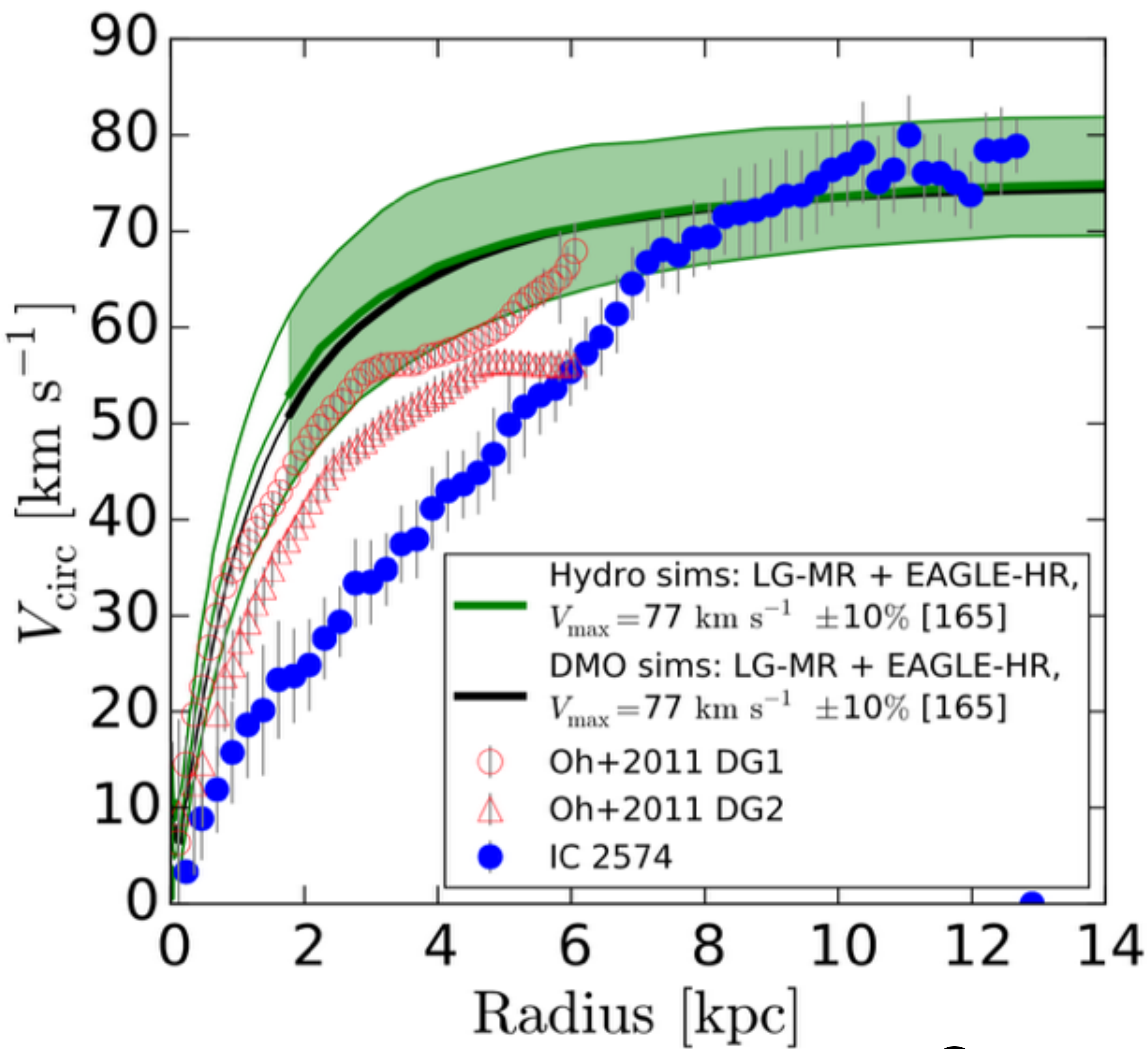
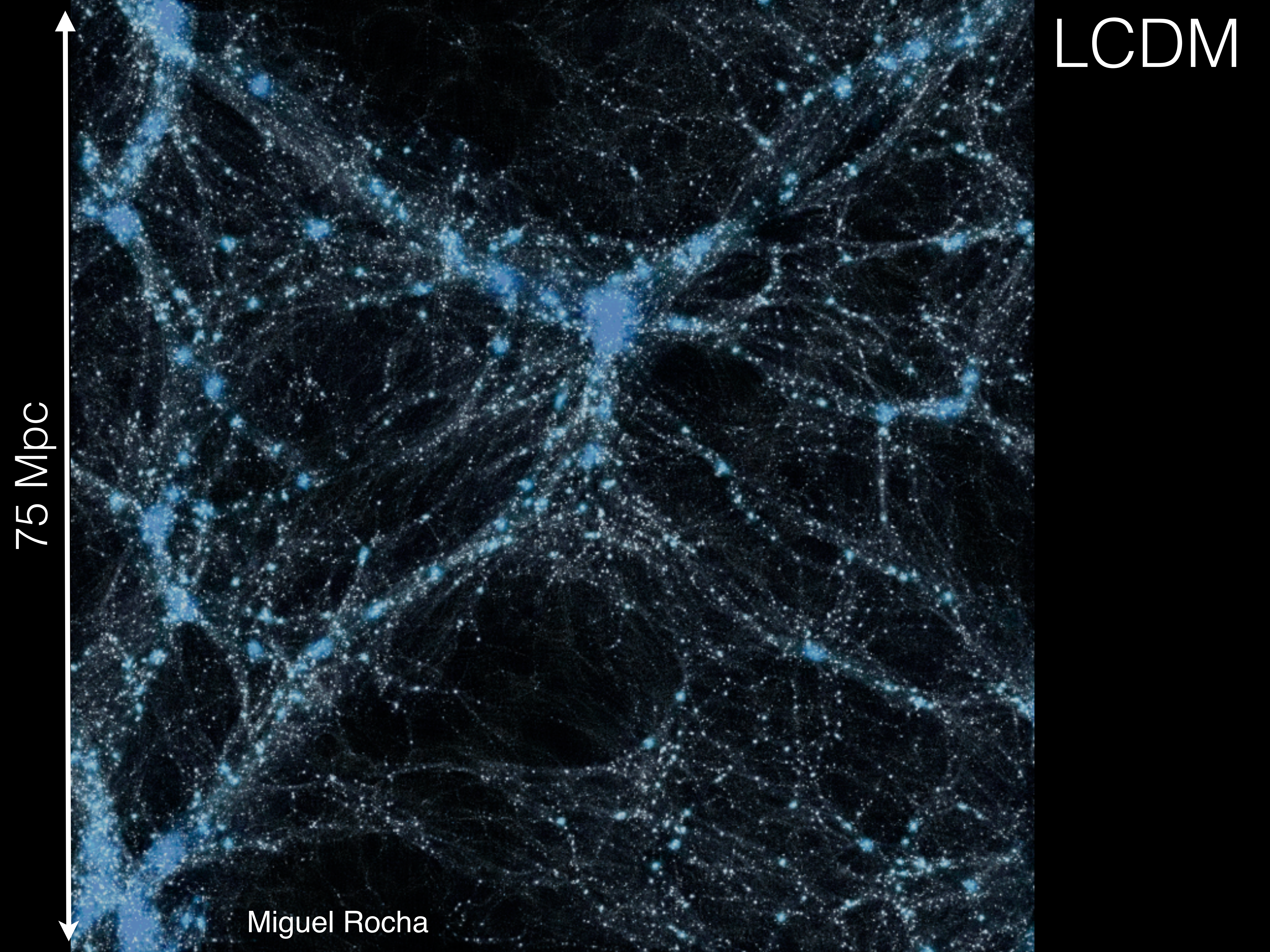
CDM: Small-scale challenges & solutions

James Bullock
(UC Irvine)

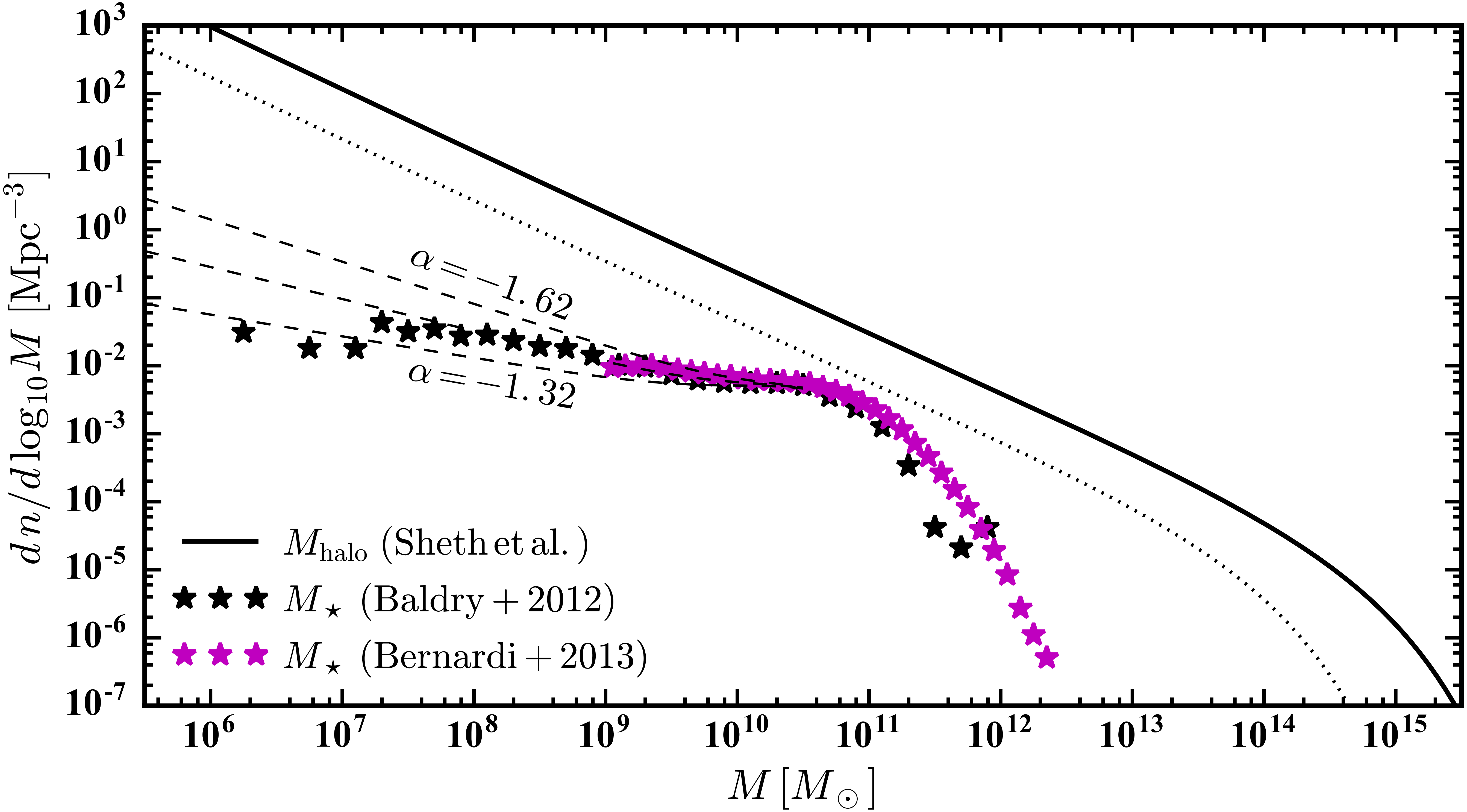
Cusp/core problem

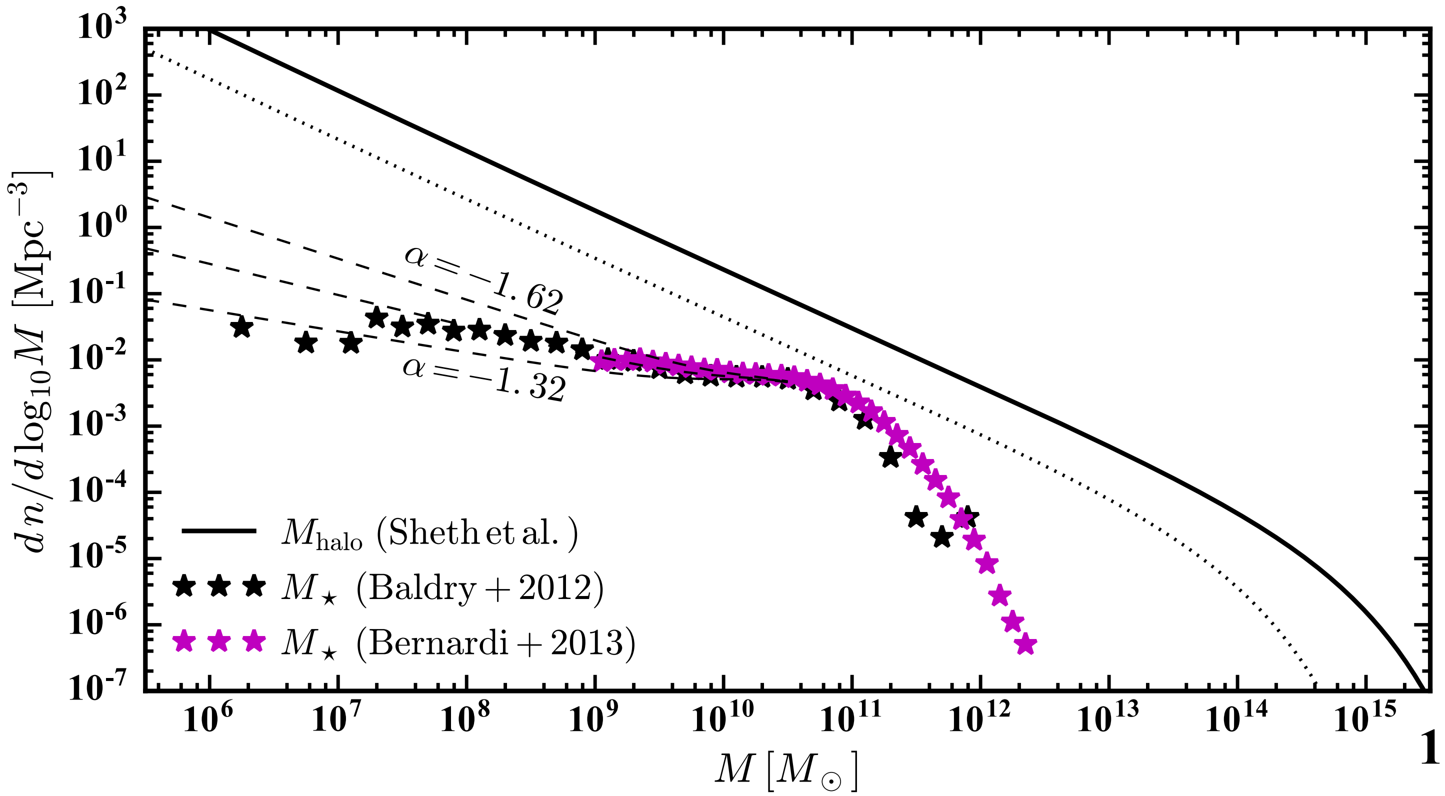


Oman+2015

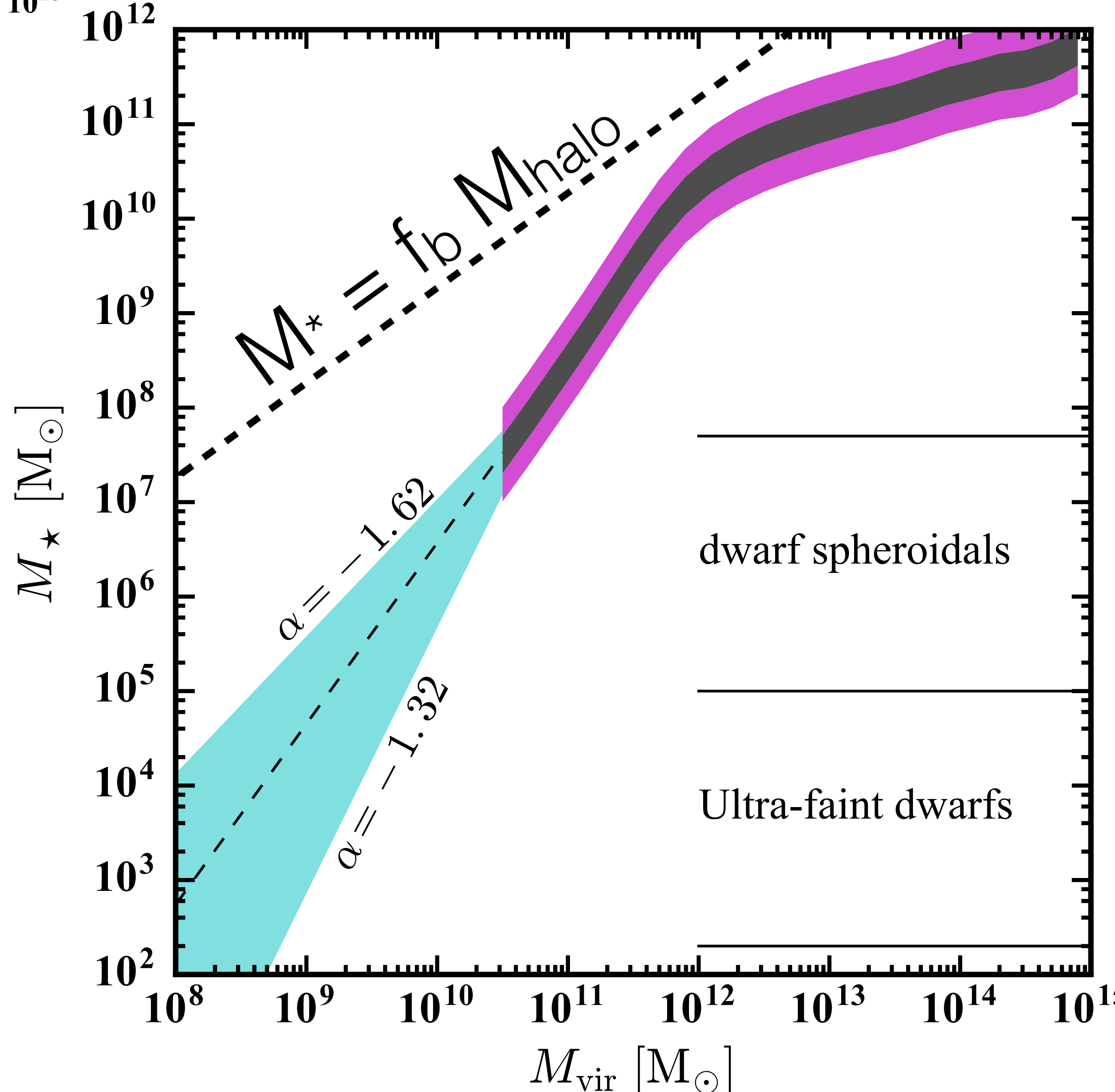

LCDM
75 Mpc
Miguel Rocha

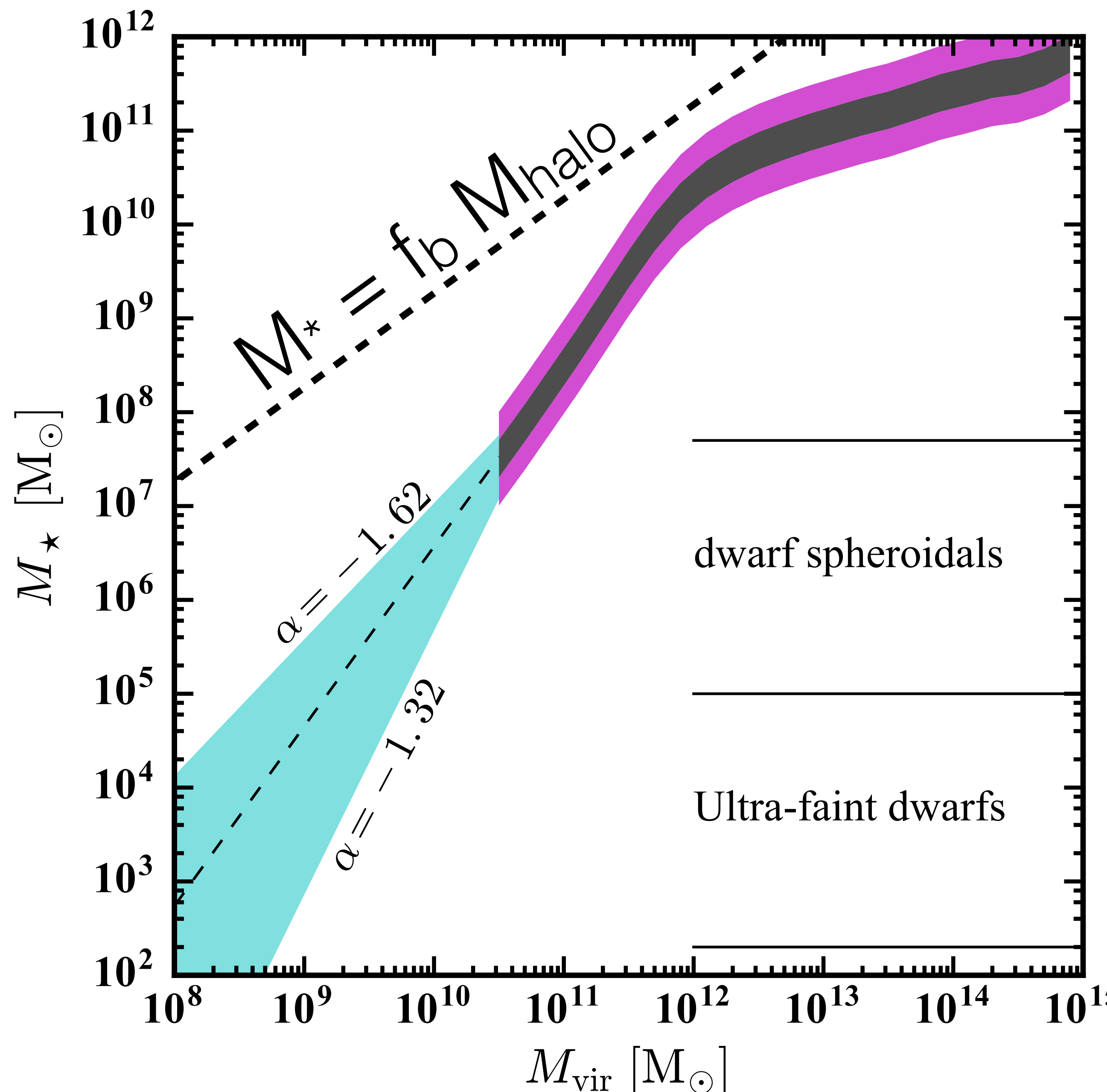
Mass functions compared:
observed stars vs. **predicted dark matter**



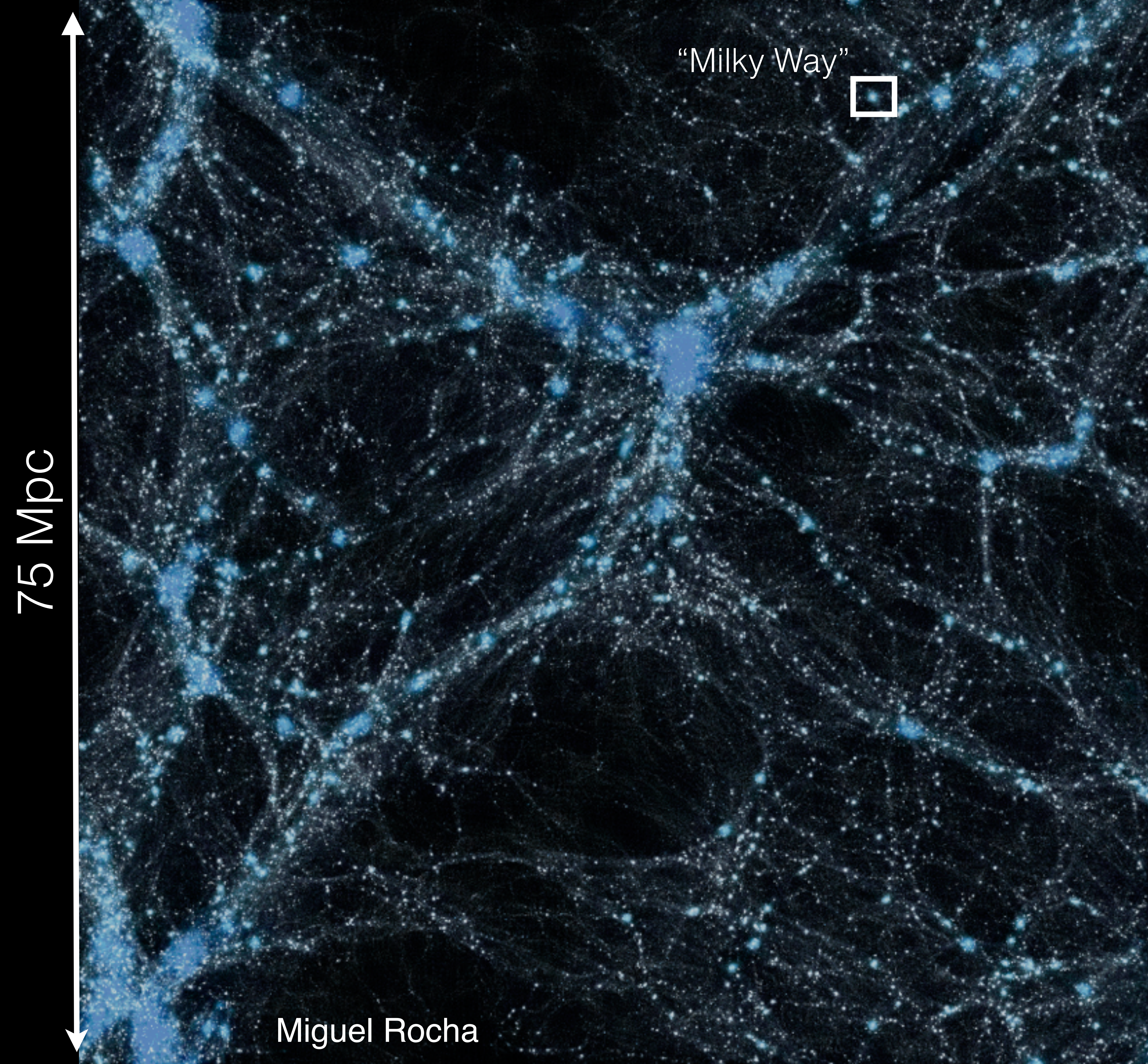


M* vs. Mhalo
that works



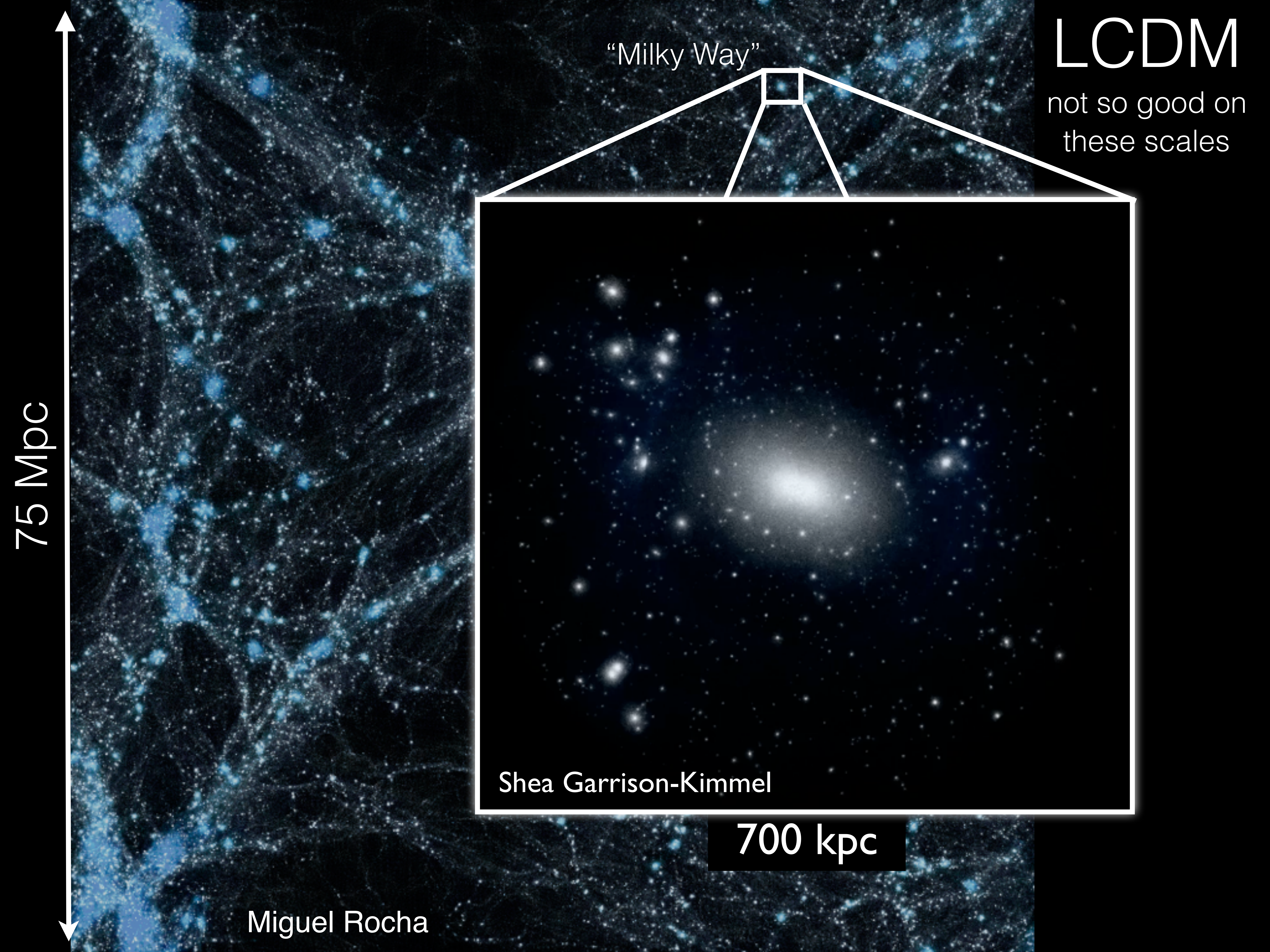


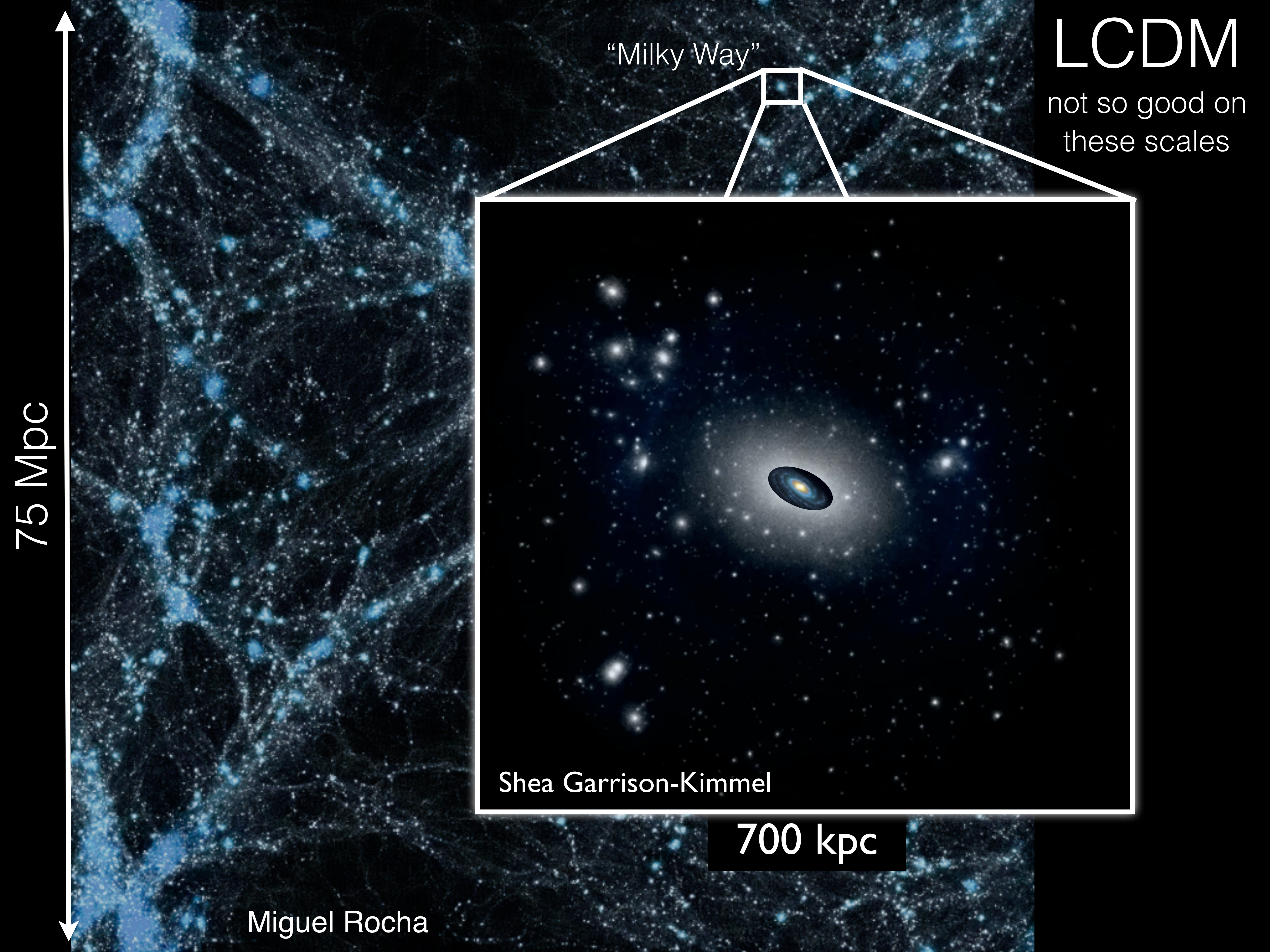
$M_* = f_b\, M_{halo}$
$\alpha = -1.62$
$\alpha = -1.32$
dwarf spheroidals
Ultra-faint dwarfs
$M_\star$ [M$_\odot$]
$M_{\rm vir}$ [M$_\odot$]



