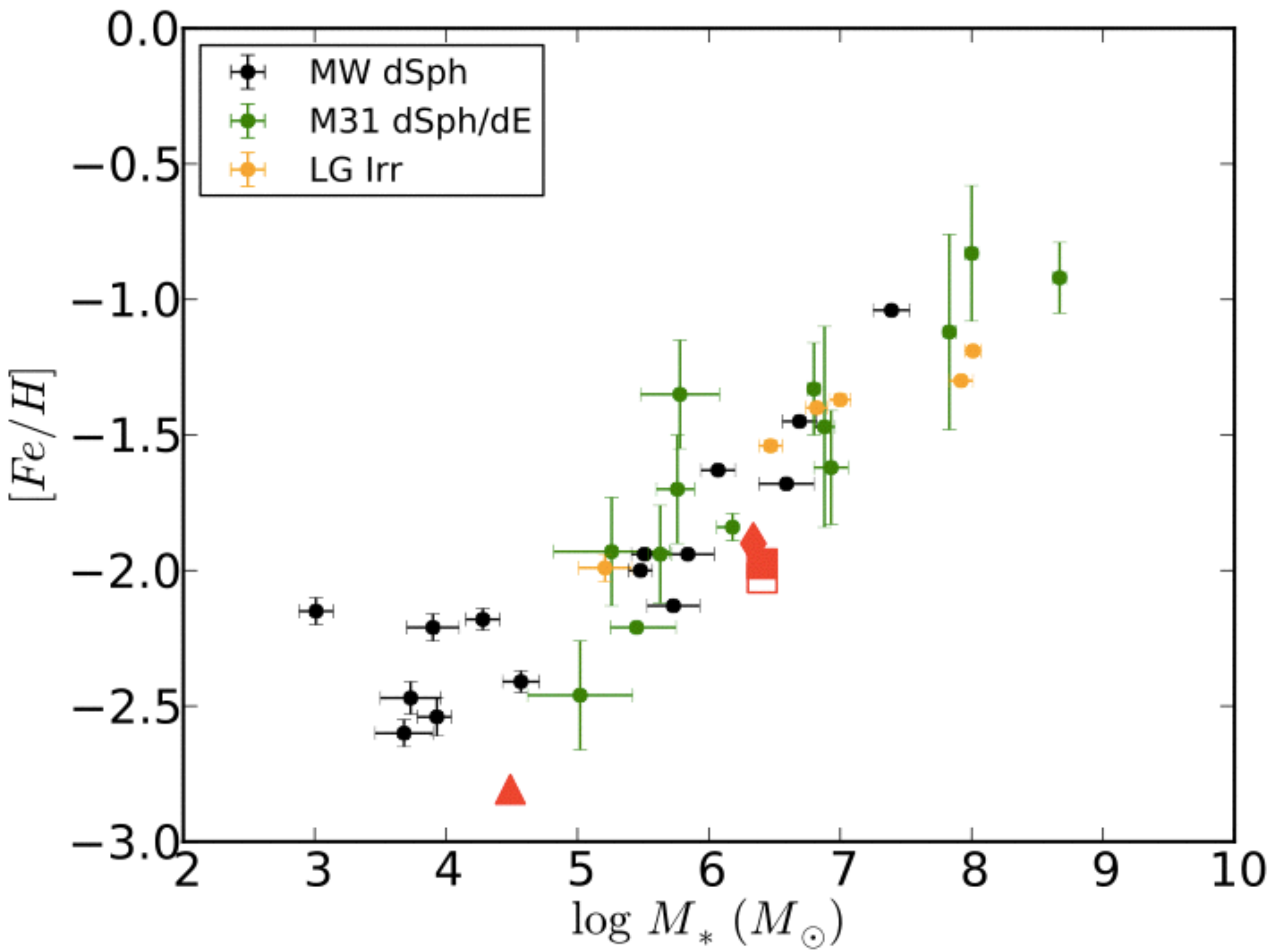
Potsdam, Potsdam

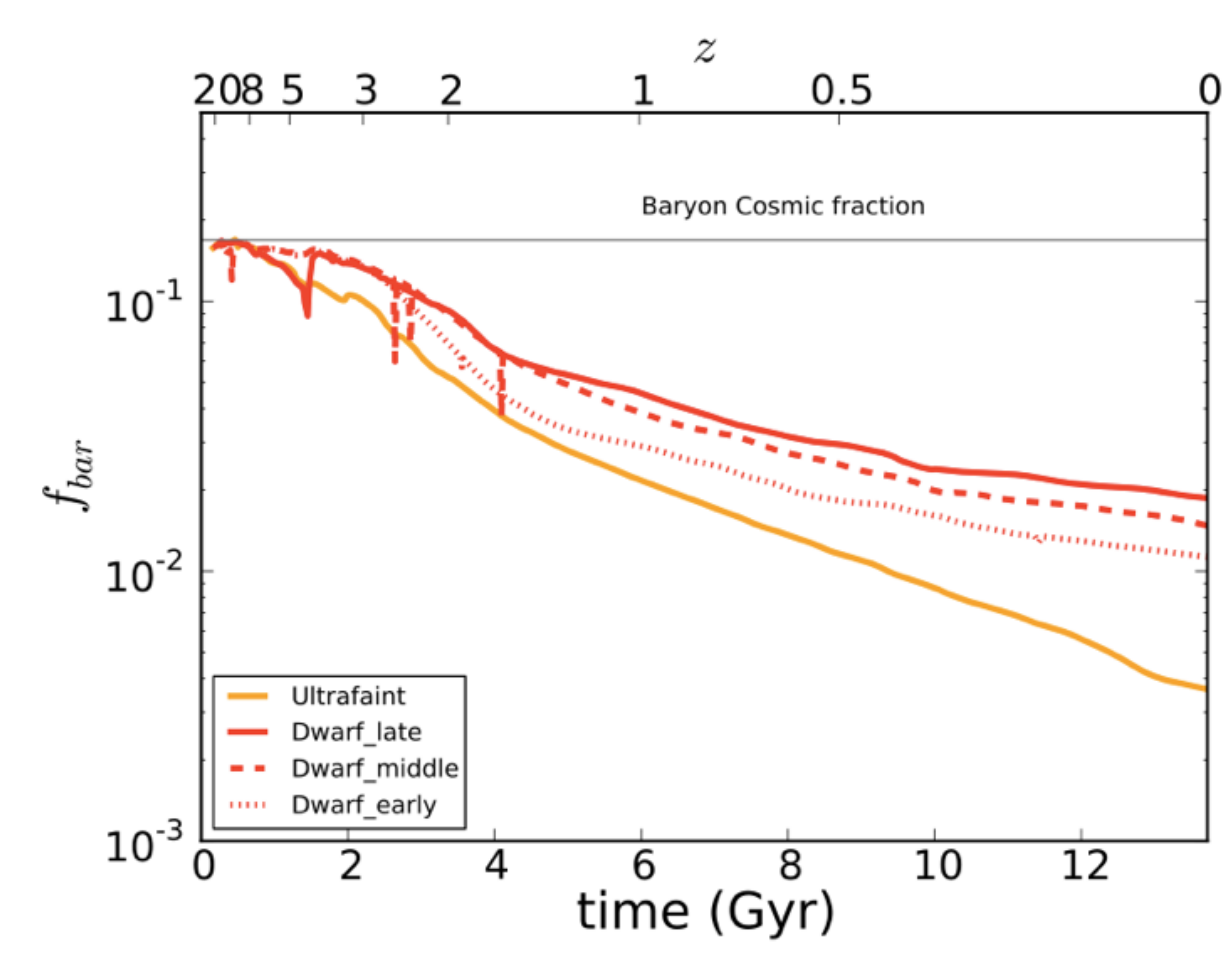
CONCLUSIONS





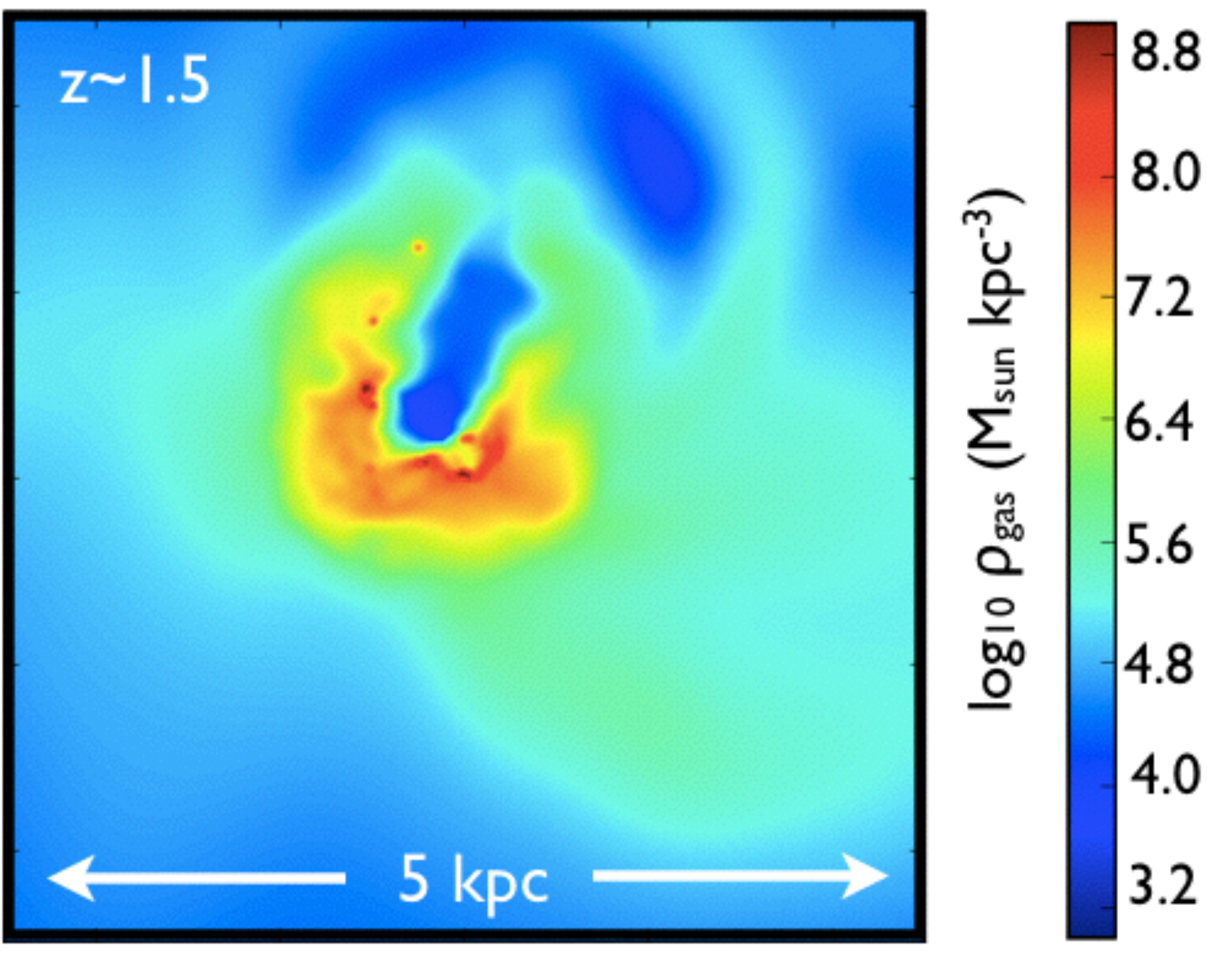
- possible to make cores in even $M_\star \sim 10^6\ M_\odot$ galaxies (first time!)
- not just about *how many* stars form, *when* they form matters
- late star formation (after DM cusps are in place) helps
- likely especially important at this crucial mass scale, where core formation is energetically limited