LCDM

looks good on these scales


LCDM
not so good on
these scales
“Milky Way”
75 Mpc
Shea Garrison-Kimmel
700 kpc
Miguel Rocha


LCDM
not so good on
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"Milky Way"
75 Mpc
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700 kpc
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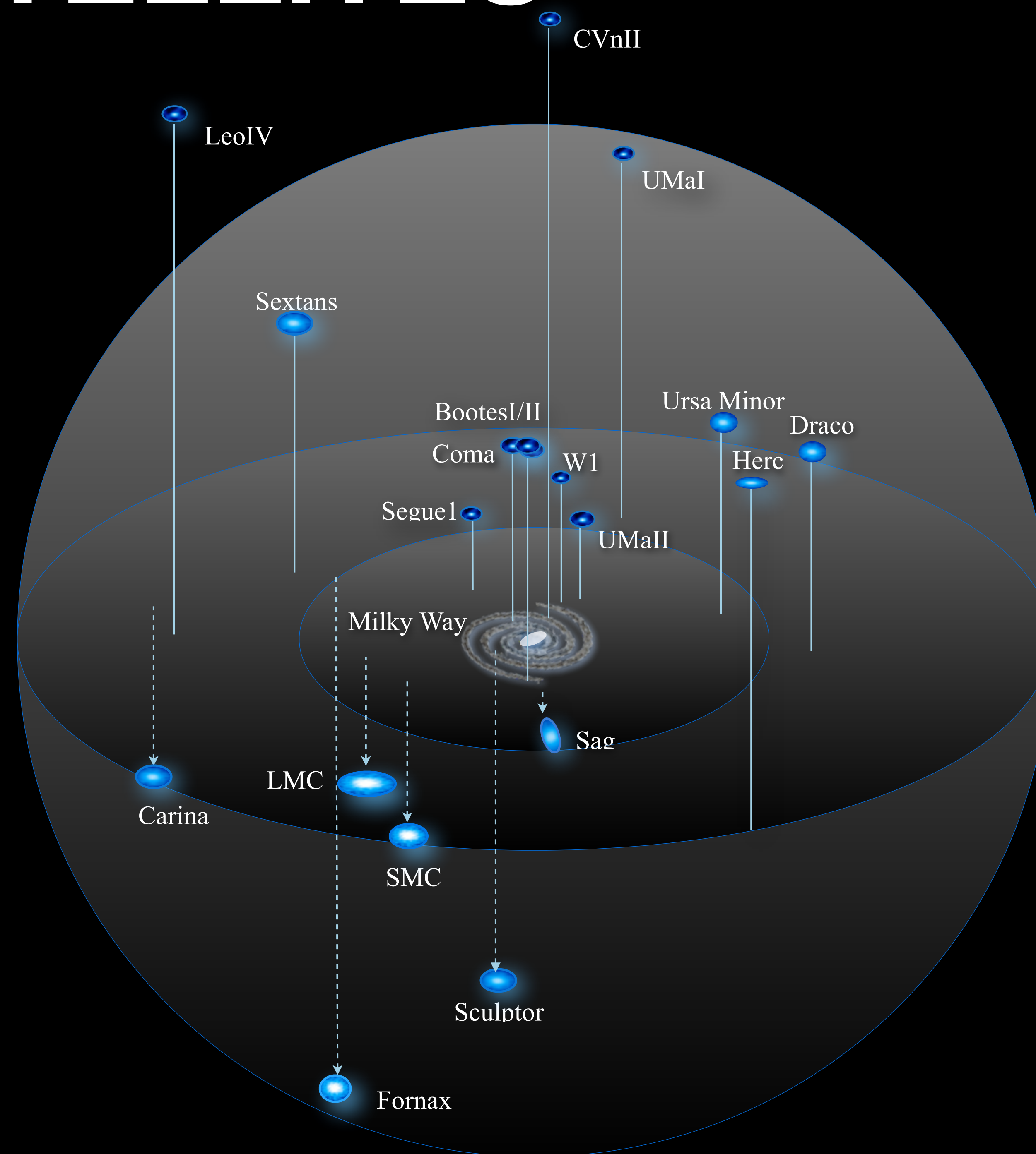
MISSING SATELLITES

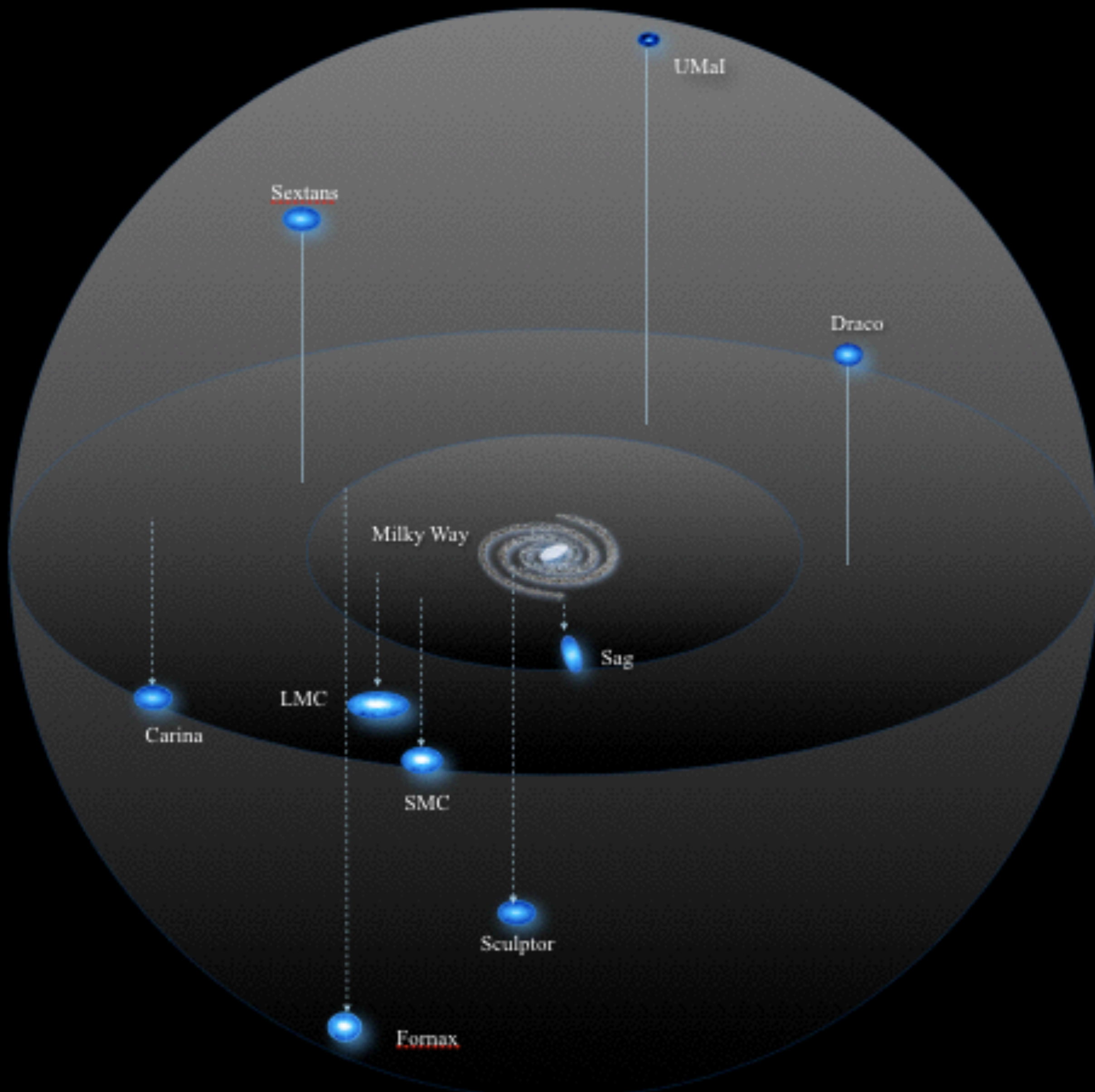


Theory: N>>1000

Observation: N~50

Klypin et al. 1999; Moore et al. 1999

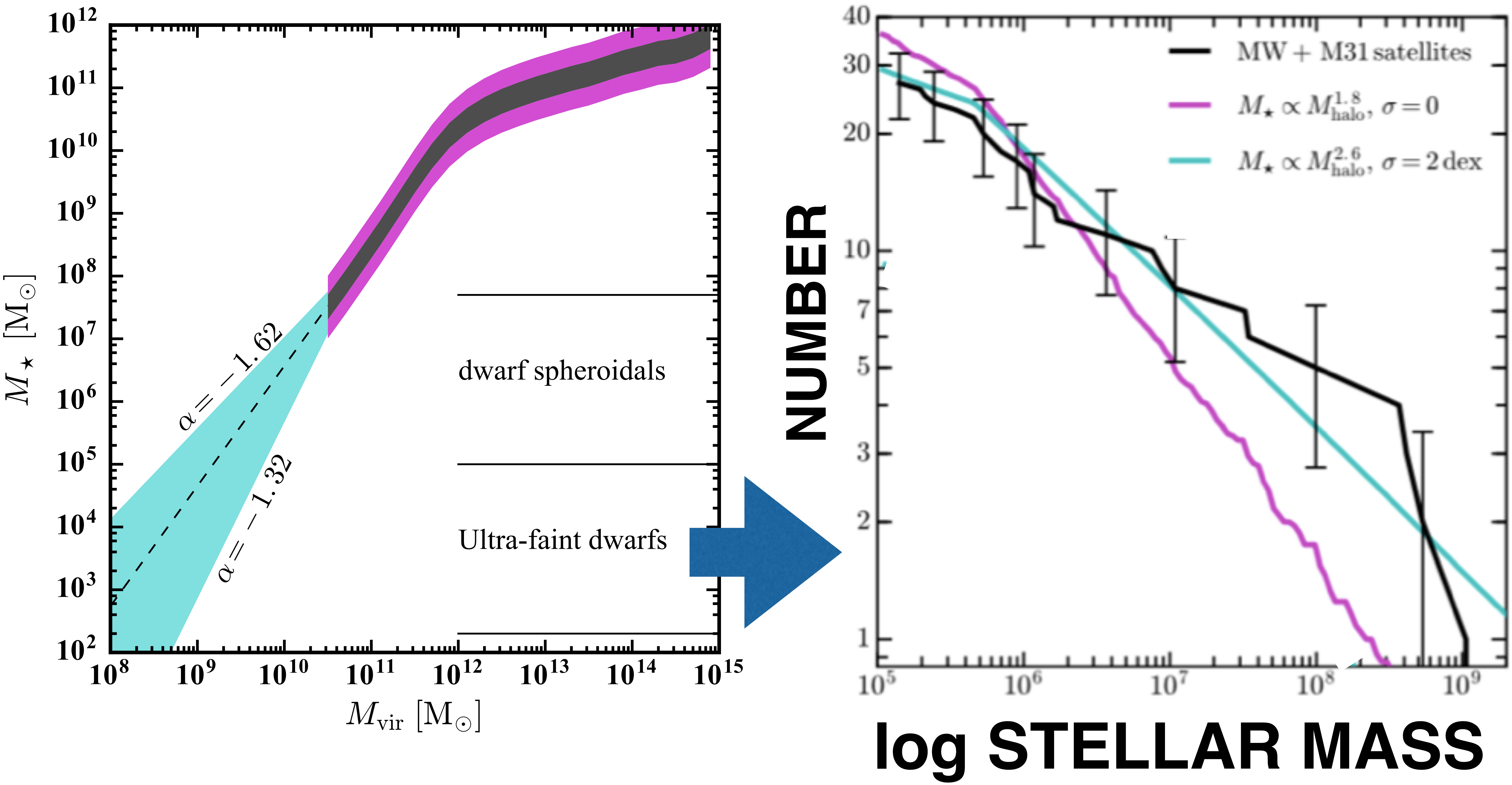
“EASY” ANSWER



only the biggest clumps have enough stars to see?