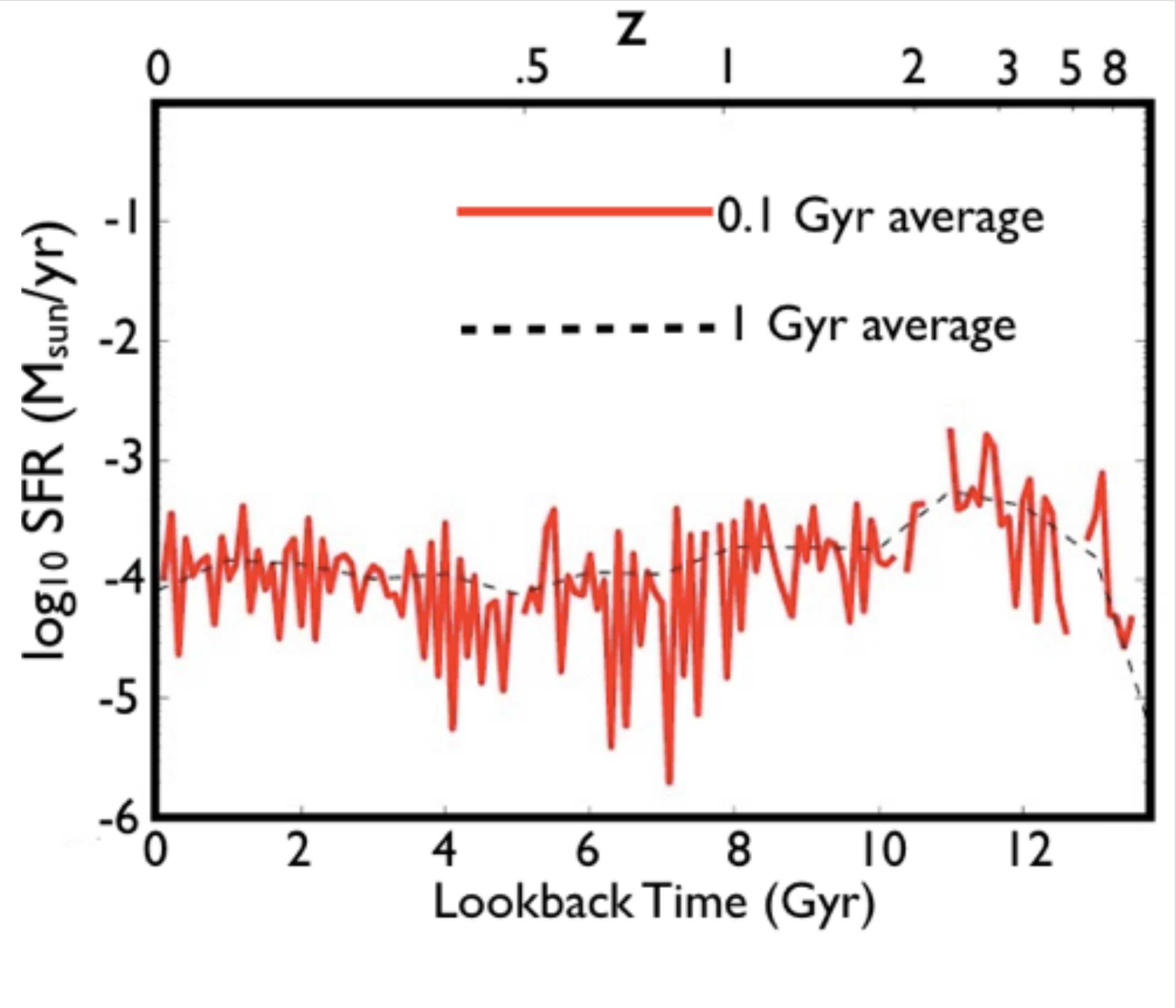

MW dSph
M31 dSph/dE
LG Irr
[Fe/H]
0.0
−0.5
−1.0
−1.5
−2.0
−2.5
−3.0
2
3
4
5
6
7
8
9
10
log M* (M⊙)



z
20
8
5
3
2
1
0.5
0
Baryon Cosmic fraction
f_{bar}
10^{-1}
10^{-2}
10^{-3}
Ultrafaint
Dwarf_late
Dwarf_middle
Dwarf_early
0
2
4
6
8
10
12
time (Gyr)

Bursty SFH


z~1.5
5 kpc
8.8
8.0
7.2
6.4
5.6
4.8
4.0
3.2
log10 ρgas (Msun kpc-3)


z
0
.5
1
2
3
5
8
0.1 Gyr average
1 Gyr average
log10 SFR (Msun/yr)
-1
-2
-3
-4
-5
-6
0
2
4
6
8
10
12
Lookback Time (Gyr)