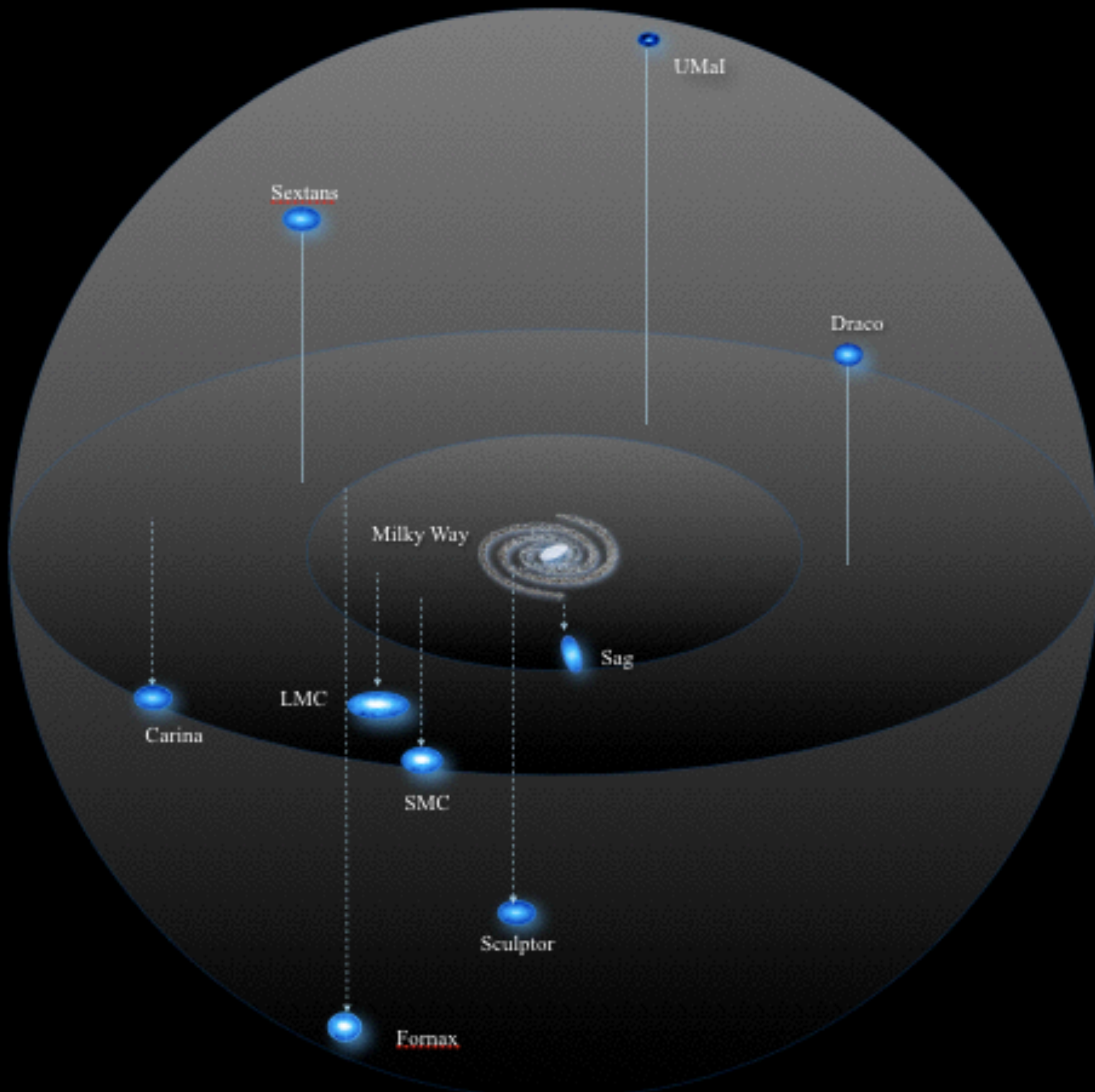
e.g. JSB, Kravtsov, & Weinberg 2000

Extrapolated large-scale relation “solves” missing satellite problem

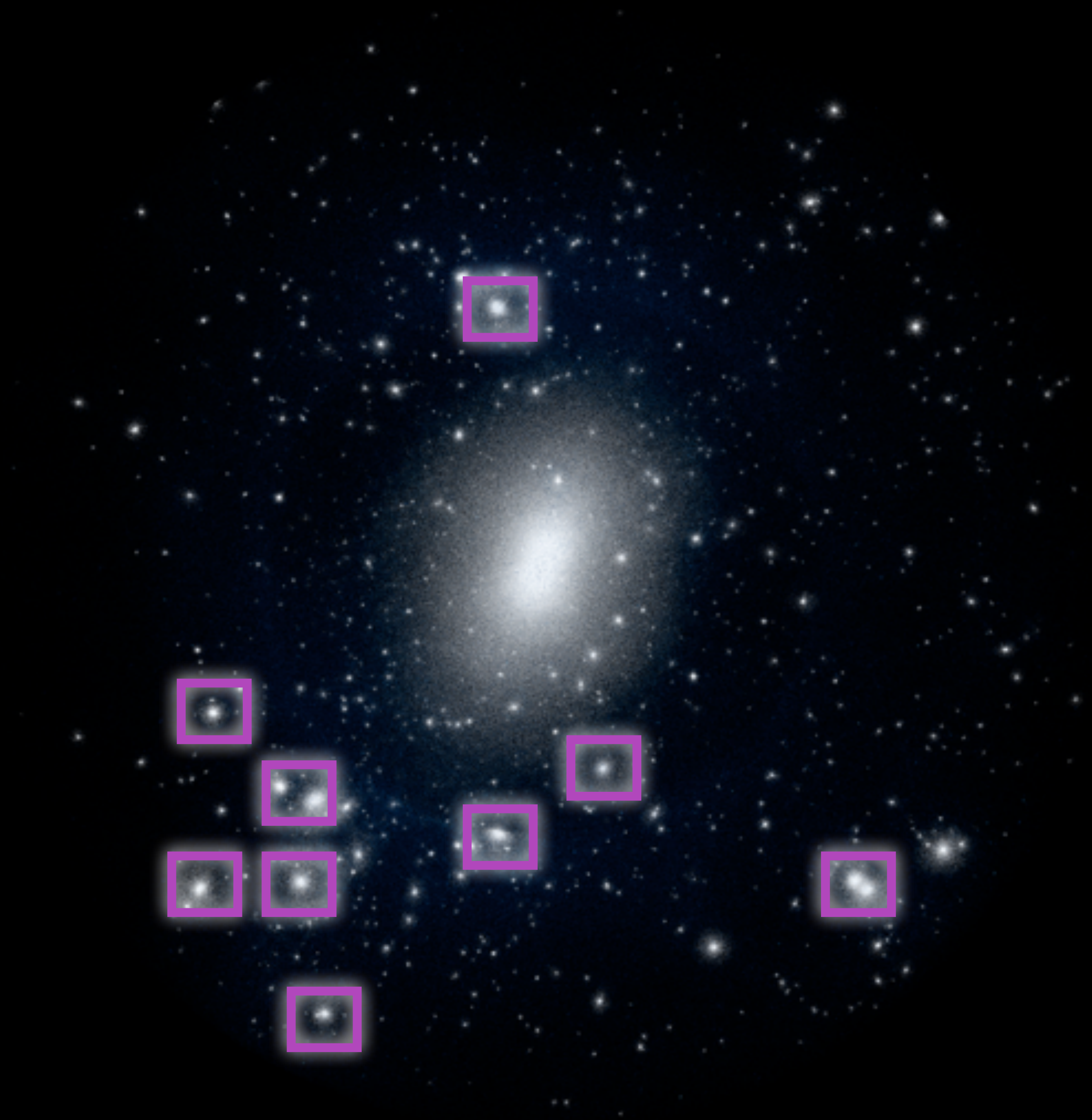


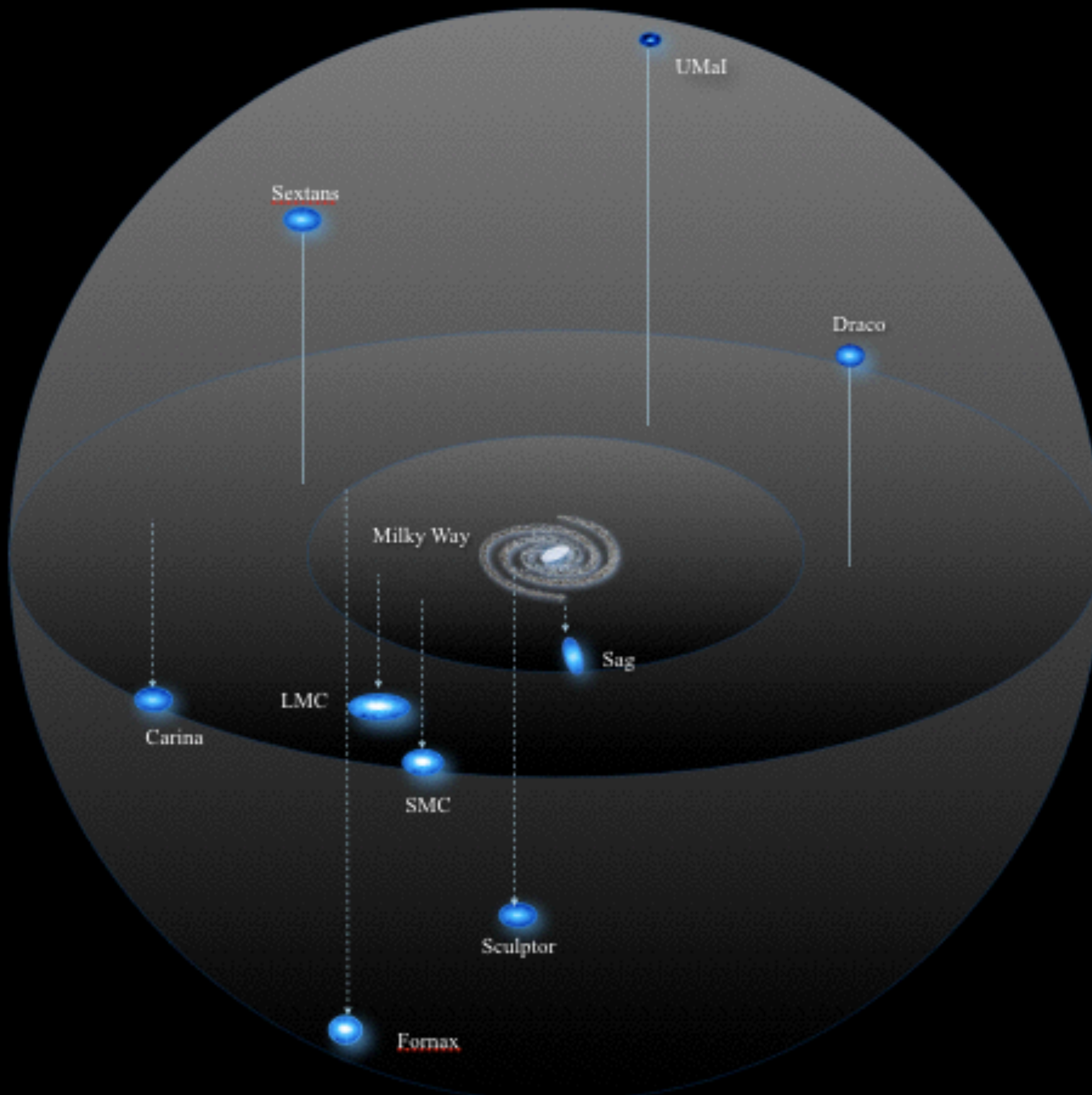
Garrison-Kimmel+2016

"EASY" ANSWER


UMaI
Sextans
Draco
Milky Way
Sag
LMC
Carina
SMC
Sculptor
Fornax

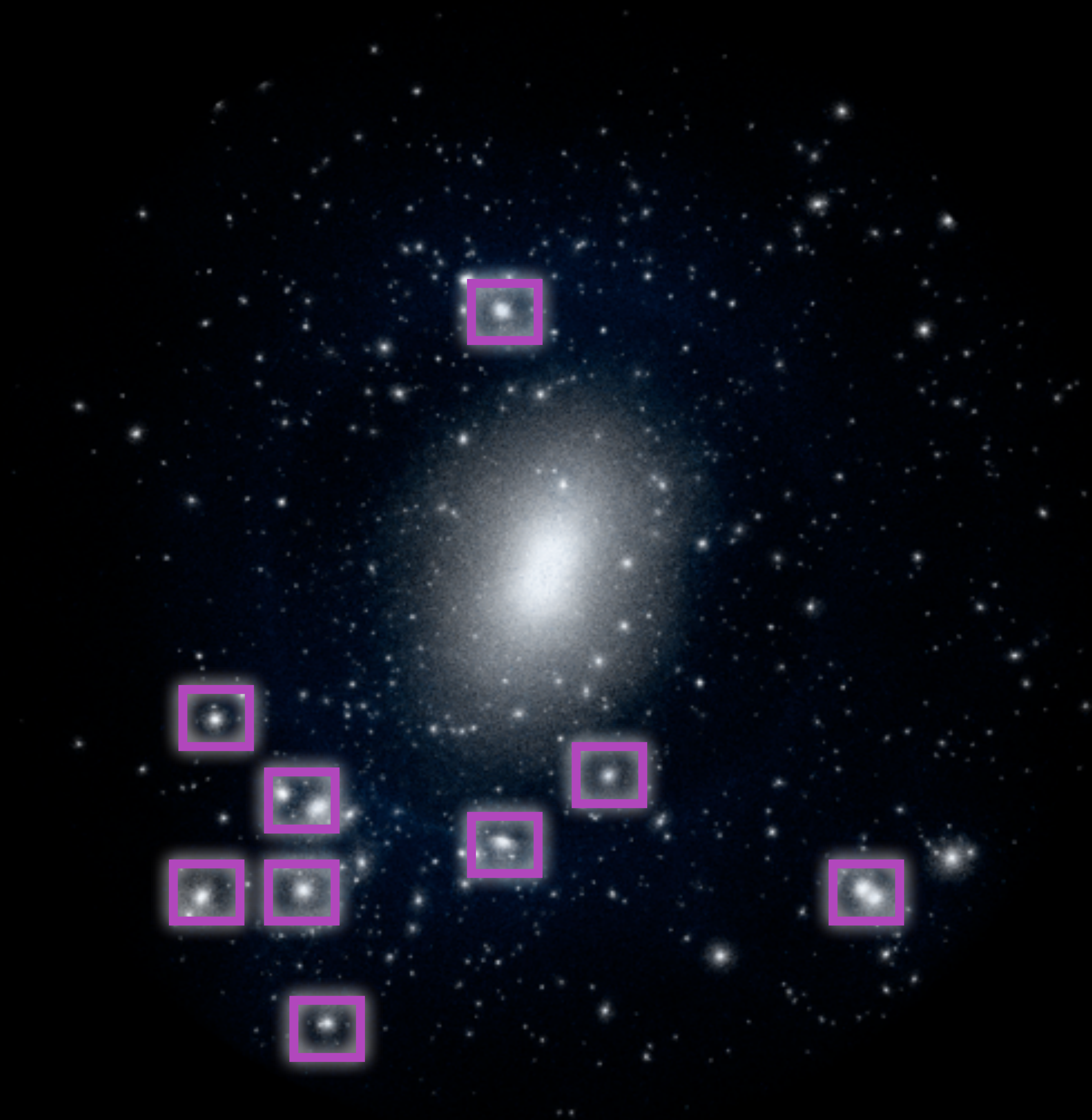
"EASY" ANSWER

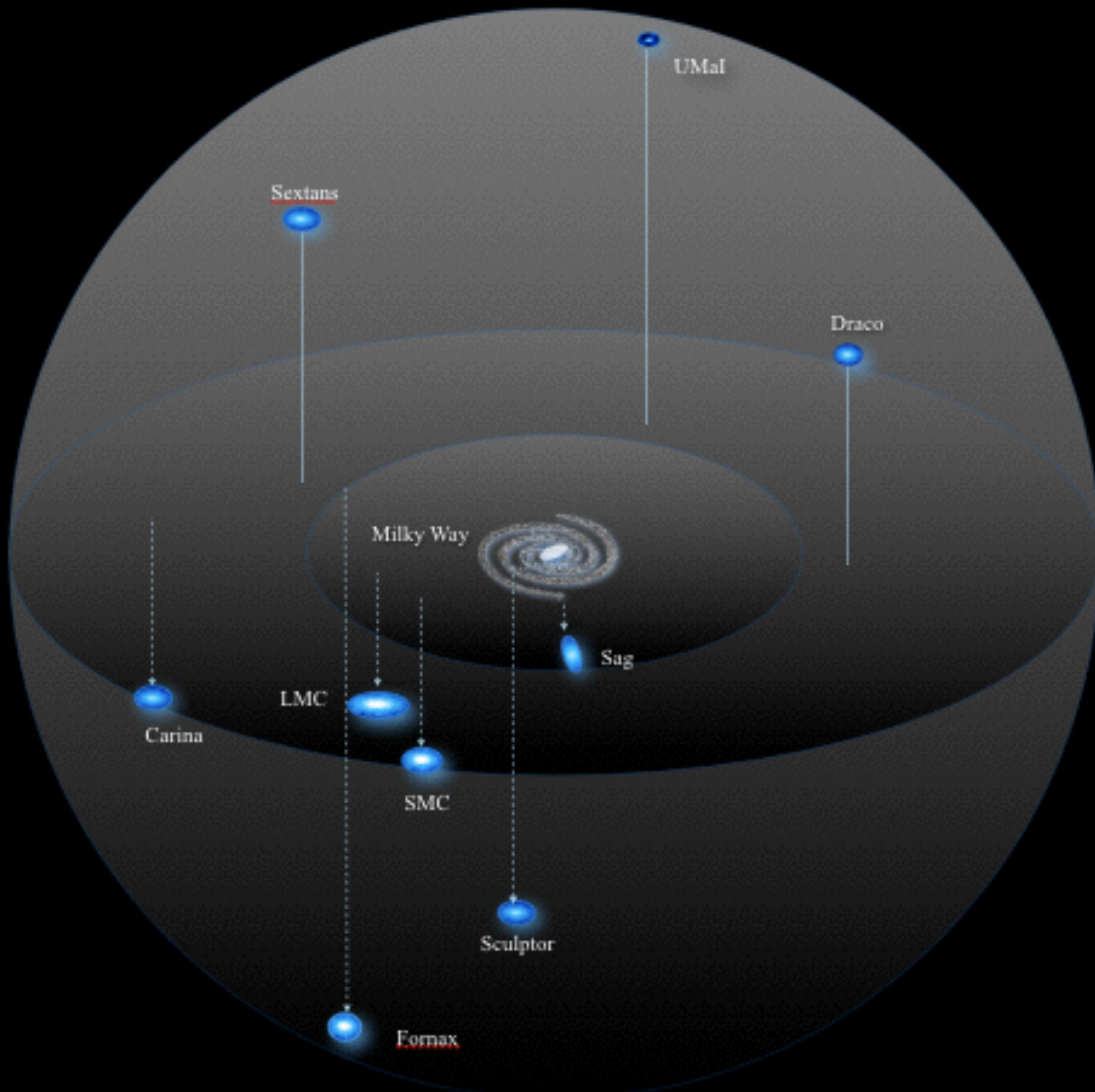




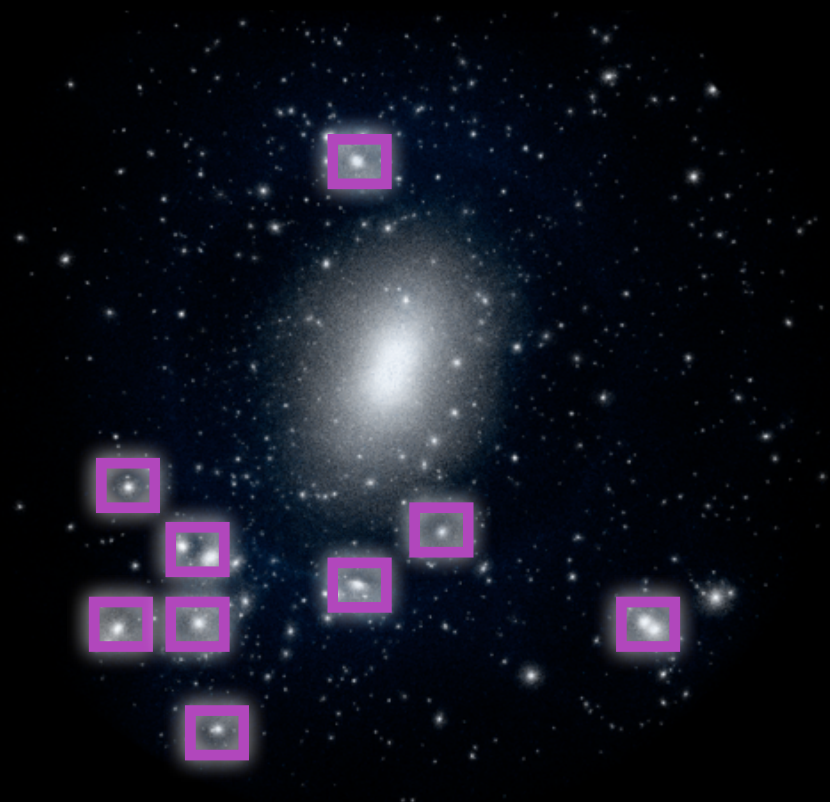
only biggest halos have enough stars to see

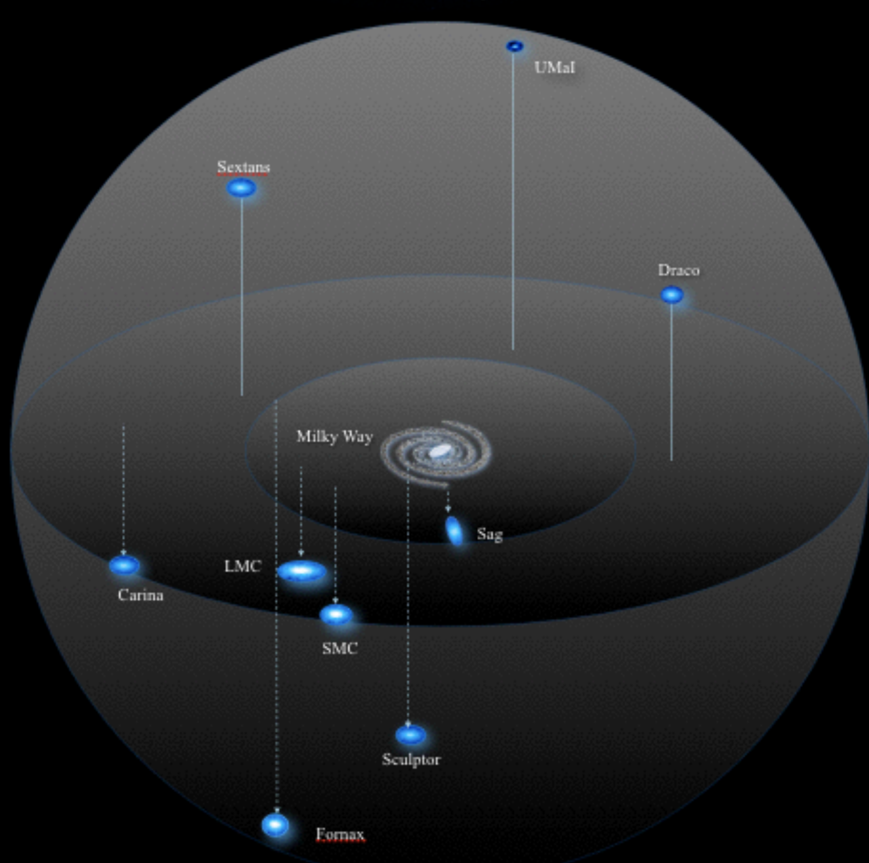
DOES THIS ACTUALLY WORK?

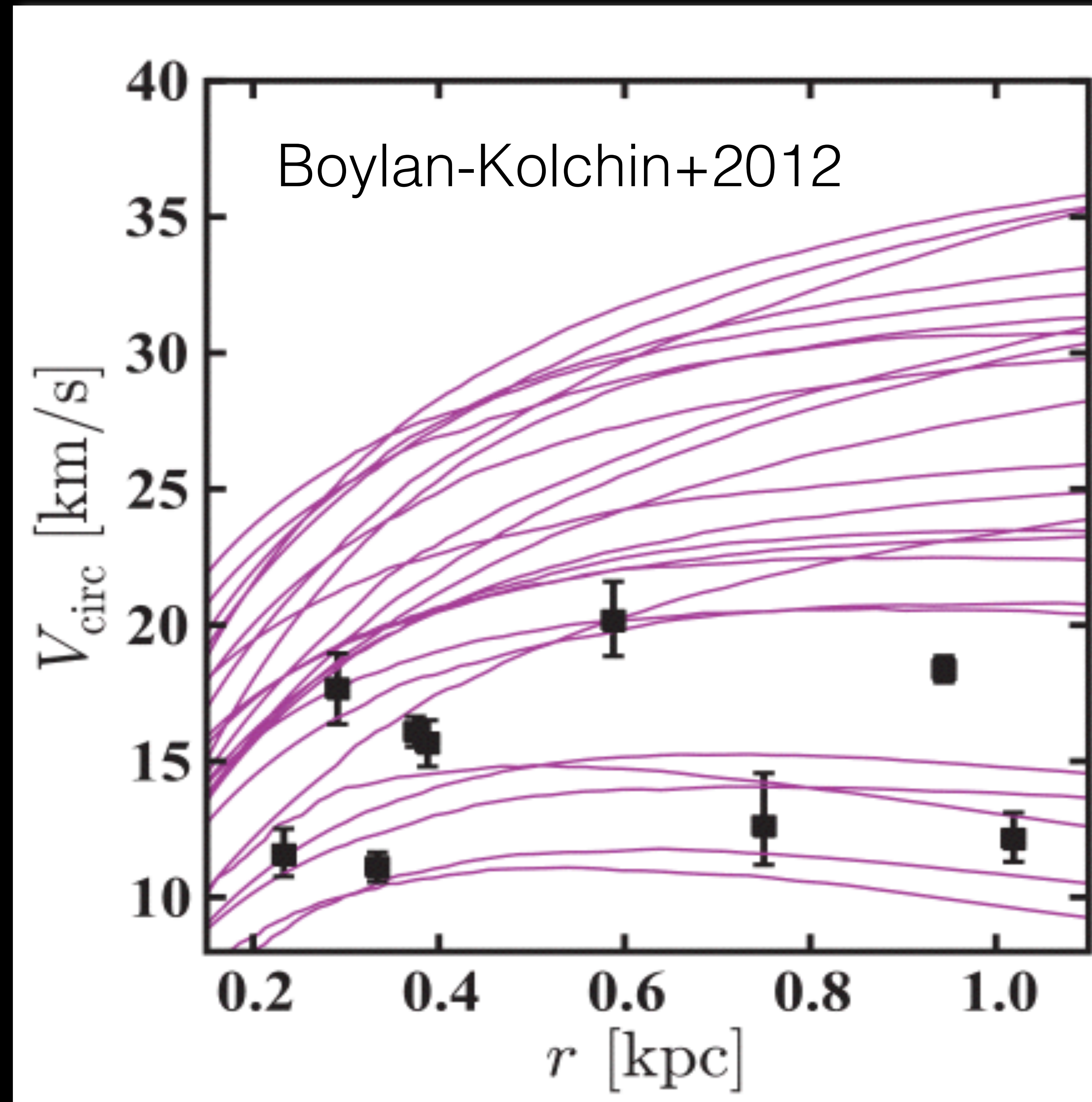




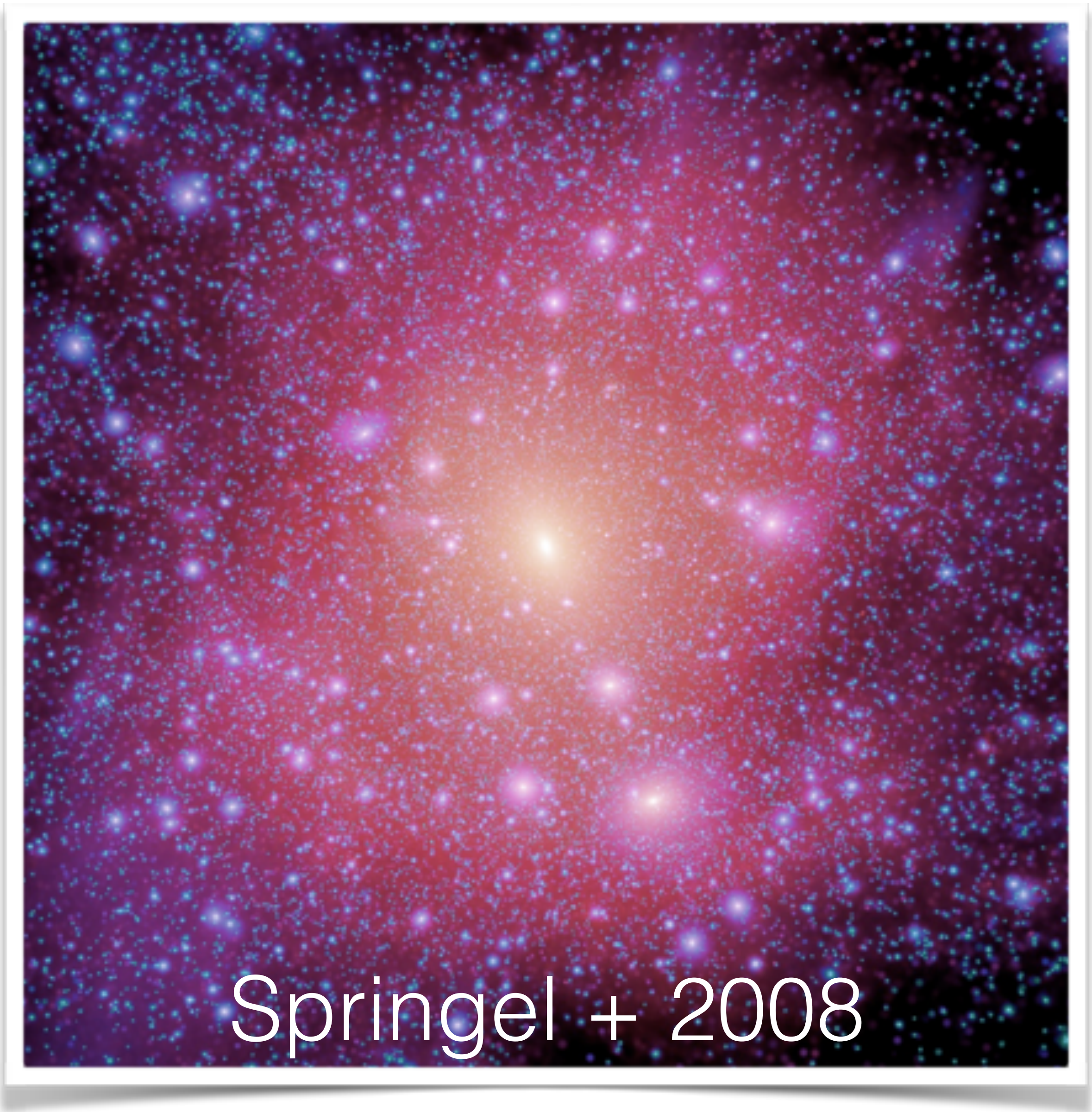
NOPE: "TOO BIG TO FAIL PROBLEM"
Massive subhalos are too dense to match data

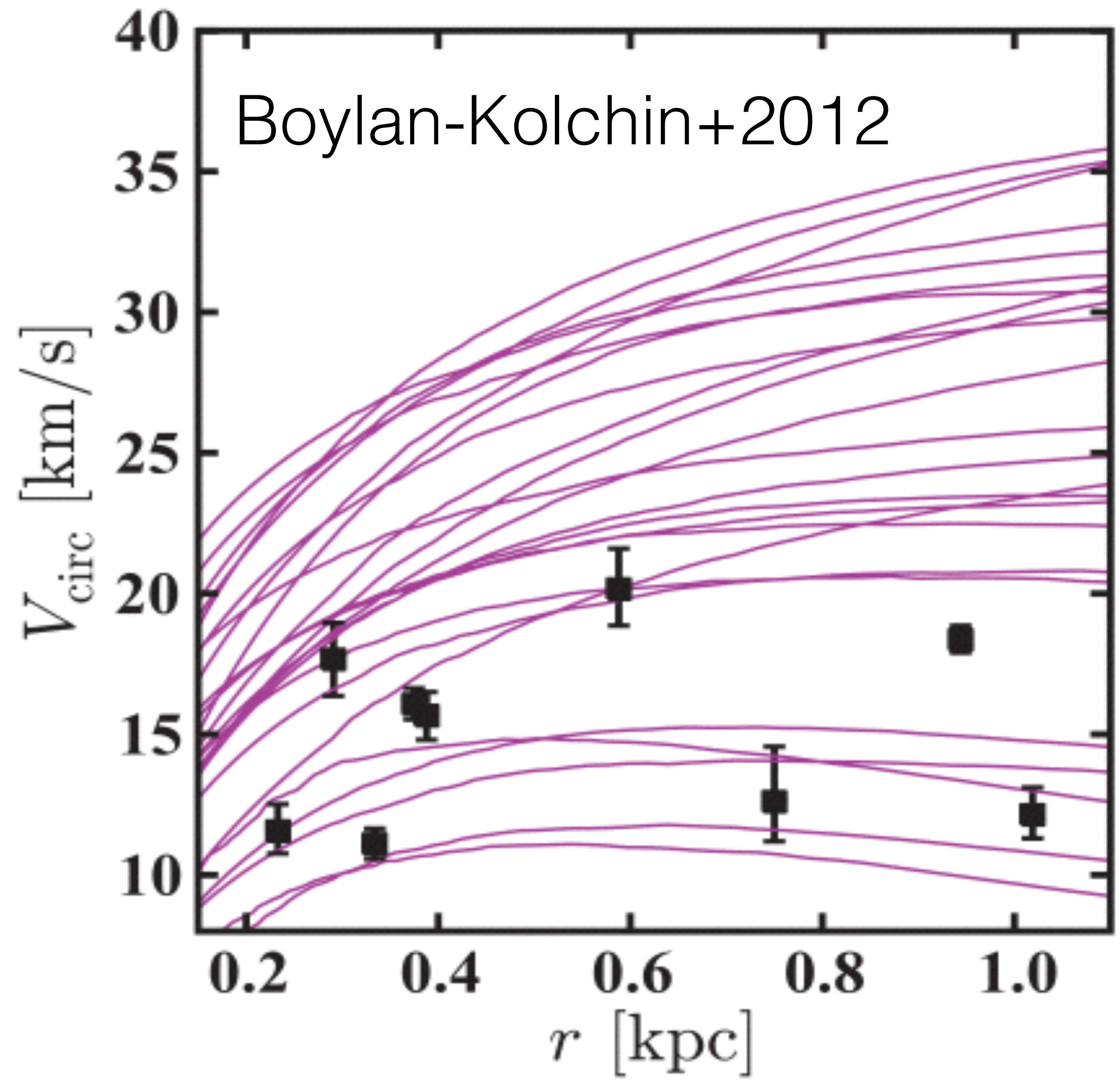




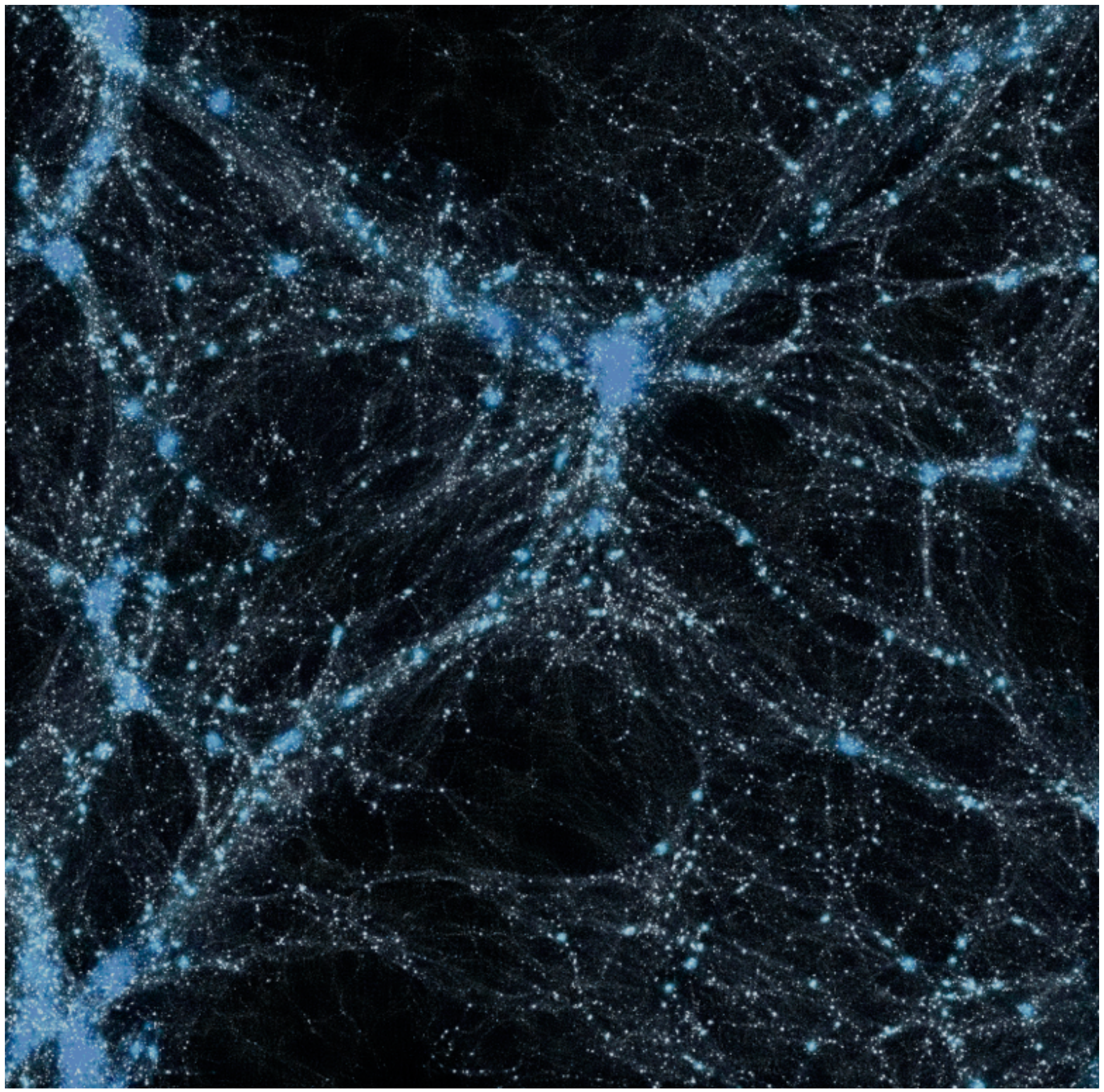


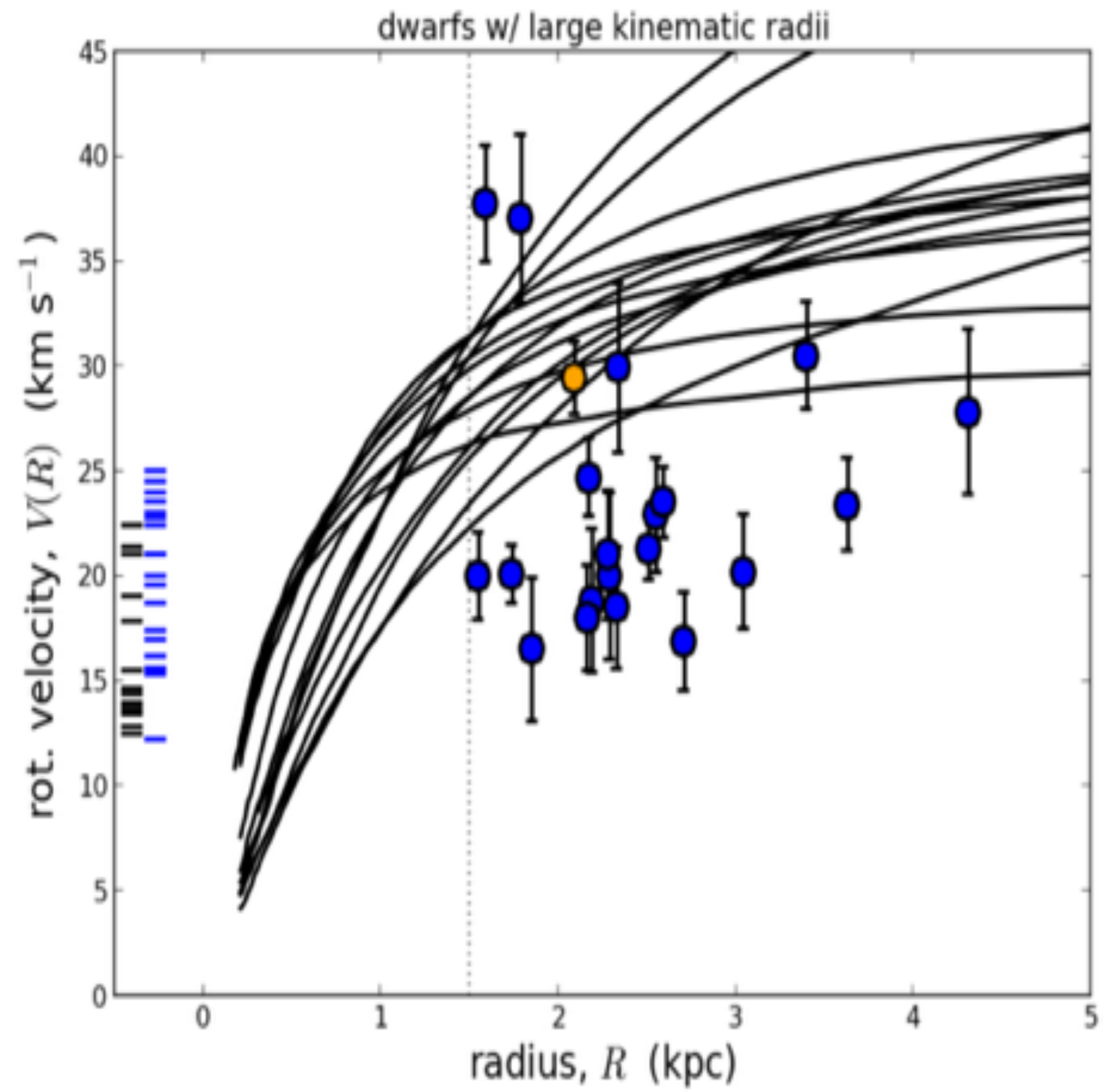
TOO BIG TO FAIL IN THE MILKY WAY



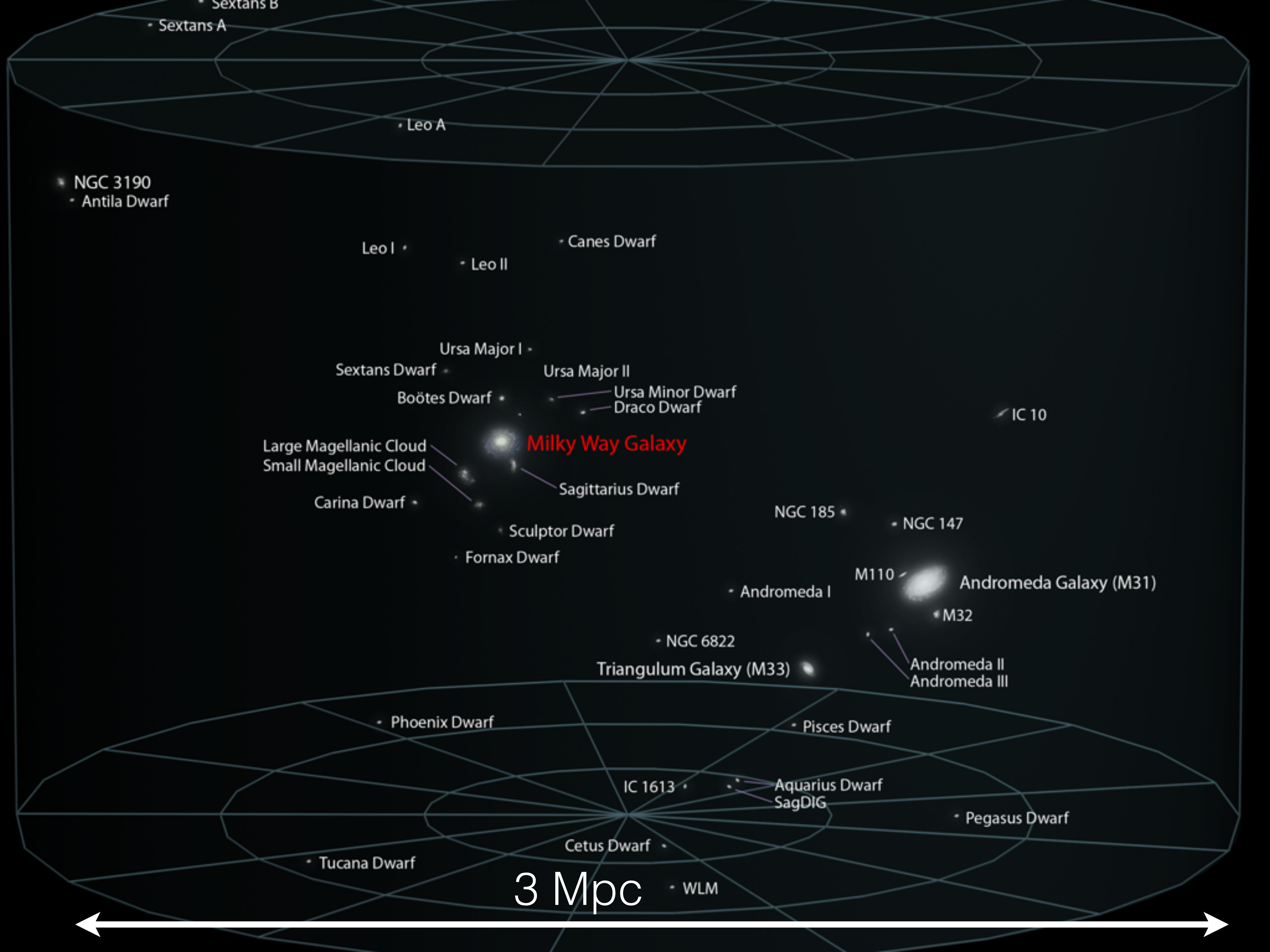


TOO BIG TO FAIL IN THE FIELD

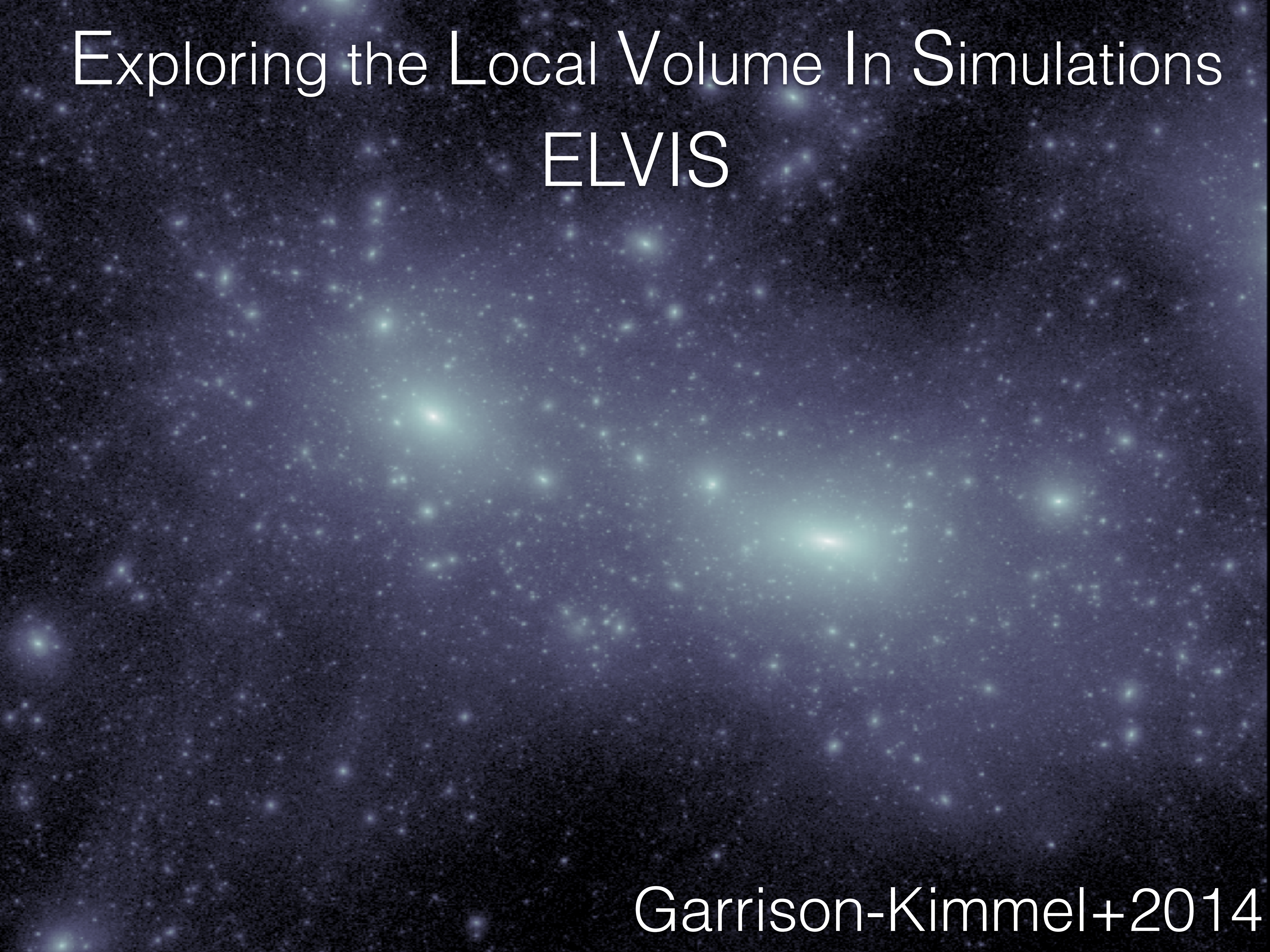




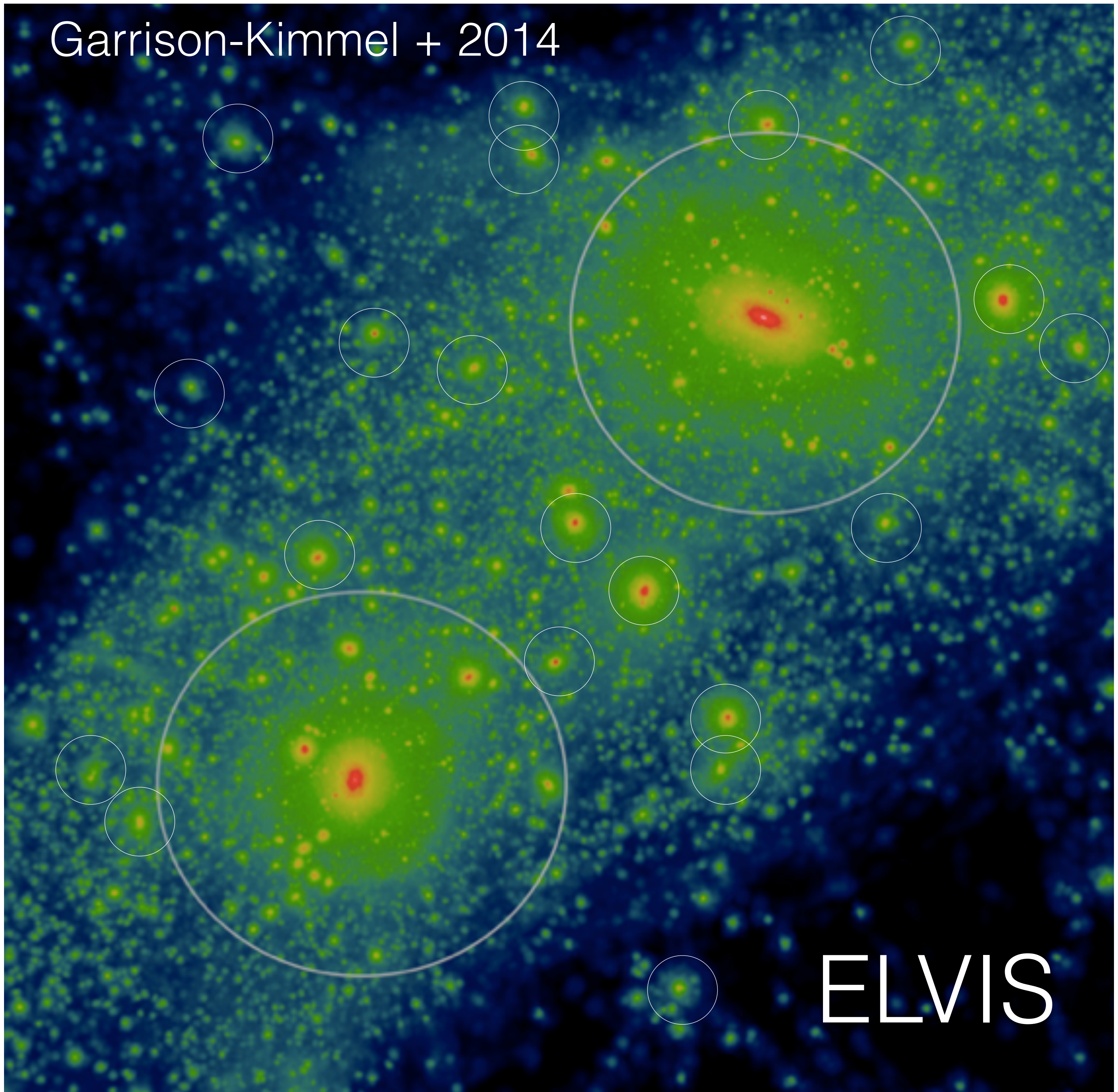
Papastergis & Ponomareva 2016



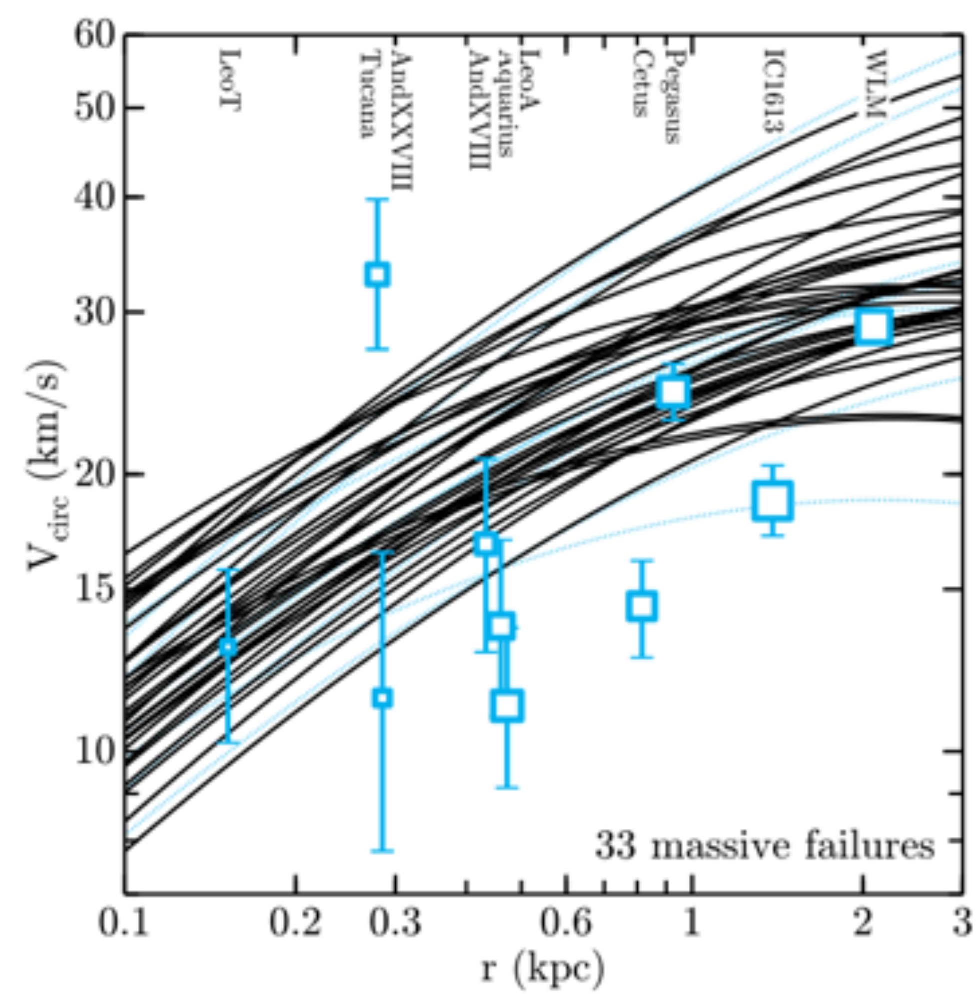
Sextans B
Sextans A
Leo A
NGC 3190
Antila Dwarf
Leo I
Canes Dwarf
Leo II
Ursa Major I
Sextans Dwarf
Ursa Major II
Ursa Minor Dwarf
Boötes Dwarf
Draco Dwarf
IC 10
Large Magellanic Cloud
Milky Way Galaxy
Small Magellanic Cloud
Sagittarius Dwarf
Carina Dwarf
NGC 185
NGC 147
Sculptor Dwarf
Fornax Dwarf
M110
Andromeda Galaxy (M31)
Andromeda I
M32
NGC 6822
Triangulum Galaxy (M33)
Andromeda II
Andromeda III
Phoenix Dwarf
Pisces Dwarf
IC 1613
Aquarius Dwarf
SagDIG
Pegasus Dwarf
Cetus Dwarf
Tucana Dwarf
3 Mpc
WLM


Exploring the Local Volume In Simulations
ELVIS
Garrison-Kimmel+2014

TOO BIG TO FAIL IN THE LOCAL GROUP

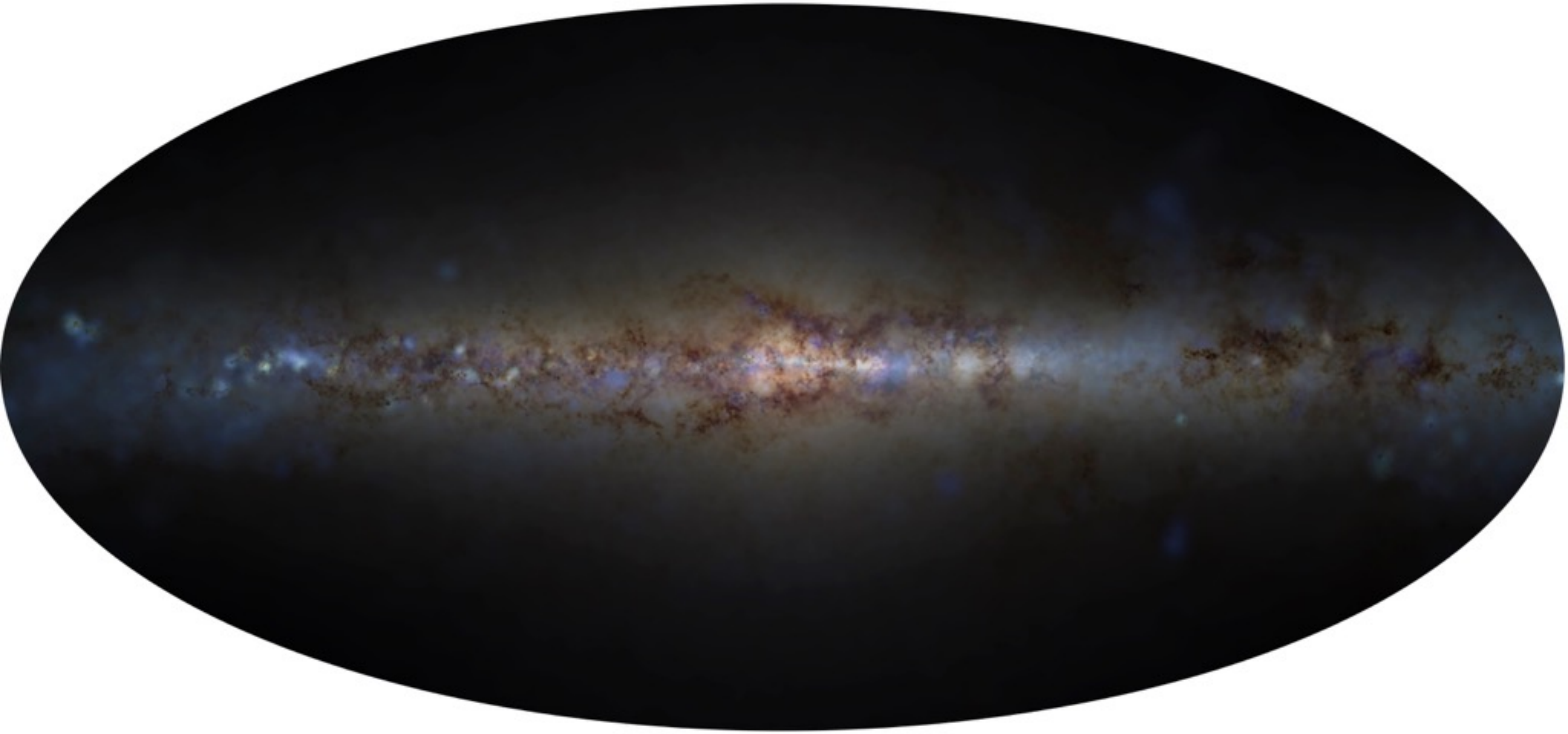


New kinematic masses for Local Group dwarfs by Kirby+2014

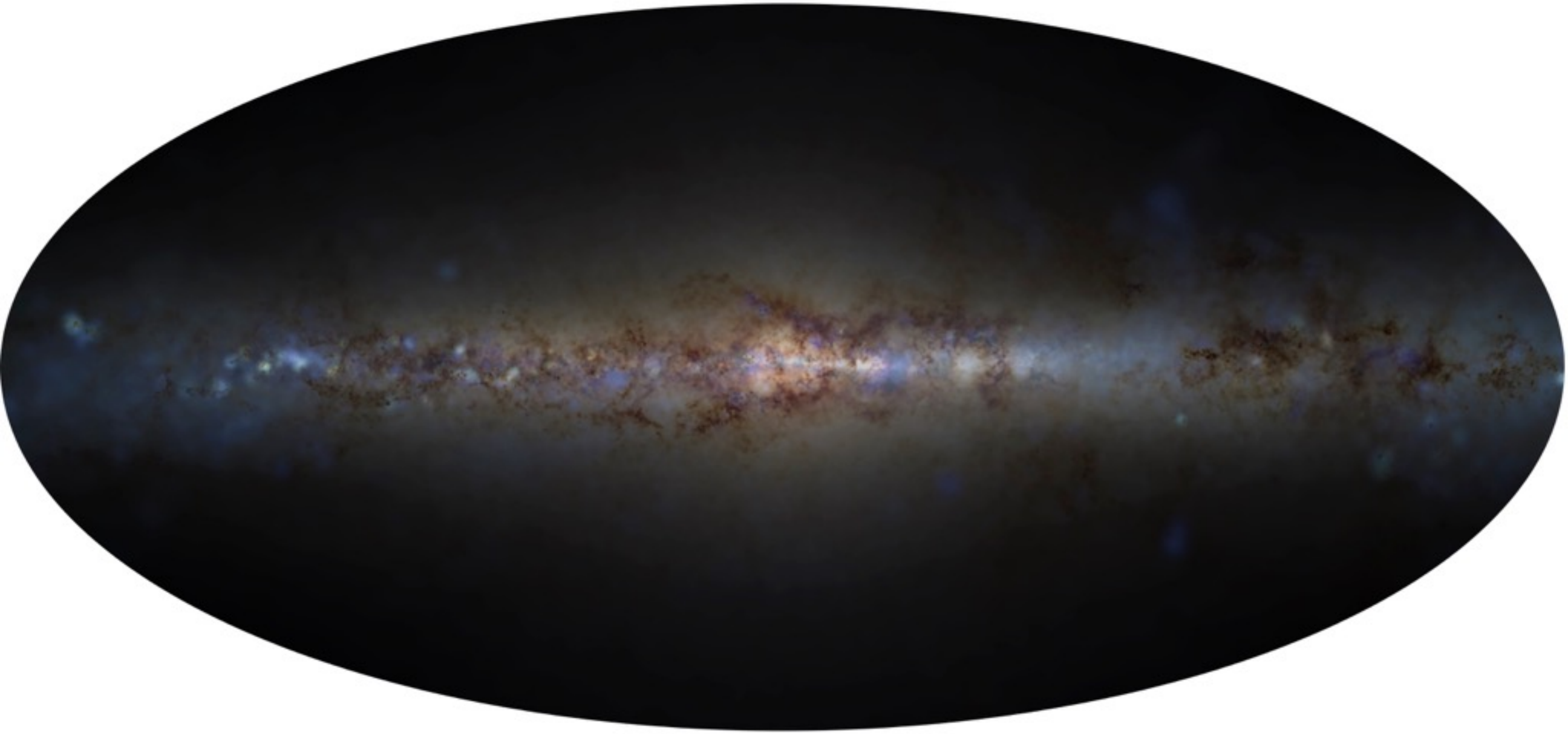


What about the baryons?

What is this?



This is a simulation

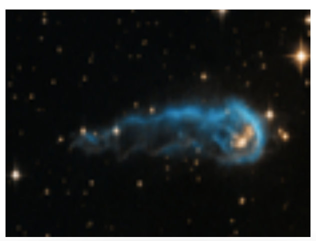


Wetzel et FIRE +2016

FIRE: Feedback in Realistic Environments

(Hopkins+2014; Chan et al. 2015; Oñorbe et al. 2015).

Star formation + Radiation pressure



Stellar winds

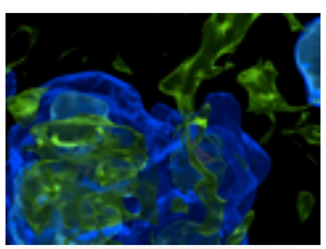
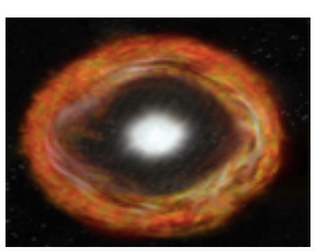
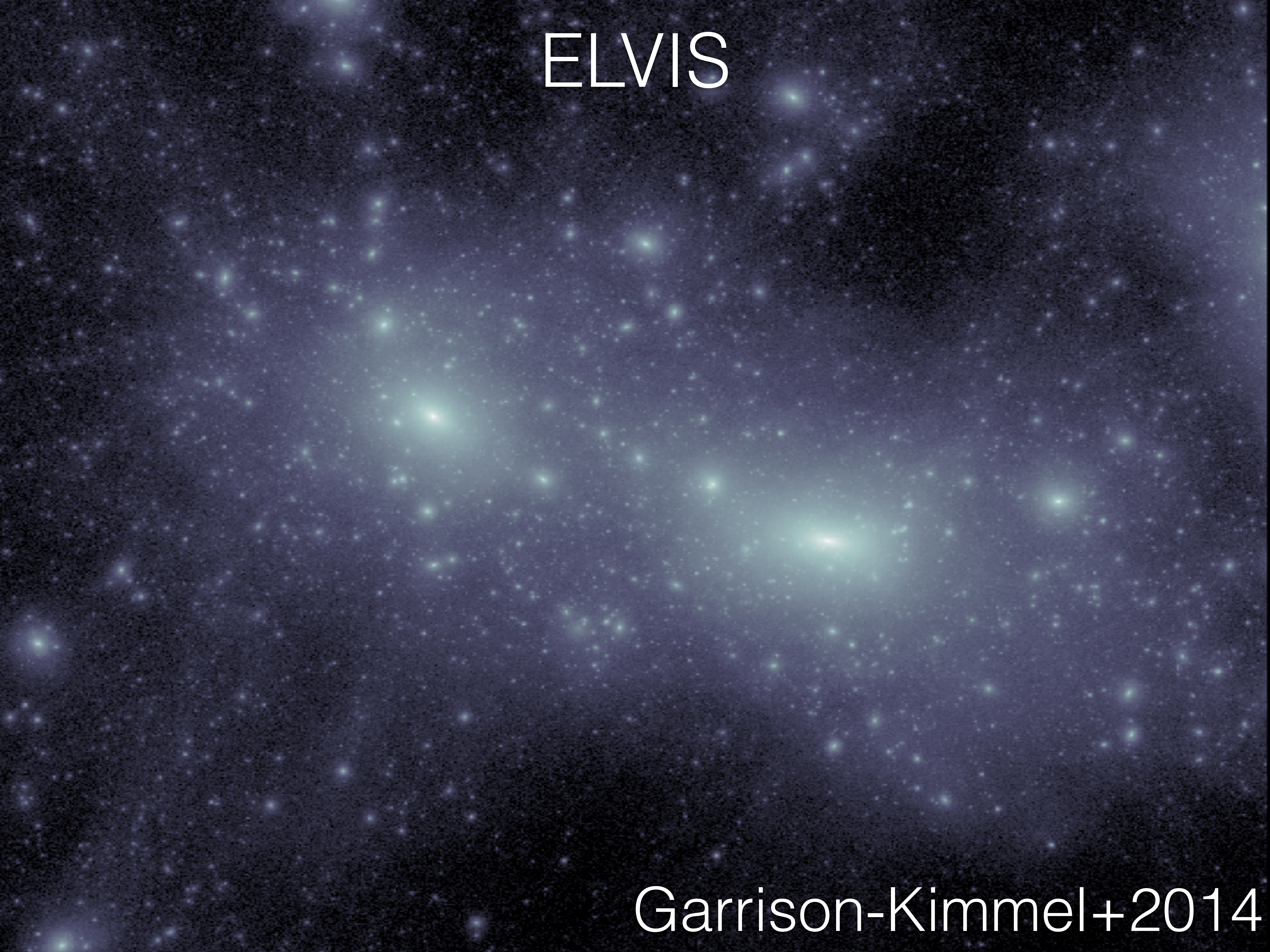


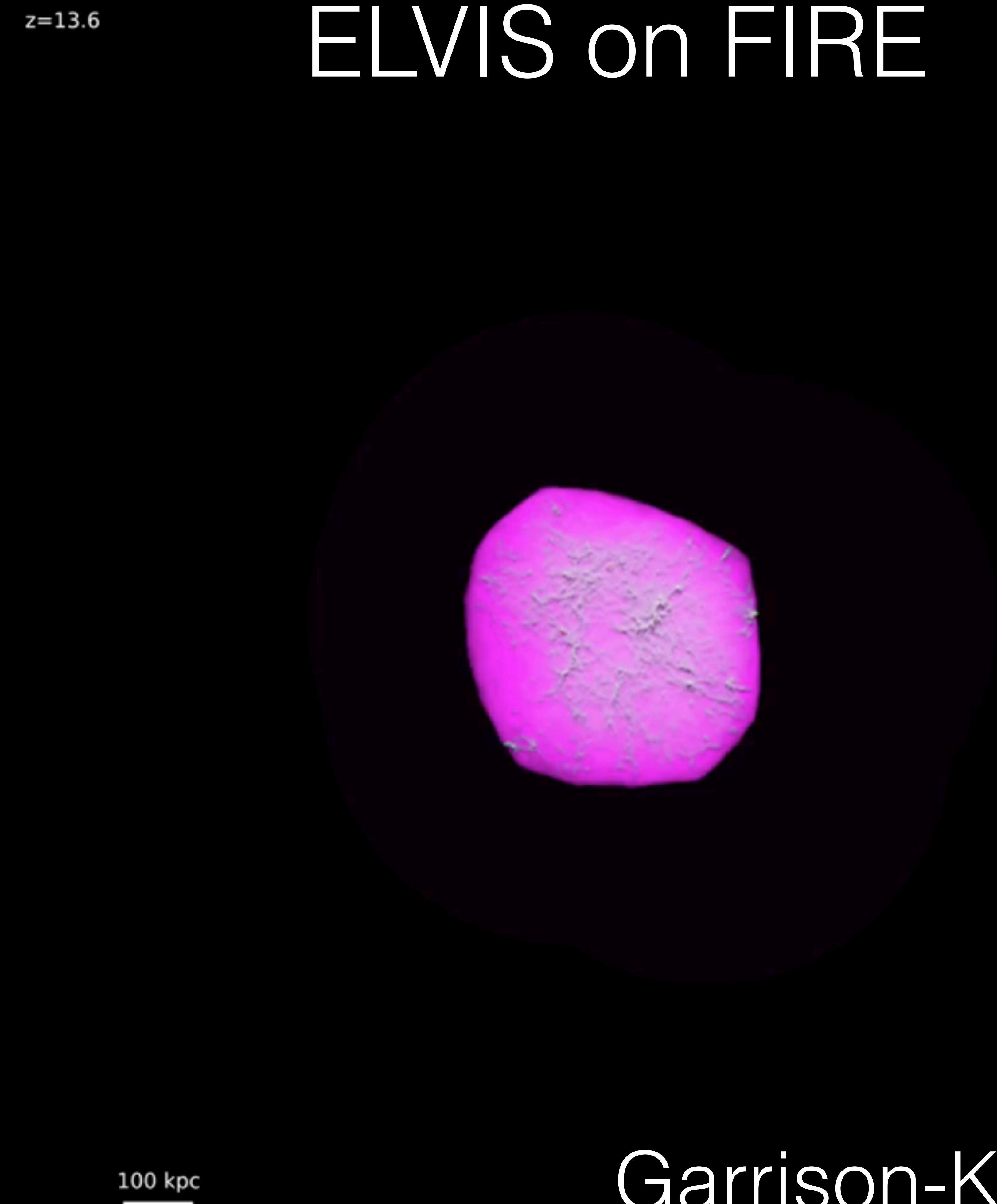
Photo-Ionization



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


ELVIS
Garrison-Kimmel+2014

ELVIS on FIRE



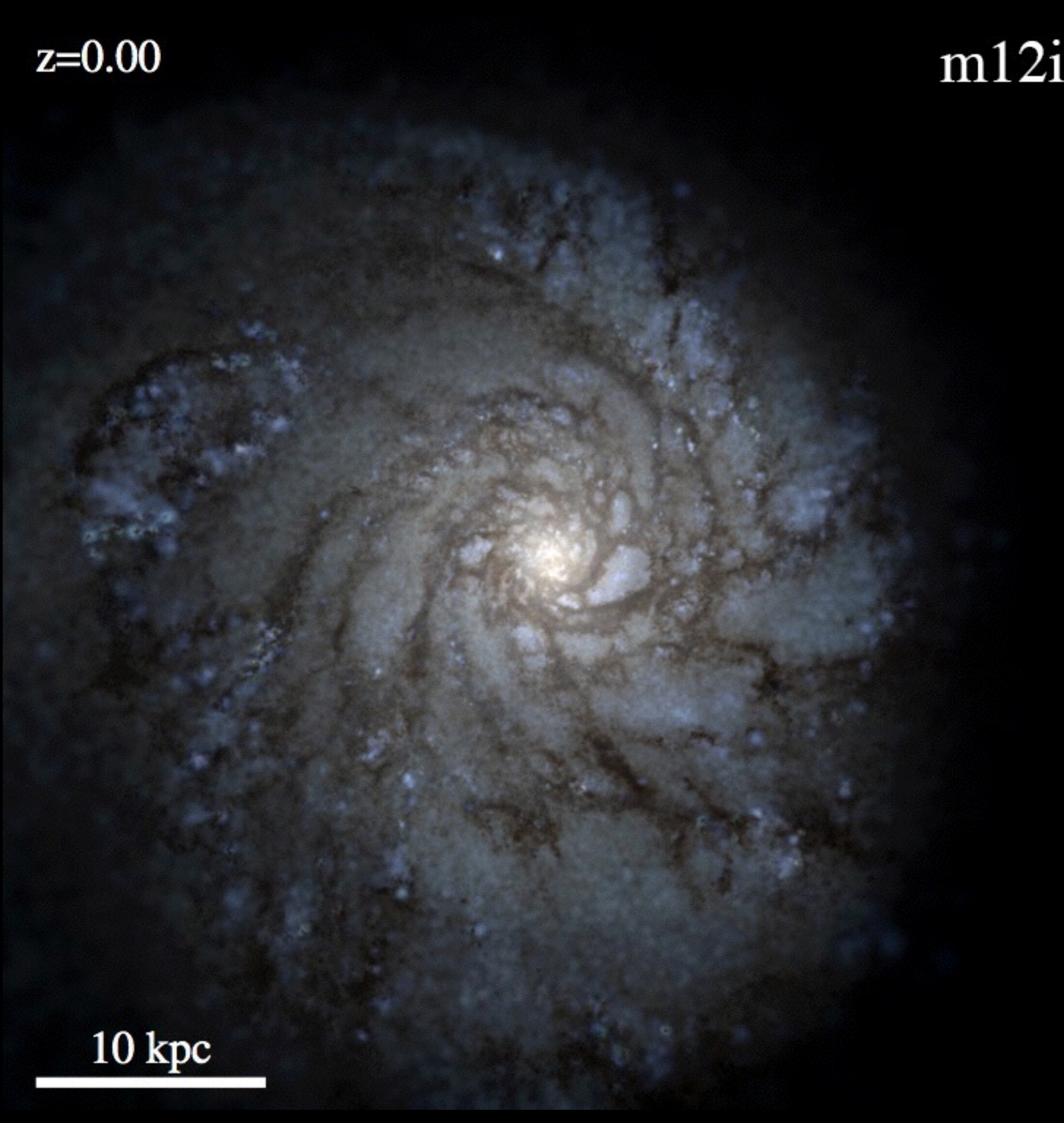
Garrison-Kimmel+2016

ELVIS on FIRE

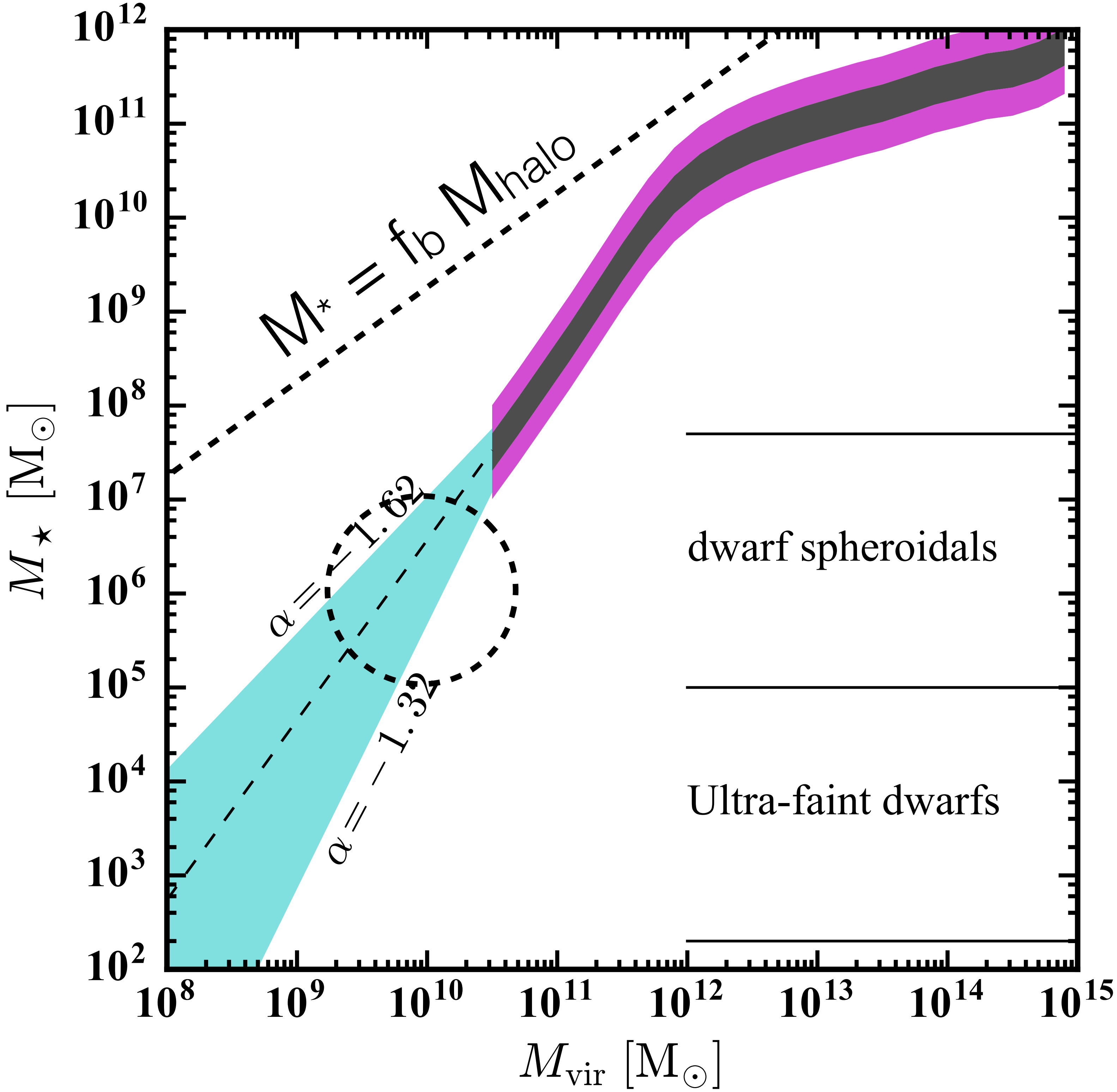
"Milky Way"

10 c-kpc

Garrison-Kimmel+2016


z=0.00
m12i
10 kpc

Scale of concern for Too Big to Fail:

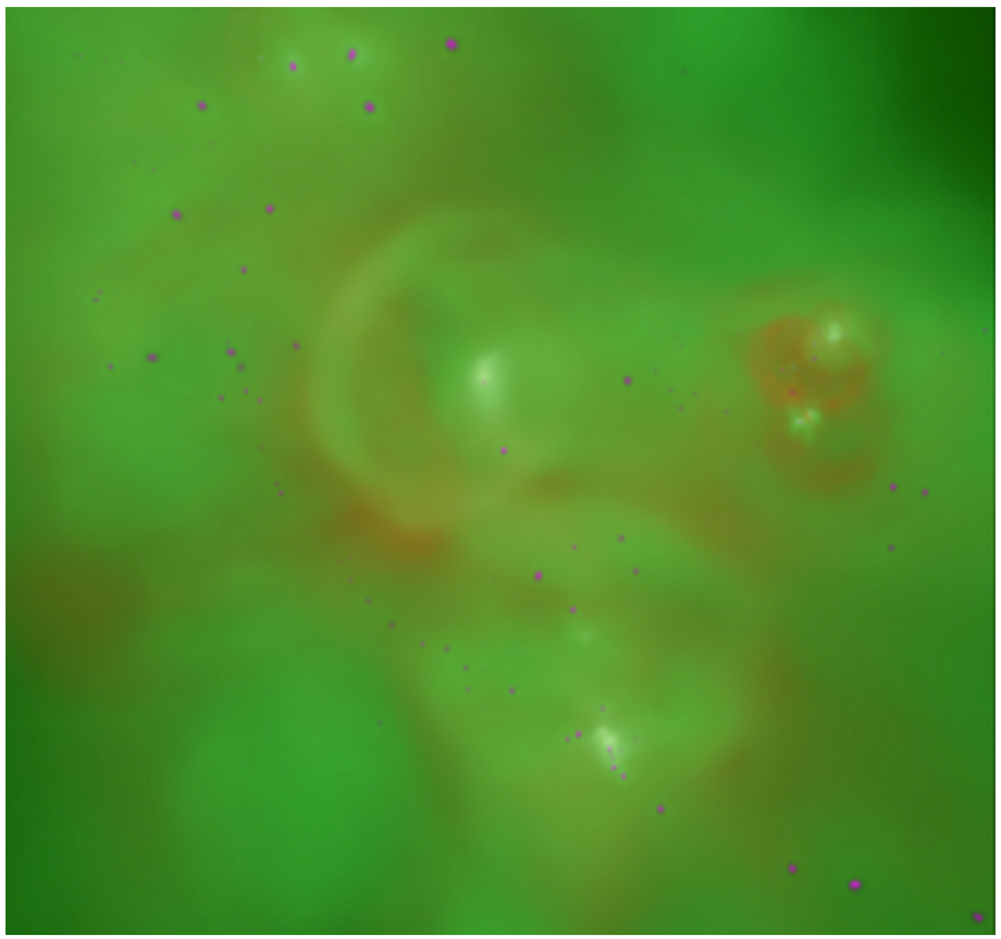


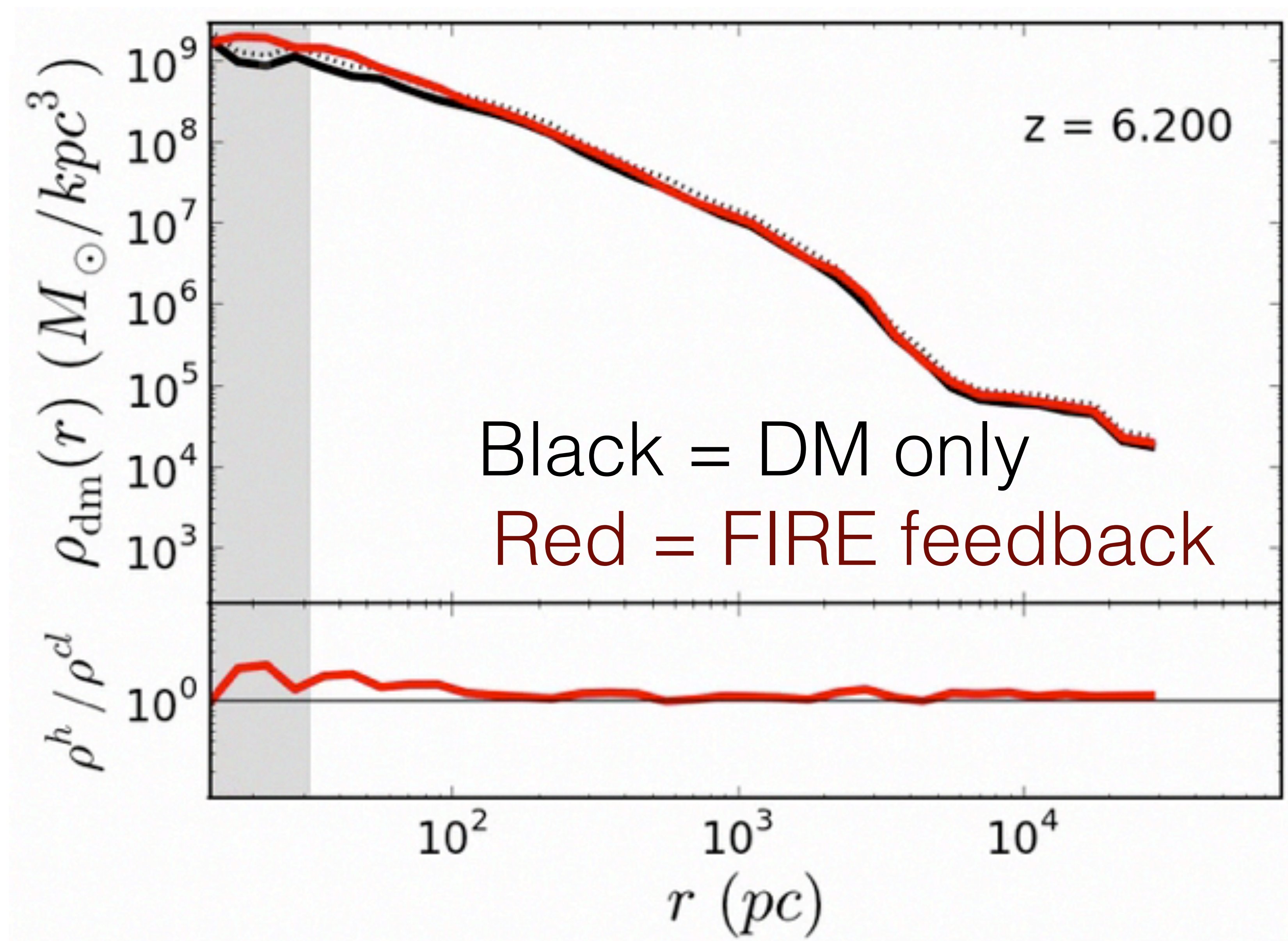
$M_{halo} \sim 10^{10} M_\odot$

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

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

Onorbe+2015



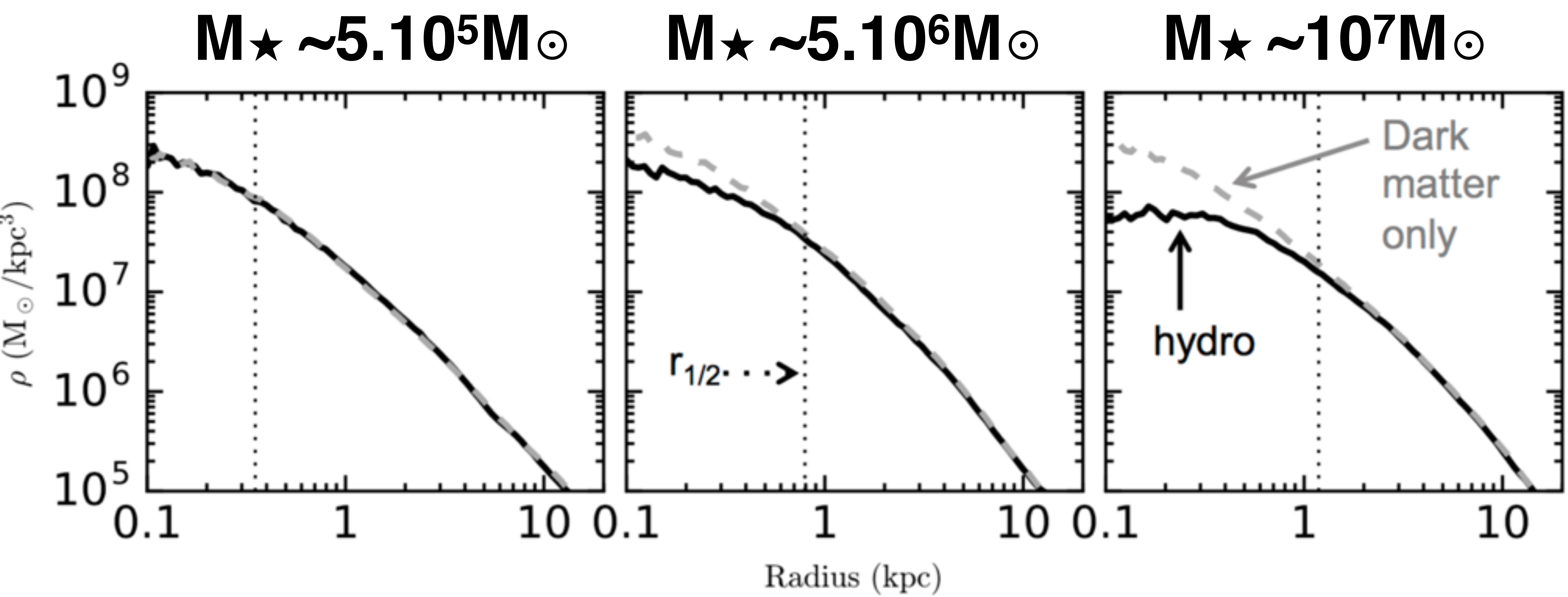


m_{dm} ~ 1000 $M_{\odot}$

m_{gas} ~ 250 $M_{\odot}$

f_{res} ~ 10 pc

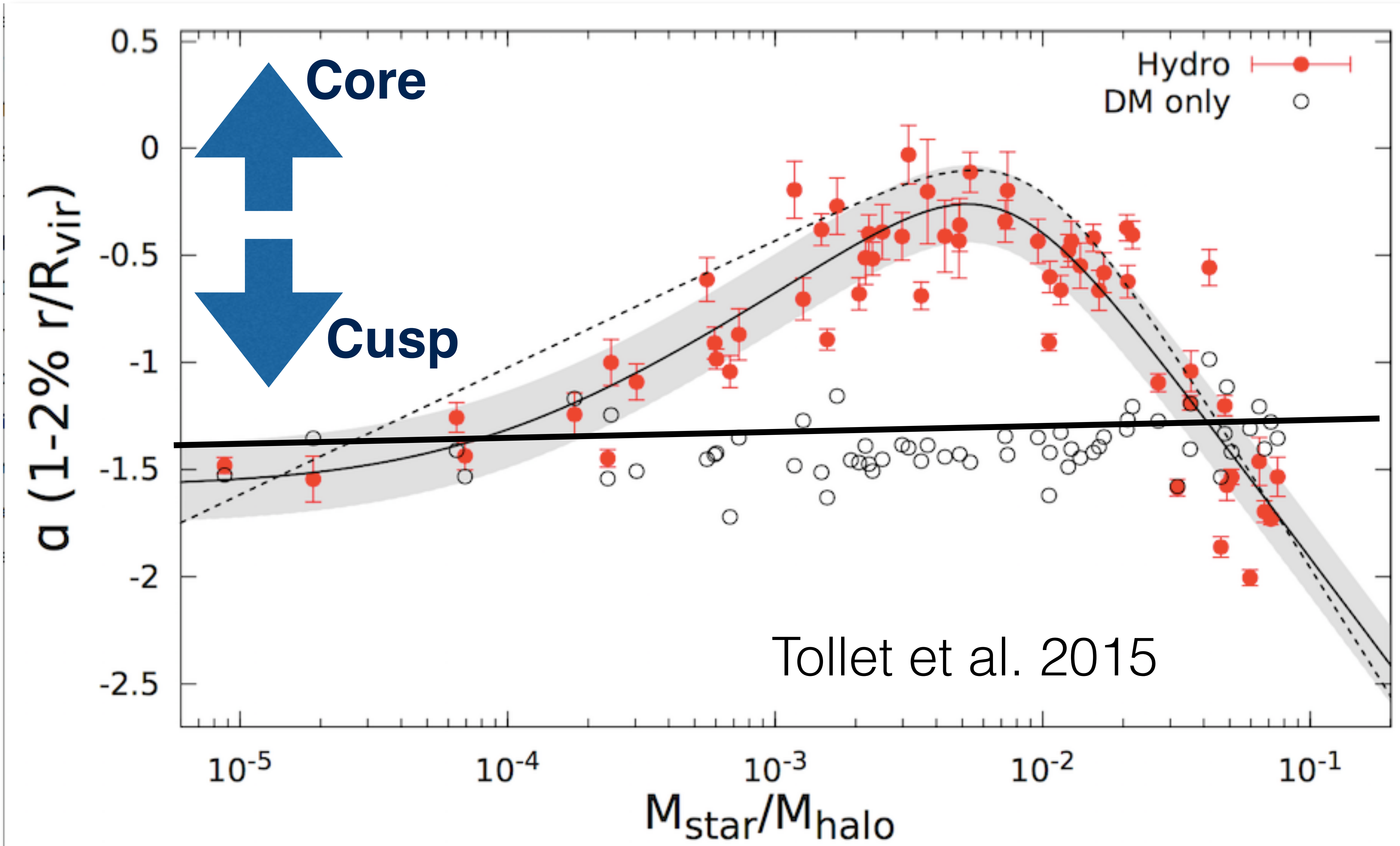
Need >3.e6M_{sun} stars to affect DM density profile



ε_{gas}~ 1.4 pc, ε_{dm}~25 pc
m_{gas}~ 500 M , m_{dm}~ 2500 M

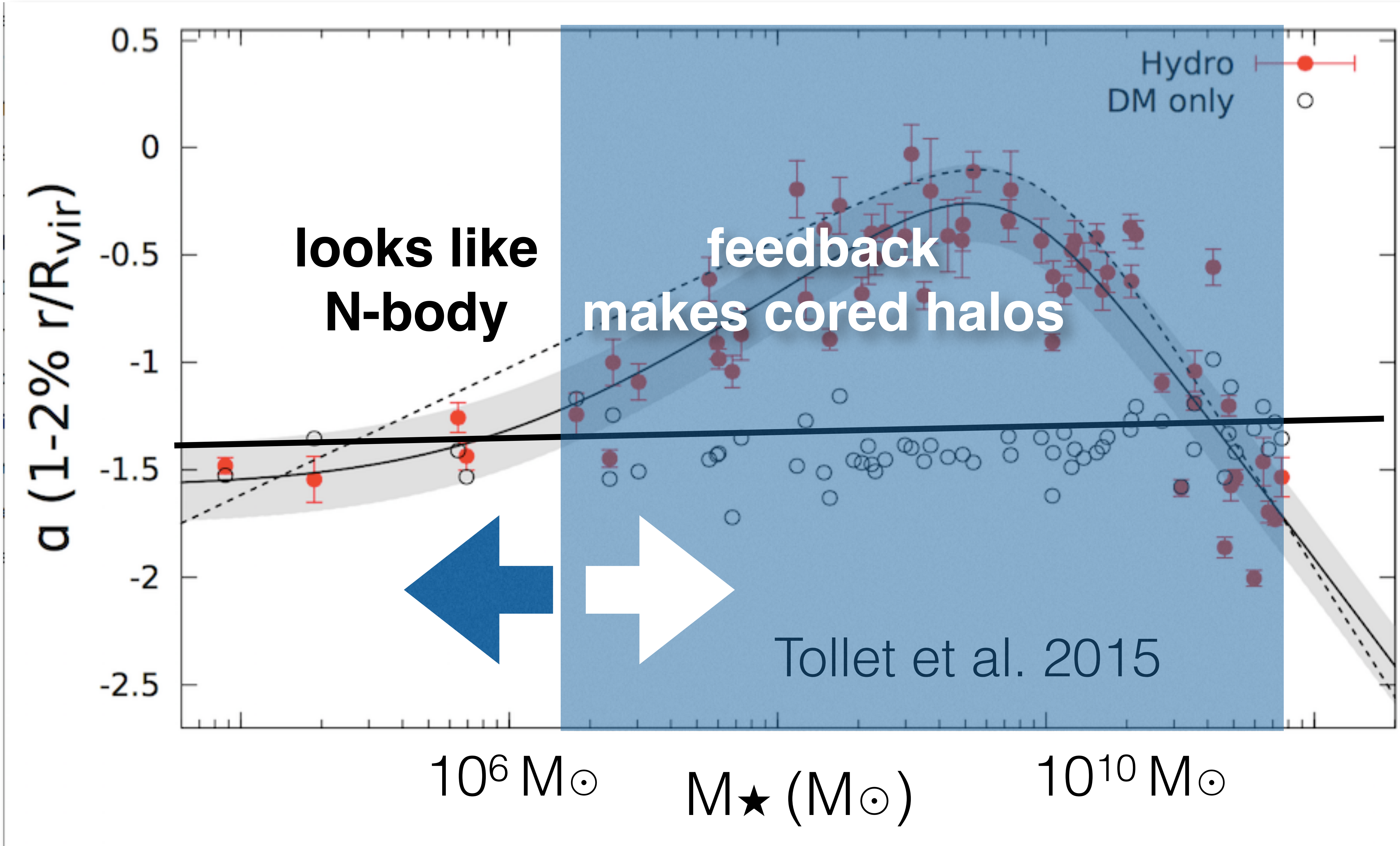
Alex Fitts et al., in prep

Core creation? Depends on # stars formed



Also: Governato+12; Penarrubia+12; Garrison-Kimmel+13, Di Cintio+14

Low stellar mass: feedback can't change DM



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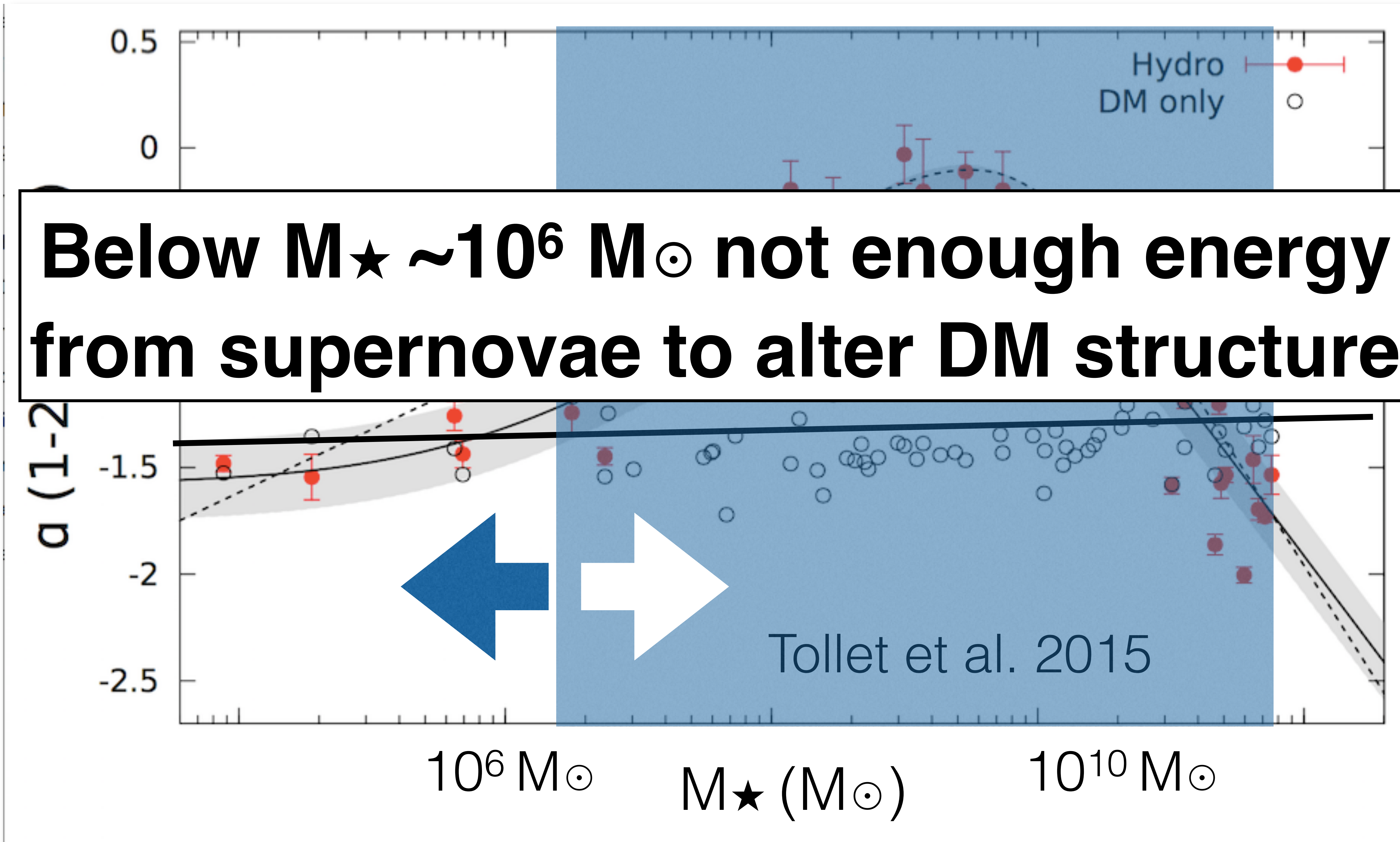
Low stellar mass: feedback can't change DM



Also: Governato+12; Penarrubia+12; Garrison-Kimmel+13, Di Cintio+14

What about SIDM?

Self-Interacting DM

Remarkably, toy models of SIDM with self-scattering cross sections as large as ~Barn/GeV are not ruled out.
(c.f. Peter+12; Rocha+12; Elbert+15; Haibo Yu's talk).

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

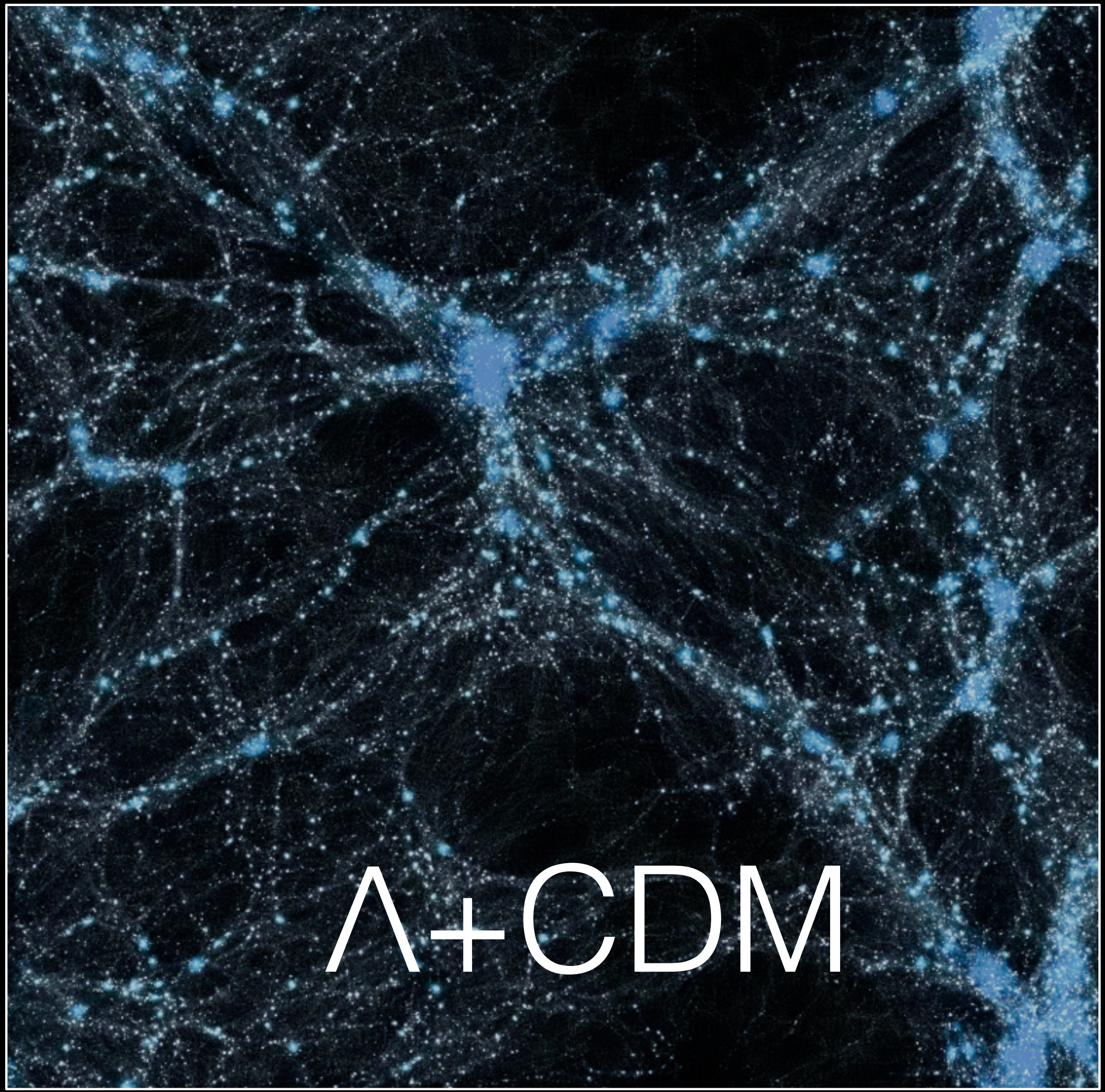
→ if rate is >~0.1/Gyr interesting things happen

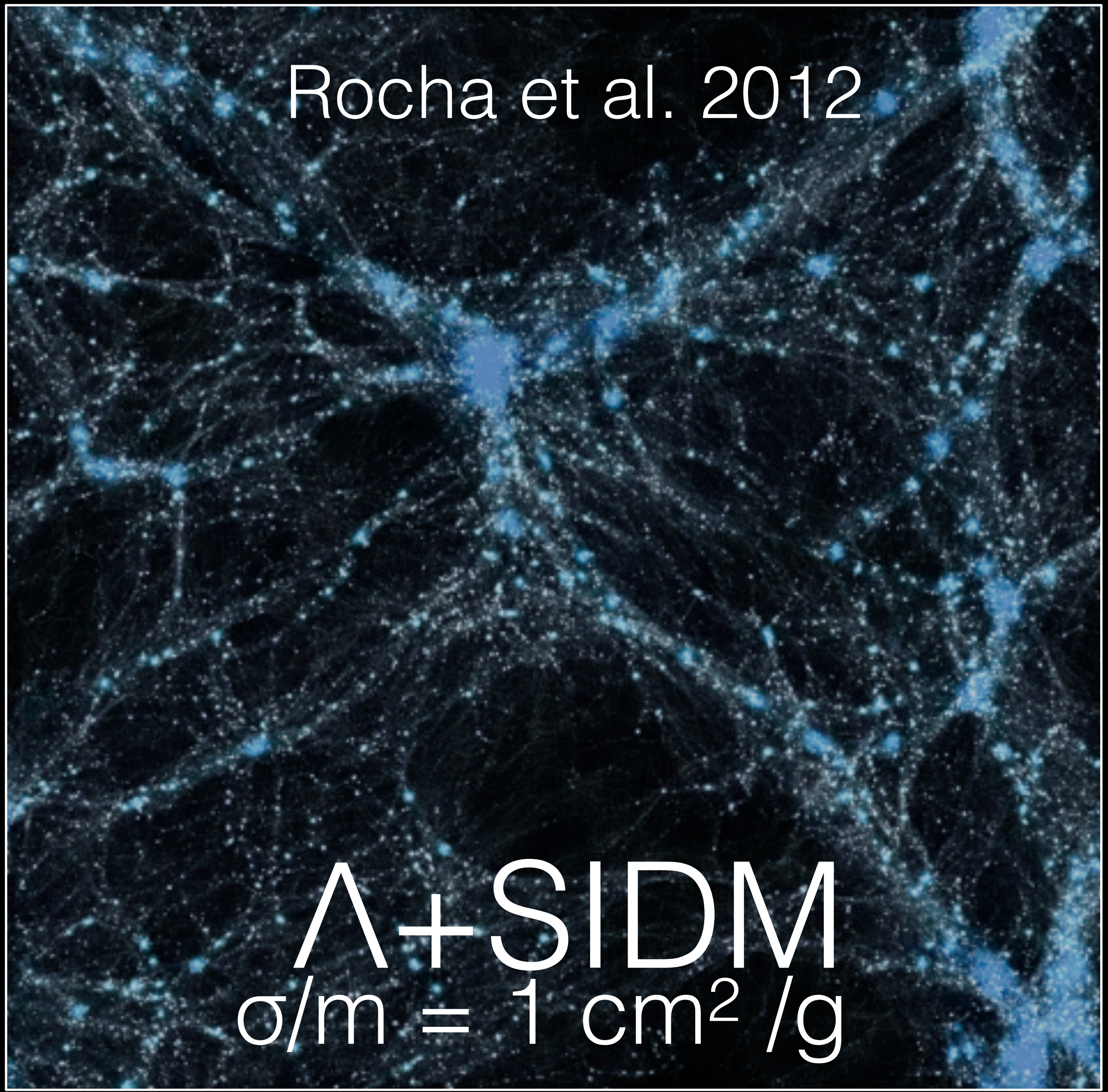
→ $$\frac{\sigma}{m} \sim 1\,{\rm cm}^2/g$$

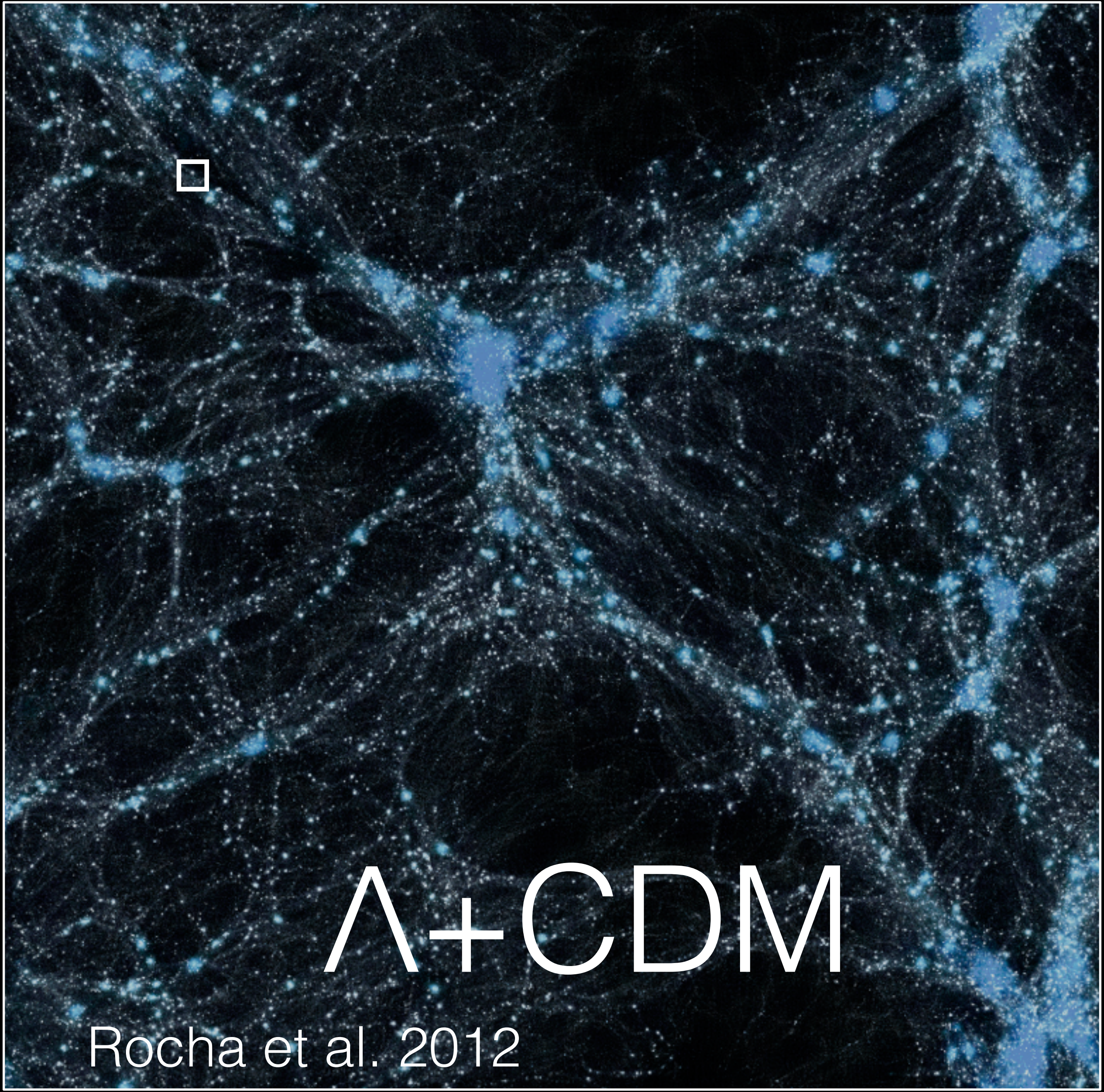
Spergel & Steinhardt (2000)

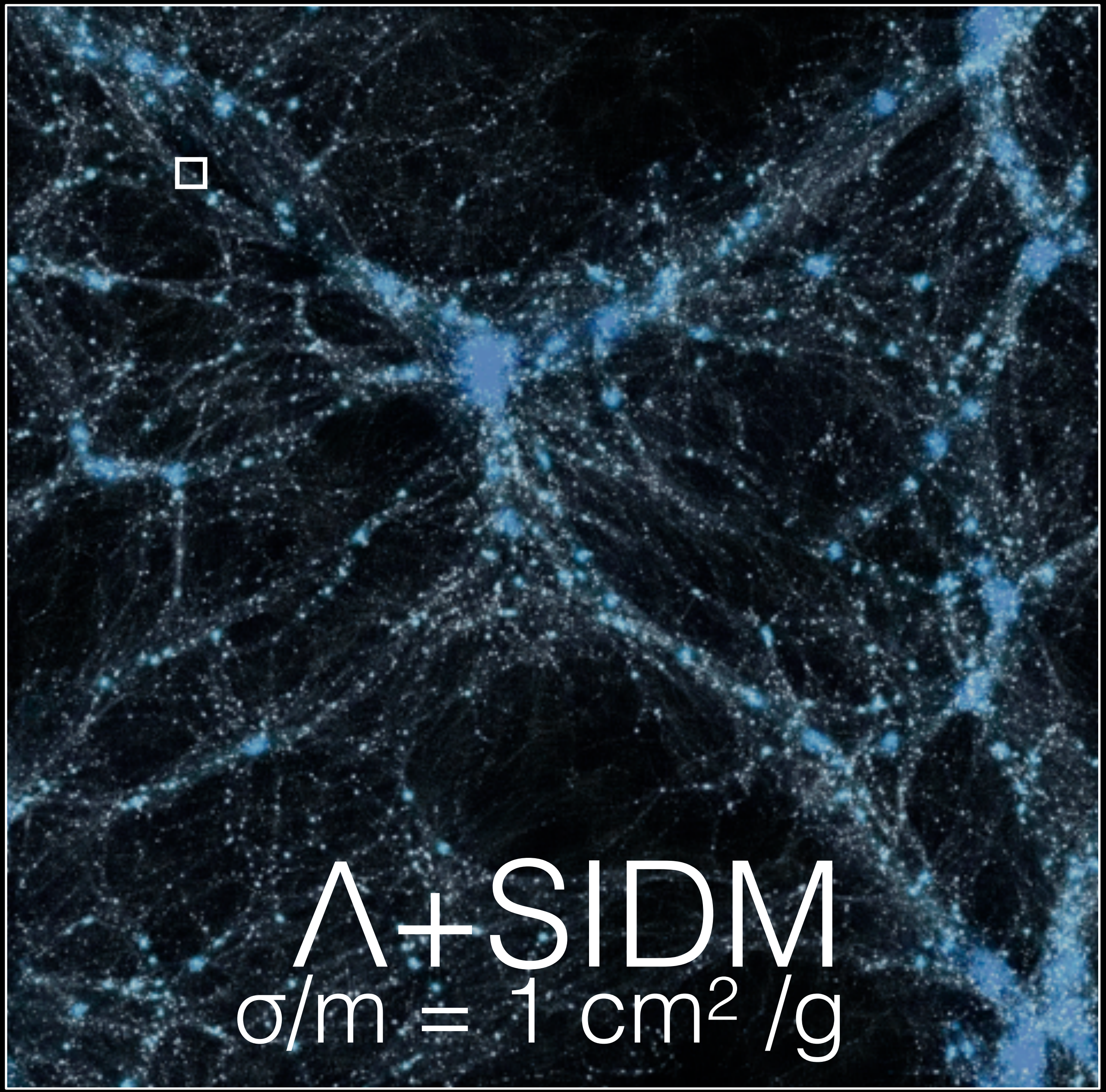
SIDM vs. CDM

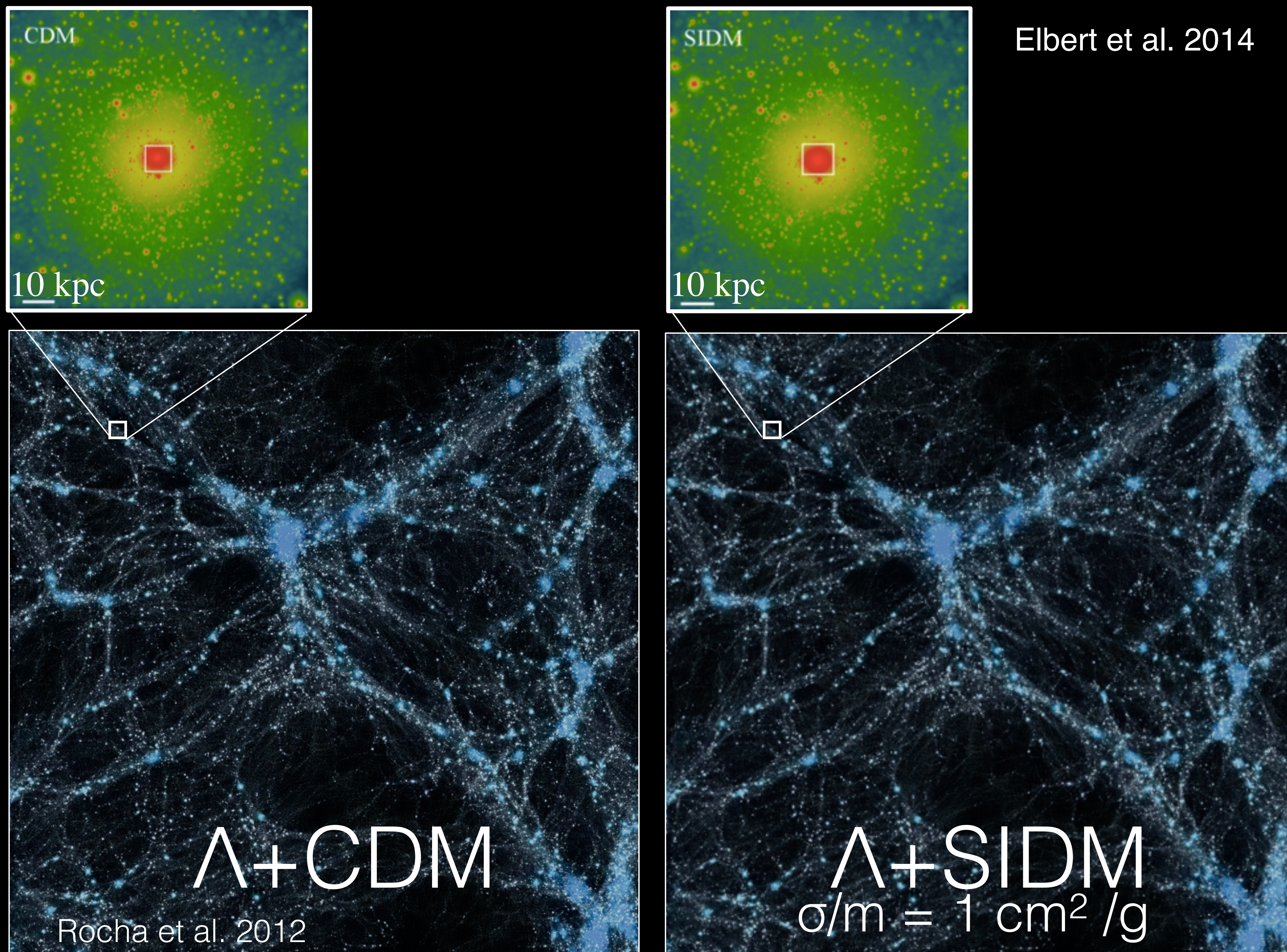
- same large scale structure
- same DM halo mass functions

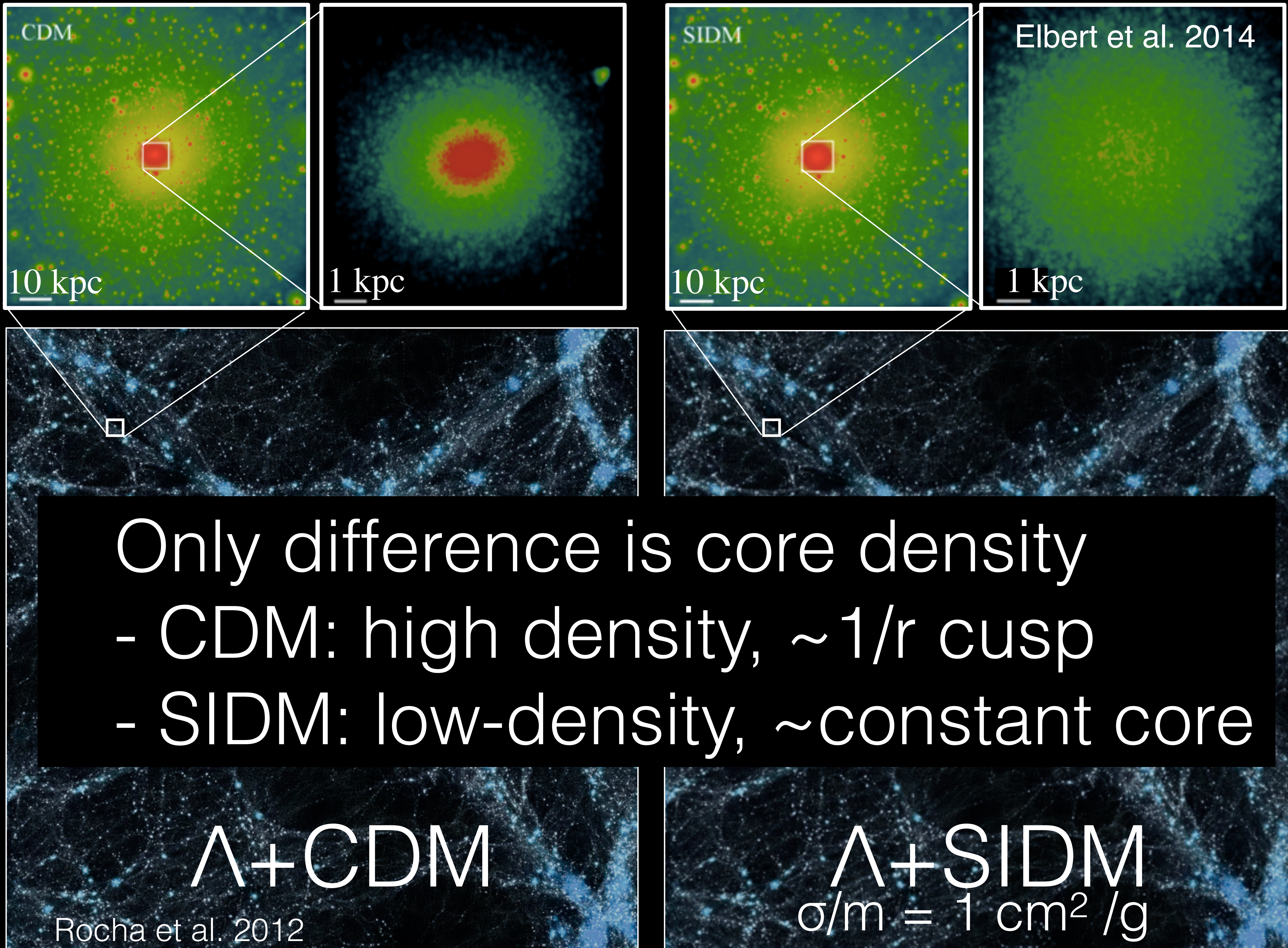




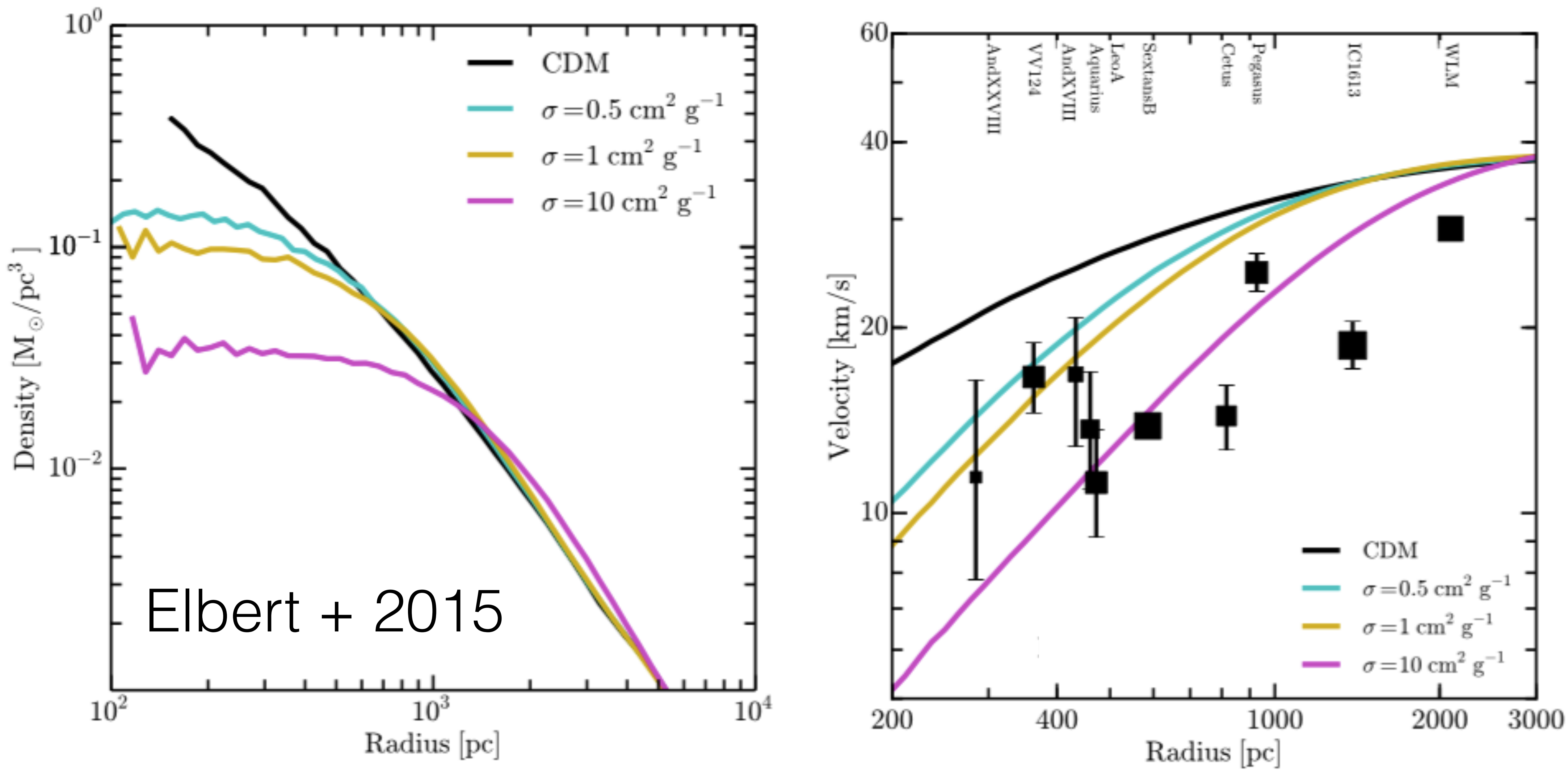

Λ+CDM
Rocha et al. 2012


Λ+SIDM
σ/m = 1 cm² /g


CDM
10 kpc
SIDM
10 kpc
Elbert et al. 2014
Λ+CDM
Rocha et al. 2012
Λ+SIDM
σ/m = 1 cm² /g


CDM
10 kpc
1 kpc
SIDM
10 kpc
Elbert et al. 2014
1 kpc
Only difference is core density
- CDM: high density, ~1/r cusp
- SIDM: low-density, ~constant core
Λ+CDM
Rocha et al. 2012
Λ+SIDM
σ/m = 1 cm² /g

SIDM: can solve TBTF w/ cored halos

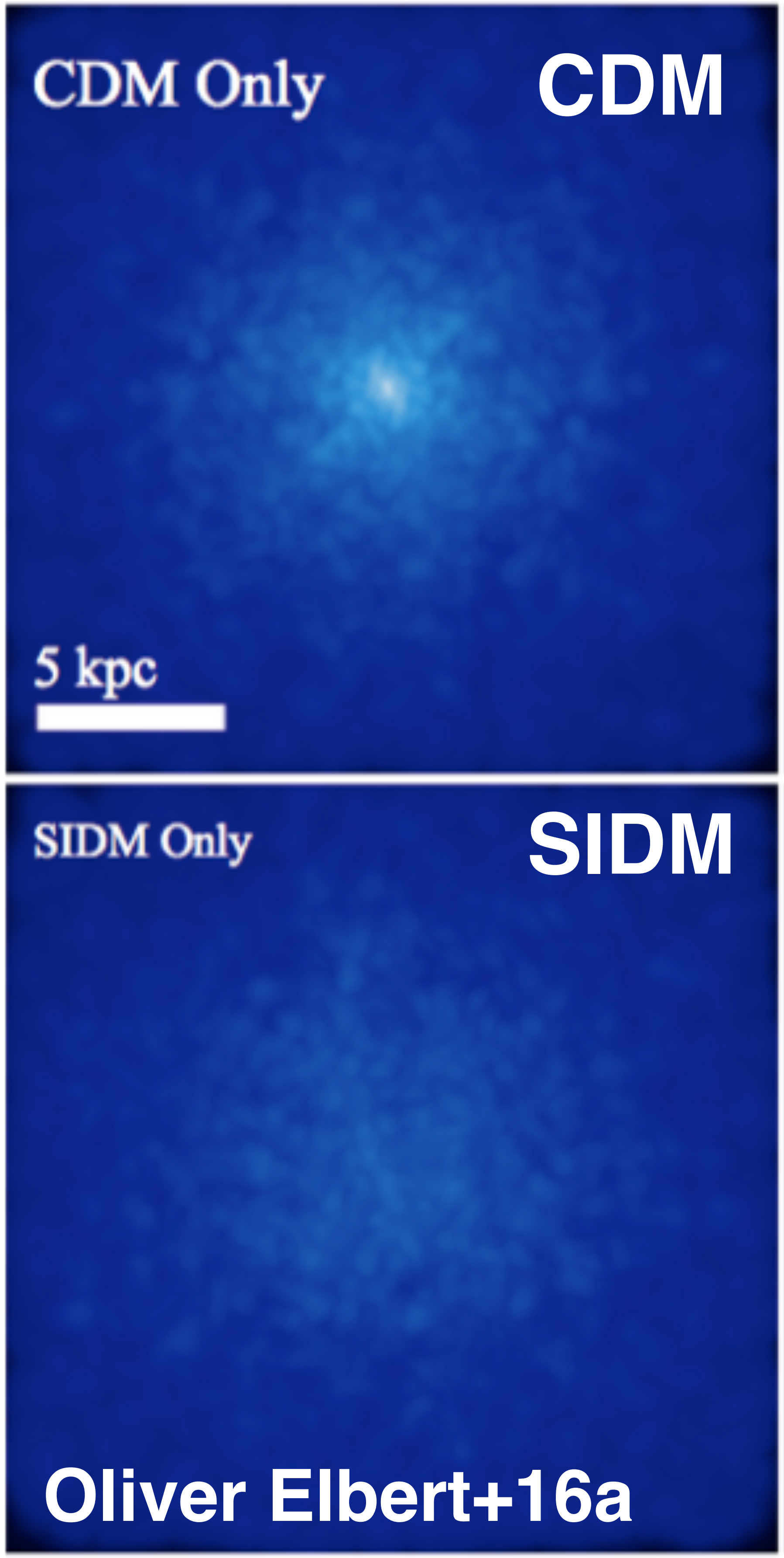


$\sigma/m = 0.5\text{-}5\ \text{cm}^2/\text{g}$

What about the baryons?

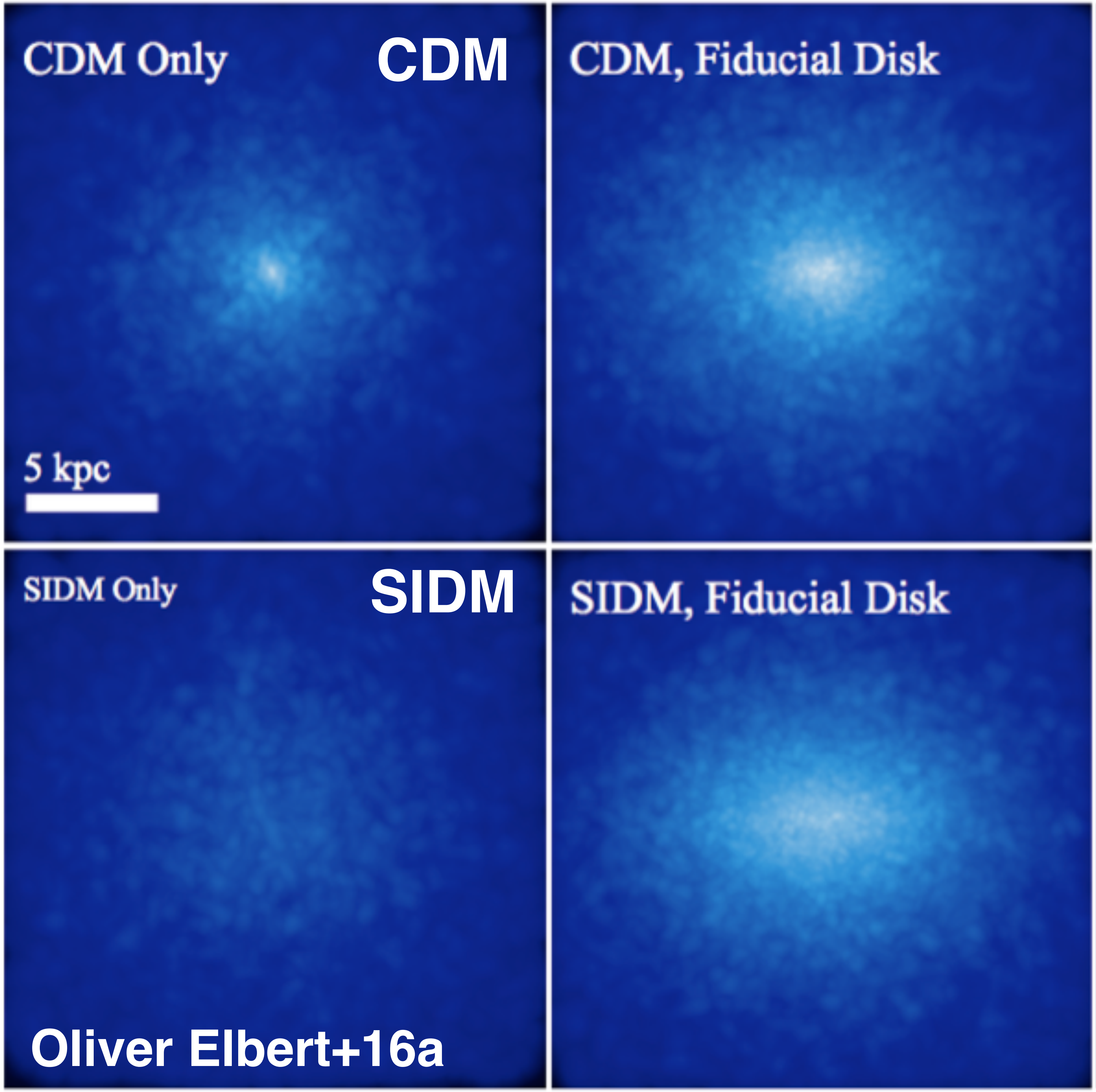
(in SIDM)

Baryonic Contraction: SIDM vs. CDM

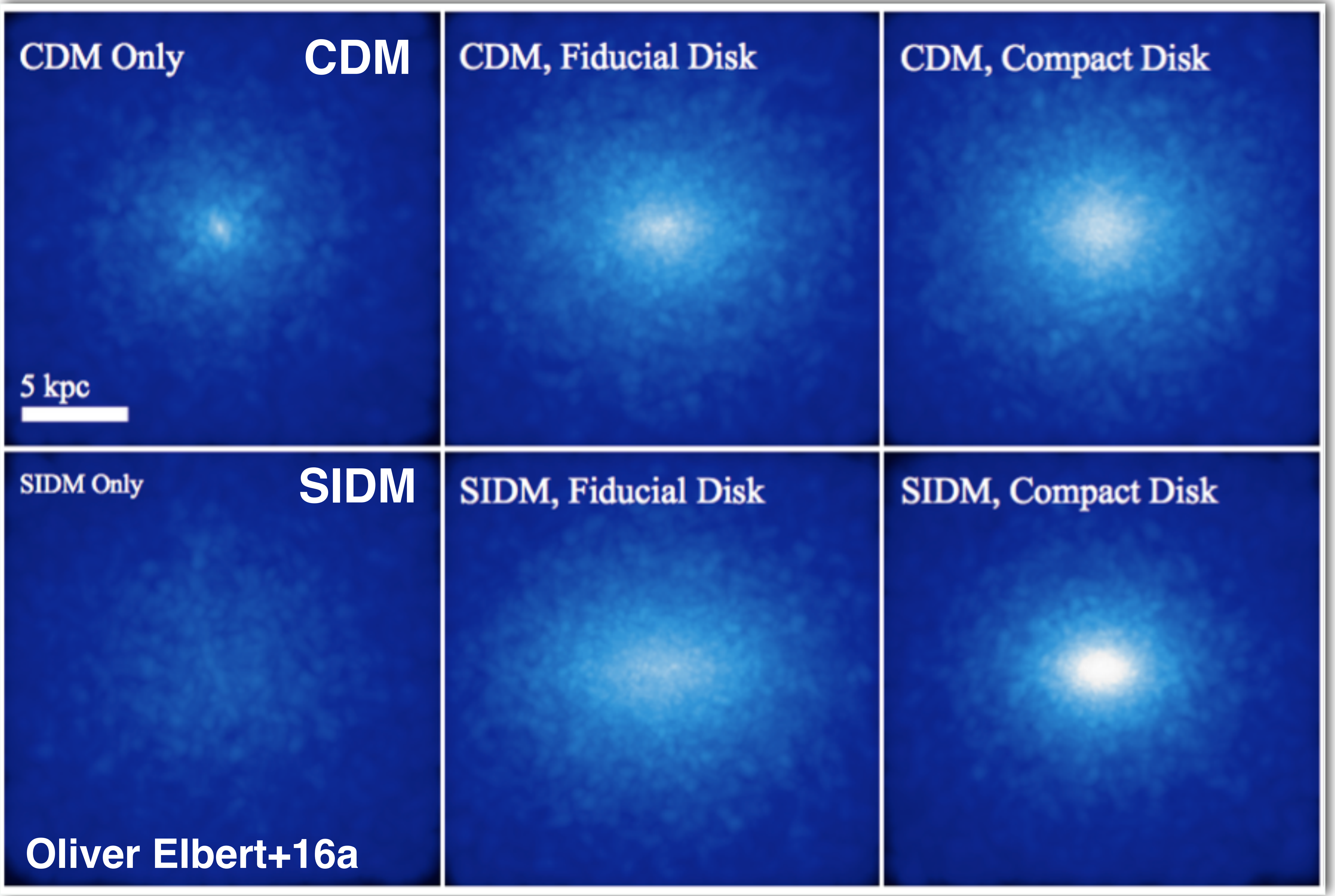


What happens if we grow a disk?

Baryonic Contraction: SIDM vs. CDM

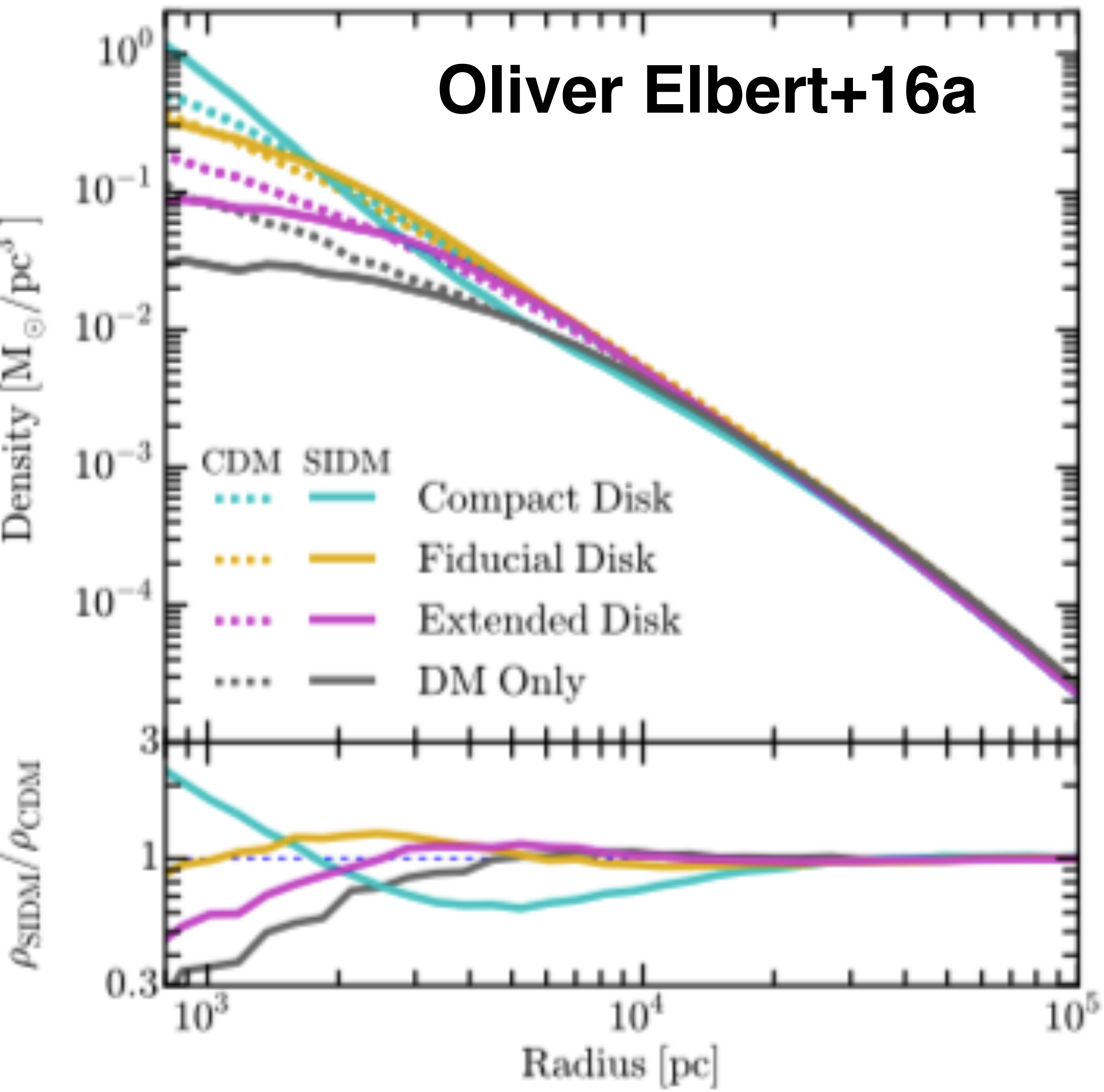


Baryonic Contraction: SIDM vs. CDM



SIDM => strong reaction to baryonic mass

MW Halo + MW-mass disk + 3 different disk radii



Baryon-rich galaxy: SIDM halos are denser than CDM

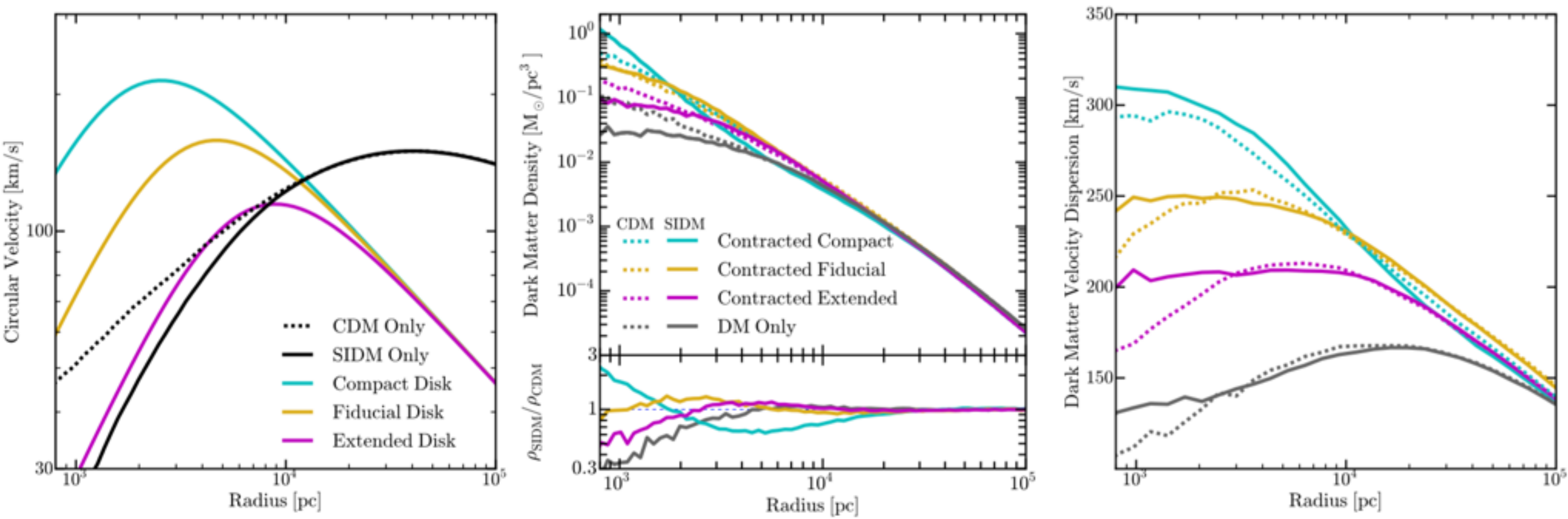
DM-dominated galaxy: SIDM halos are less dense than CDM

One implication:
SIDM=>more scatter in core densities

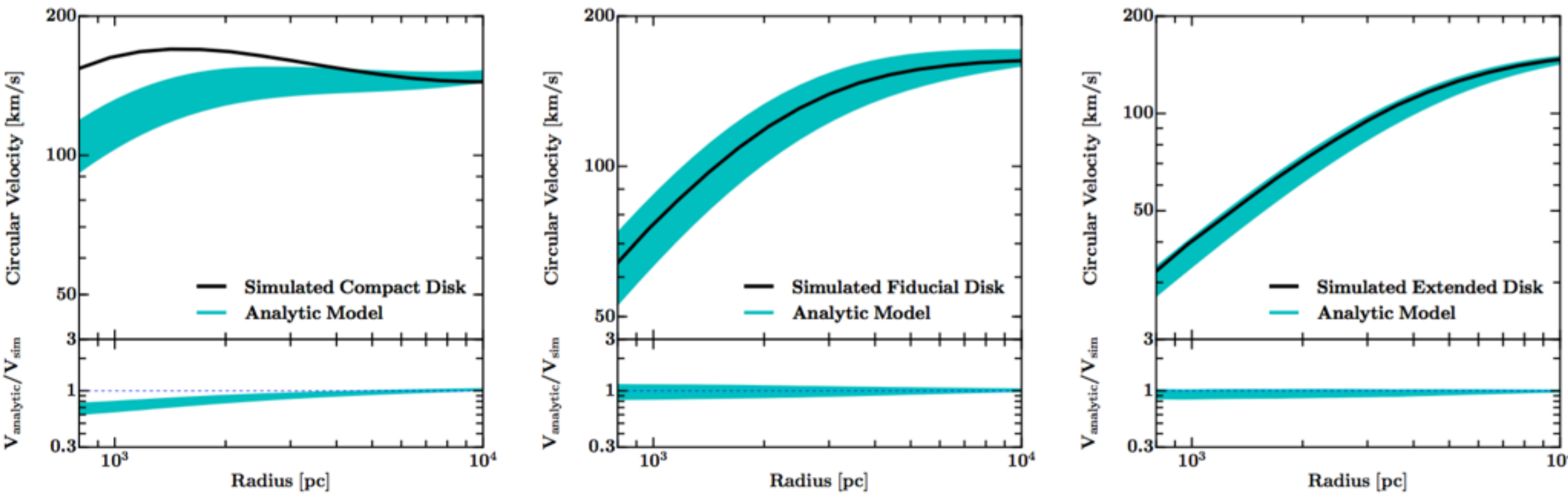
(Haibo Yu's talk)

SIDM = much more responsive than CDM

Oliver Elbert+16a



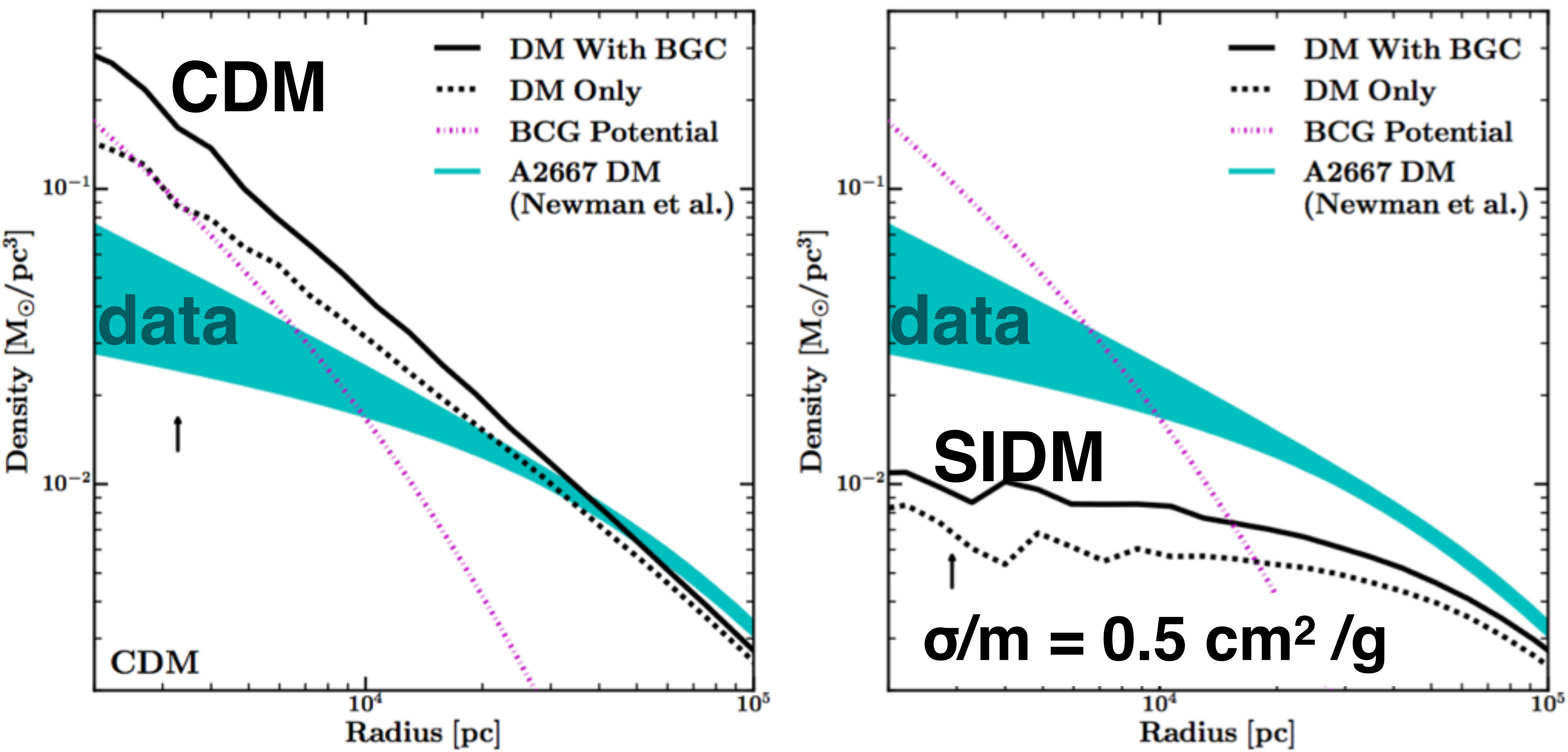
Simulations vs. Kaplinghat, Tulin, & Yu (2015) analytic model



works well except for core collapse case (very high baryon content)

Oliver Elbert+16a

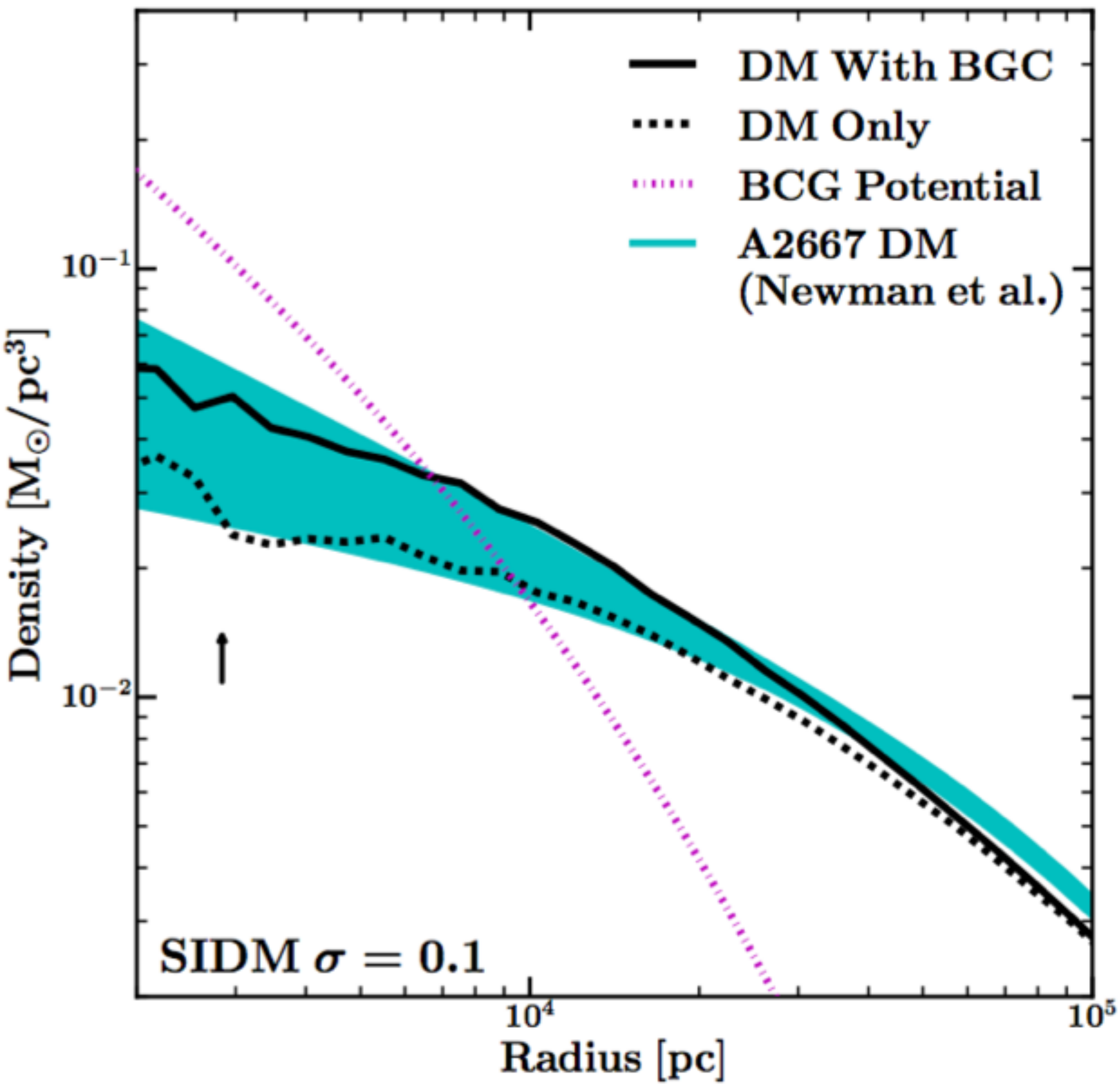
Cluster profiles: strong constraints on SIDM



Too dense **Not dense enough**

Oliver Elbert+16a

Cluster profiles: strong constraints on SIDM



Preferred

$\sigma/m = 0.1\ cm^2/g$

Constraint:

$\sigma/m < 0.2\ cm^2/g$

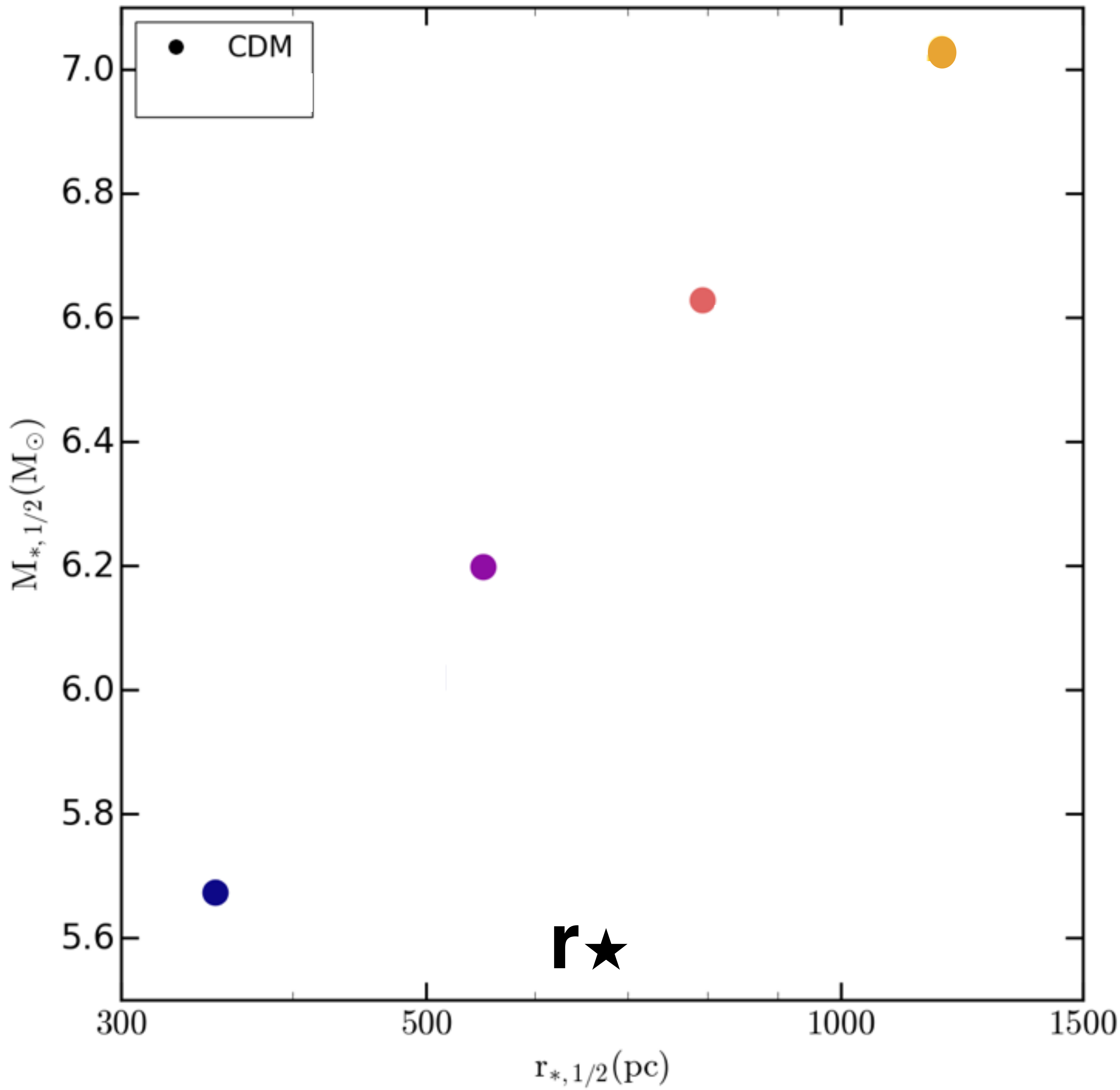
(better than bullet cluster)

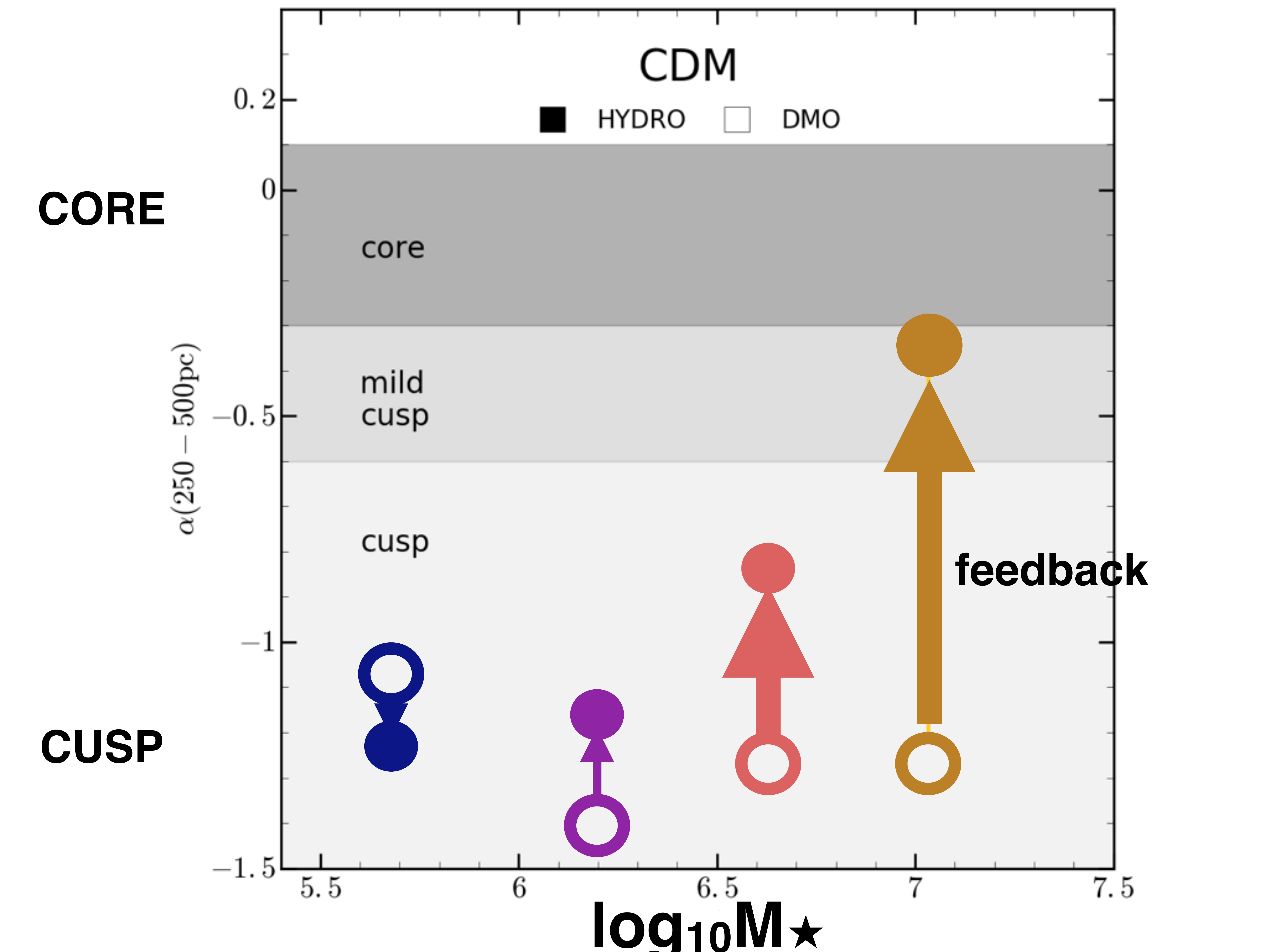
What about feedback?

(in CDM vs. SIDM)

high-res FIRE simulations

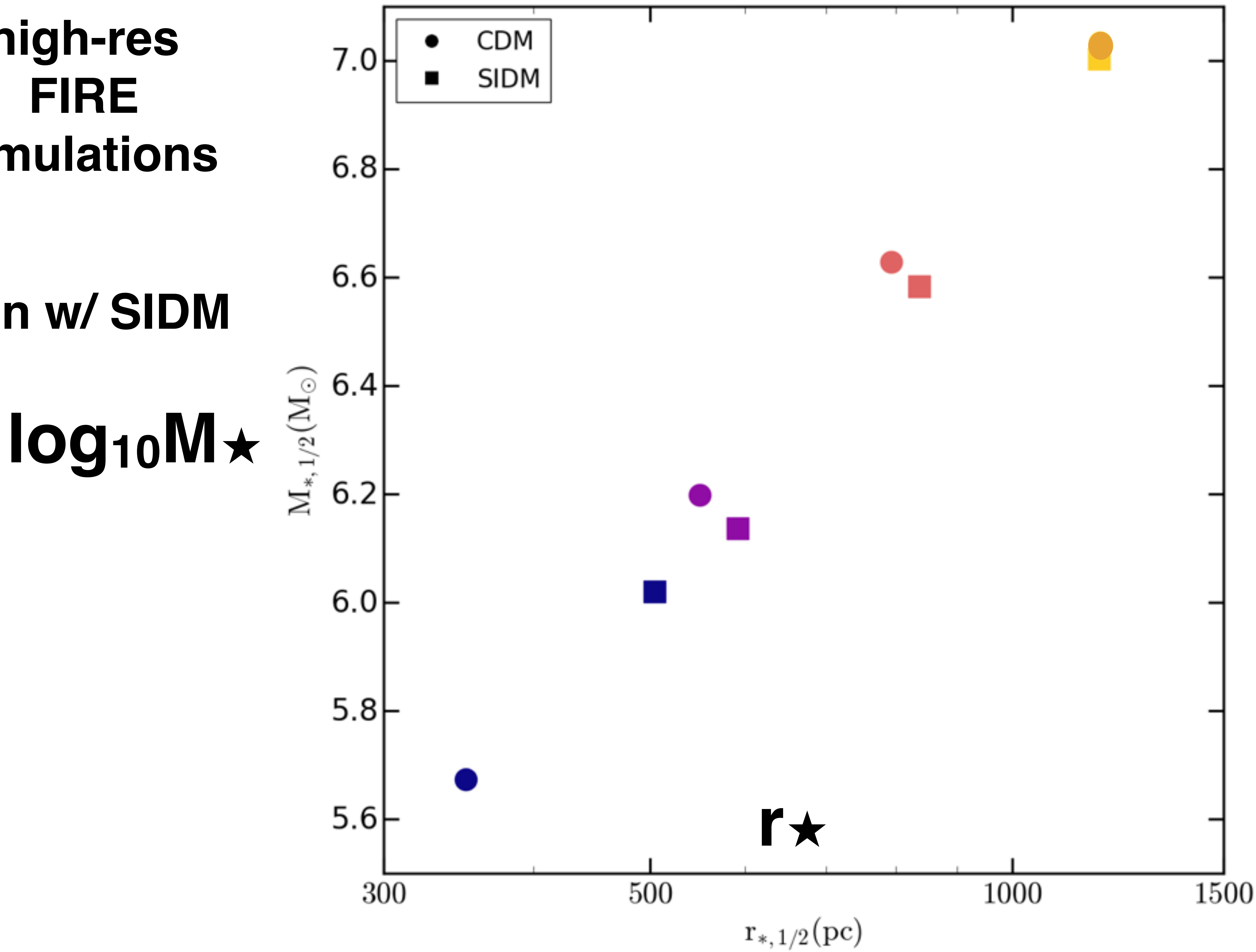
$\log_{10} M_\star$



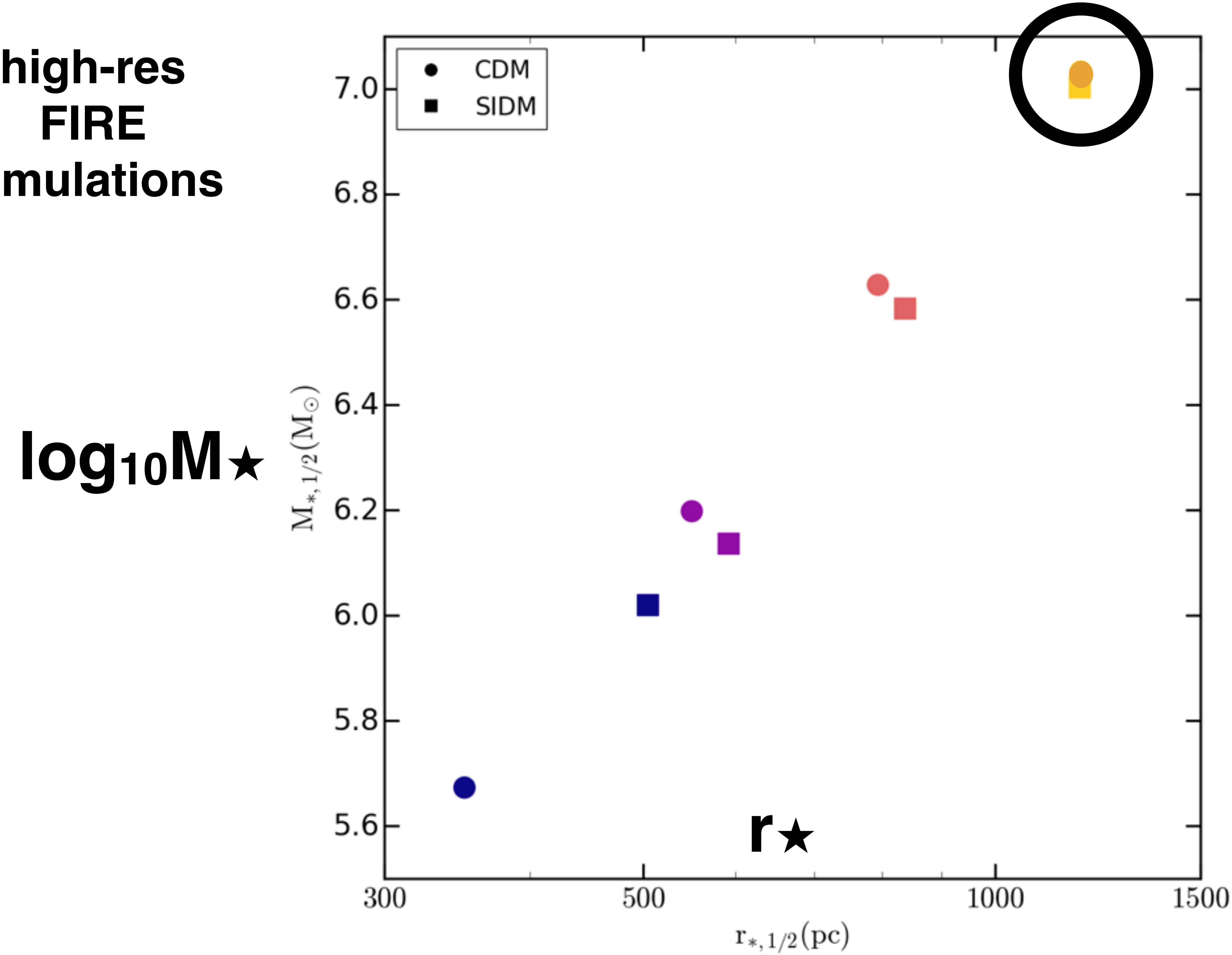

CDM
HYDRO
DMO
CORE
core
mild
cusp
cusp
CUSP
feedback
$\alpha(250-500\mathrm{pc})$
0.2
0
−0.5
−1
−1.5
5.5
6
6.5
7
7.5
$\log_{10} M_\star$

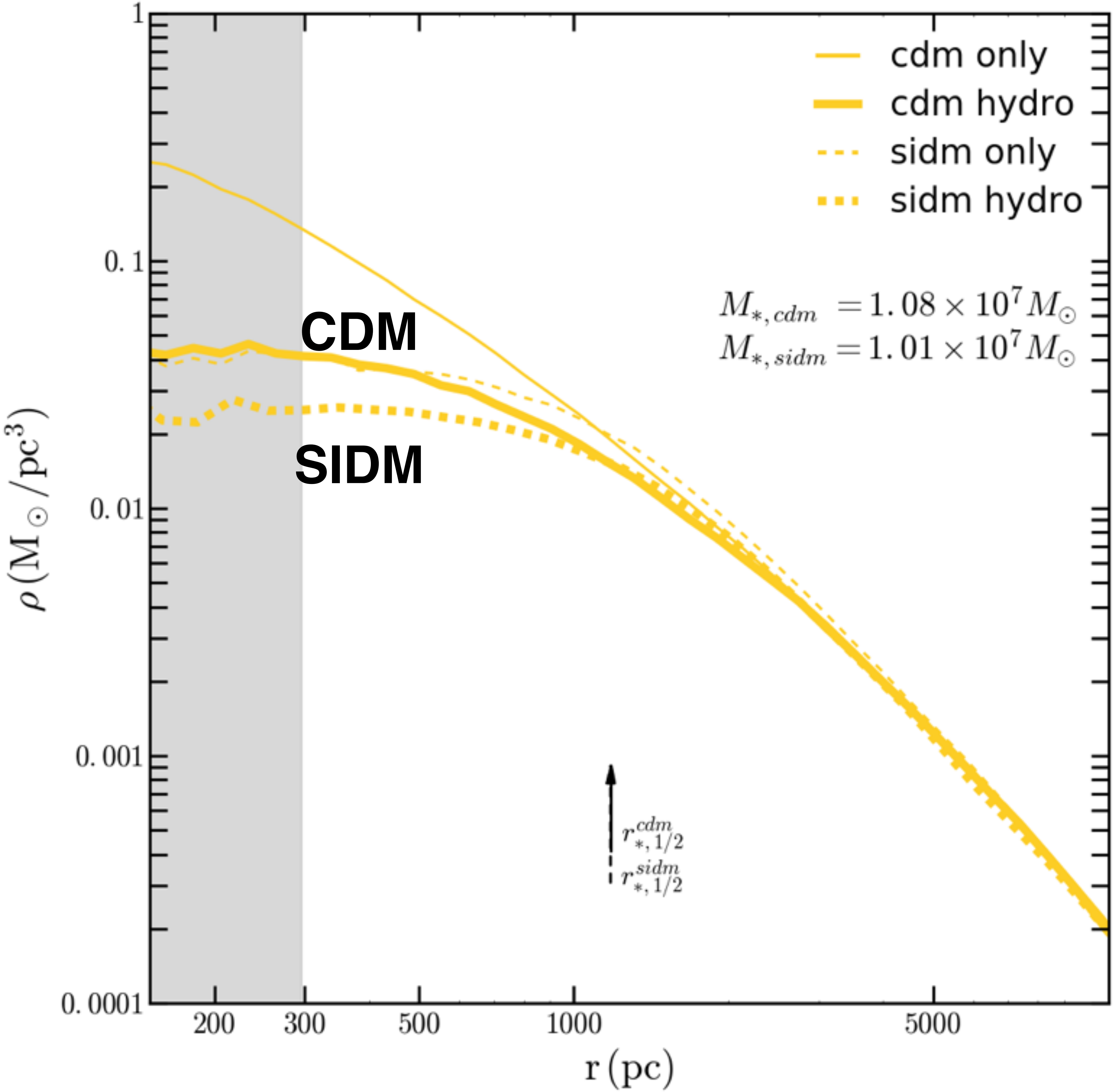
high-res
FIRE
simulations

Run w/ SIDM



high-res
FIRE
simulations



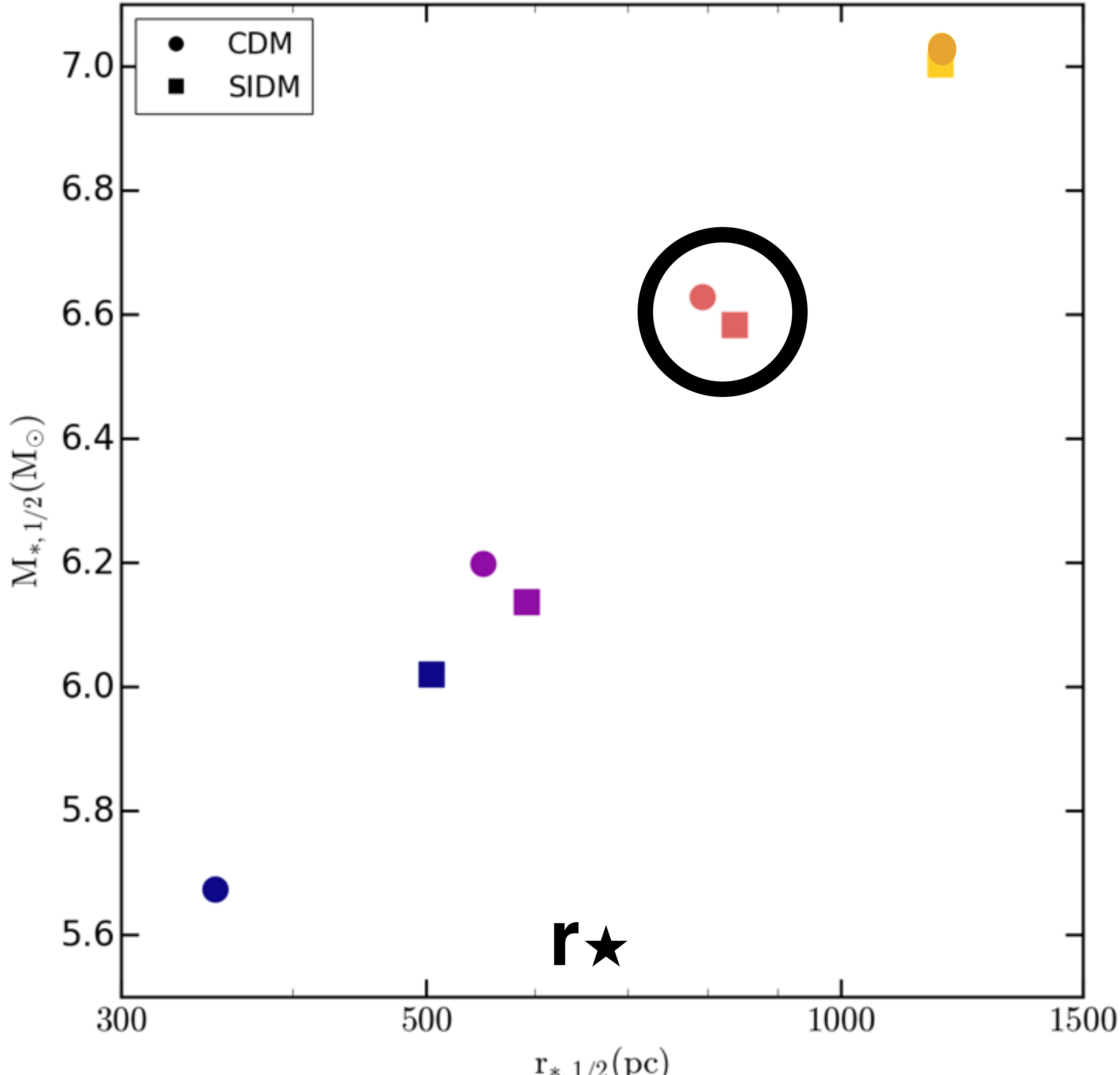


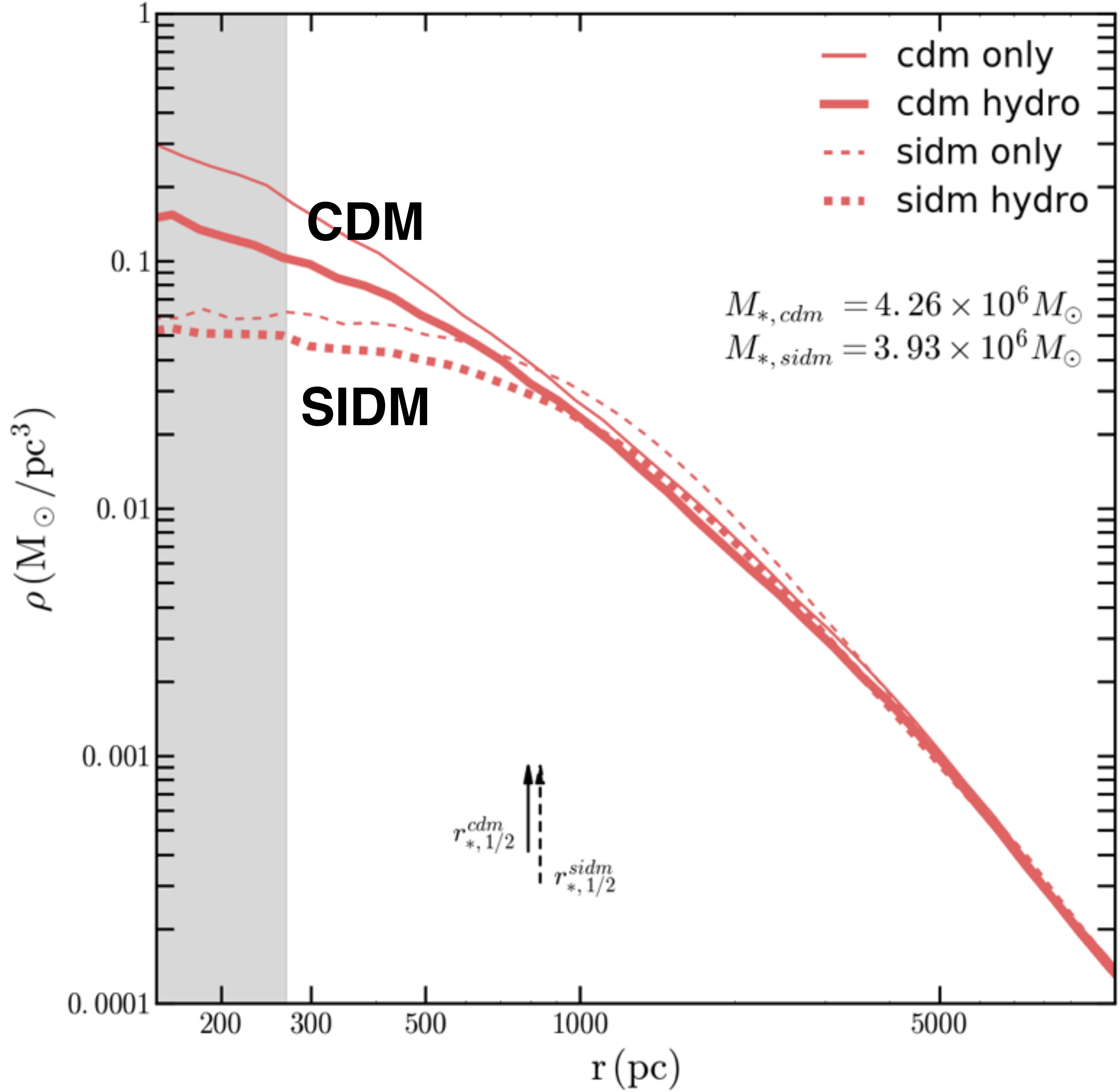
cdm only
cdm hydro
sidm only
sidm hydro
$M_{*,cdm} = 1.08 \times 10^7 M_\odot$
$M_{*,sidm} = 1.01 \times 10^7 M_\odot$
CDM
SIDM
$r^{cdm}_{*,1/2}$
$r^{sidm}_{*,1/2}$
$\rho\,(\mathrm{M}_\odot/\mathrm{pc}^3)$
r (pc)
1
0.1
0.01
0.001
0.0001
200
300
500
1000
5000

high-res FIRE simulations

Run w/ SIDM

$\log_{10}M_\star$



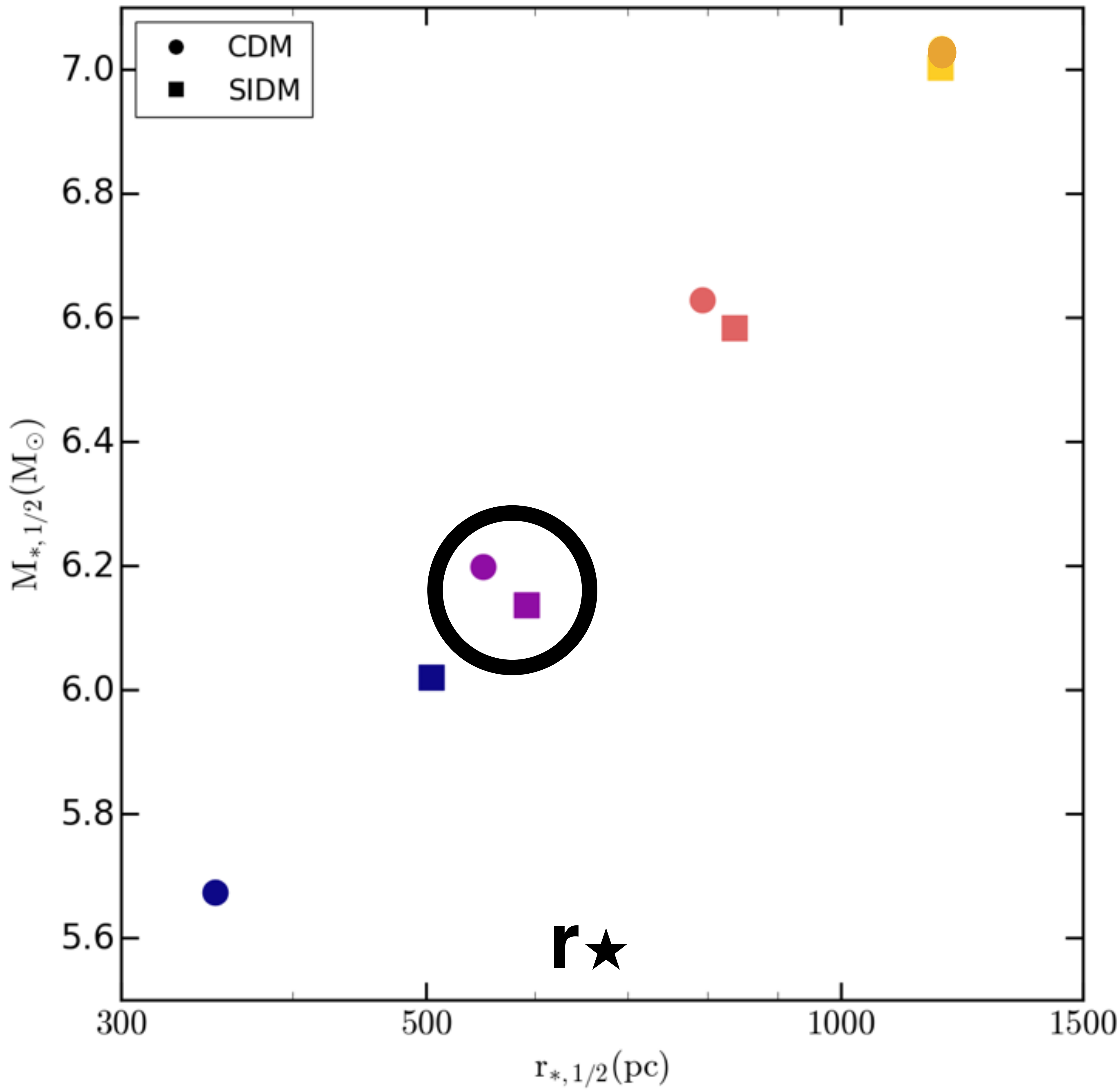


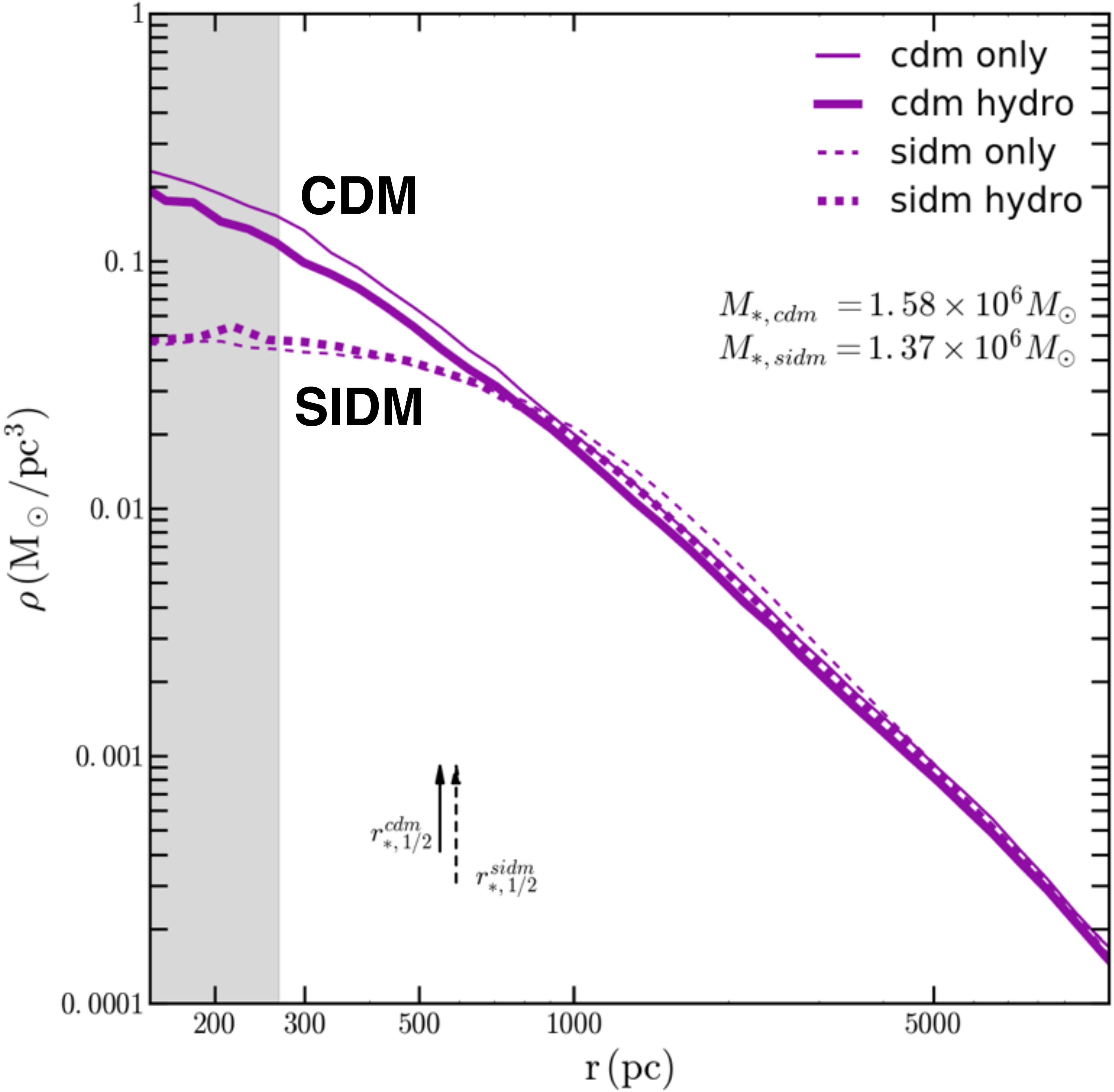
cdm only
cdm hydro
sidm only
sidm hydro
CDM
SIDM
$M_{*,cdm} = 4.26 \times 10^6 M_\odot$
$M_{*,sidm} = 3.93 \times 10^6 M_\odot$
$r_{*,1/2}^{cdm}$
$r_{*,1/2}^{sidm}$
$\rho\,(\mathrm{M_\odot/pc^3})$
r (pc)
1
0.1
0.01
0.001
0.0001
200
300
500
1000
5000

high-res FIRE simulations

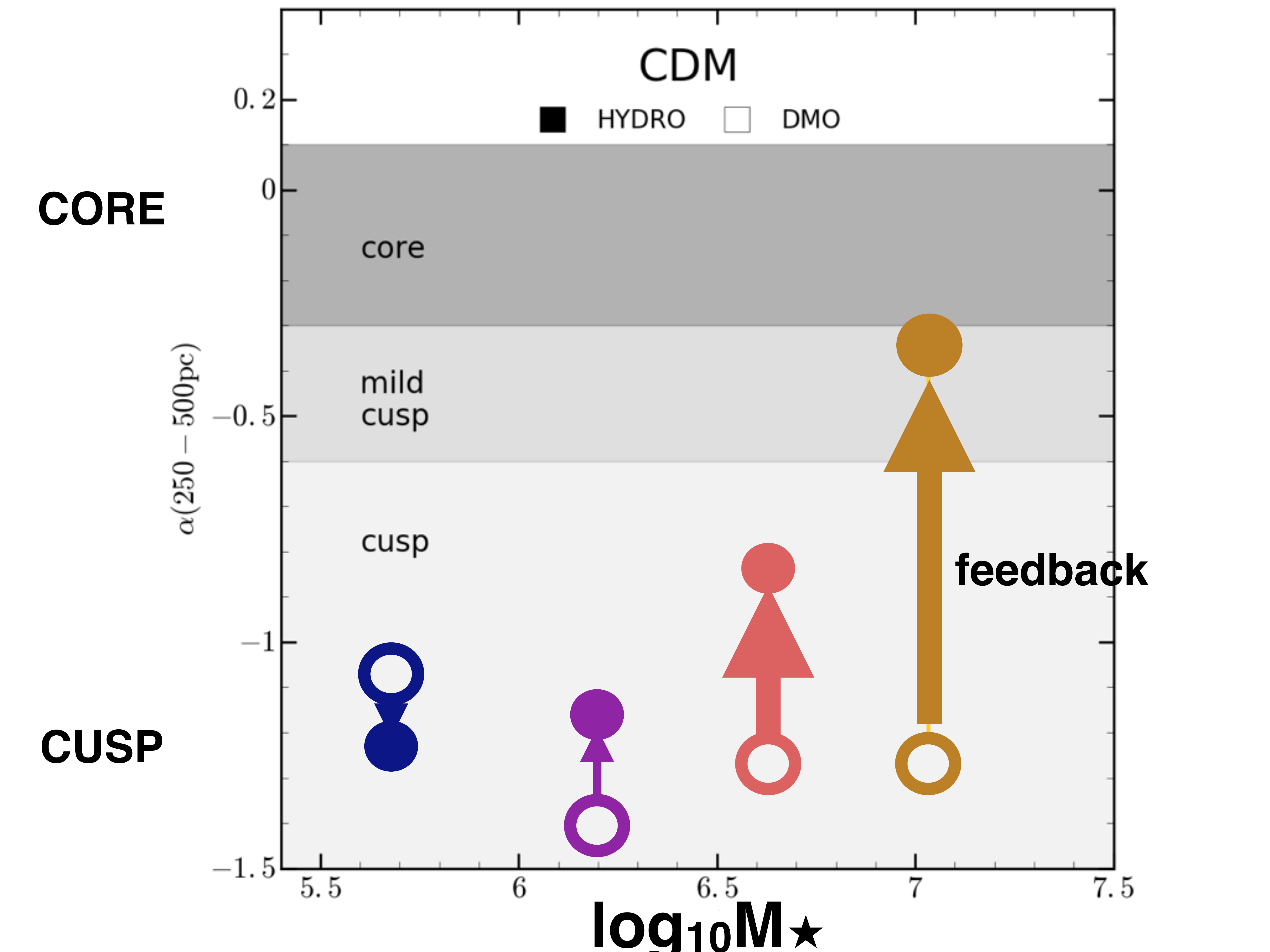
Run w/ SIDM

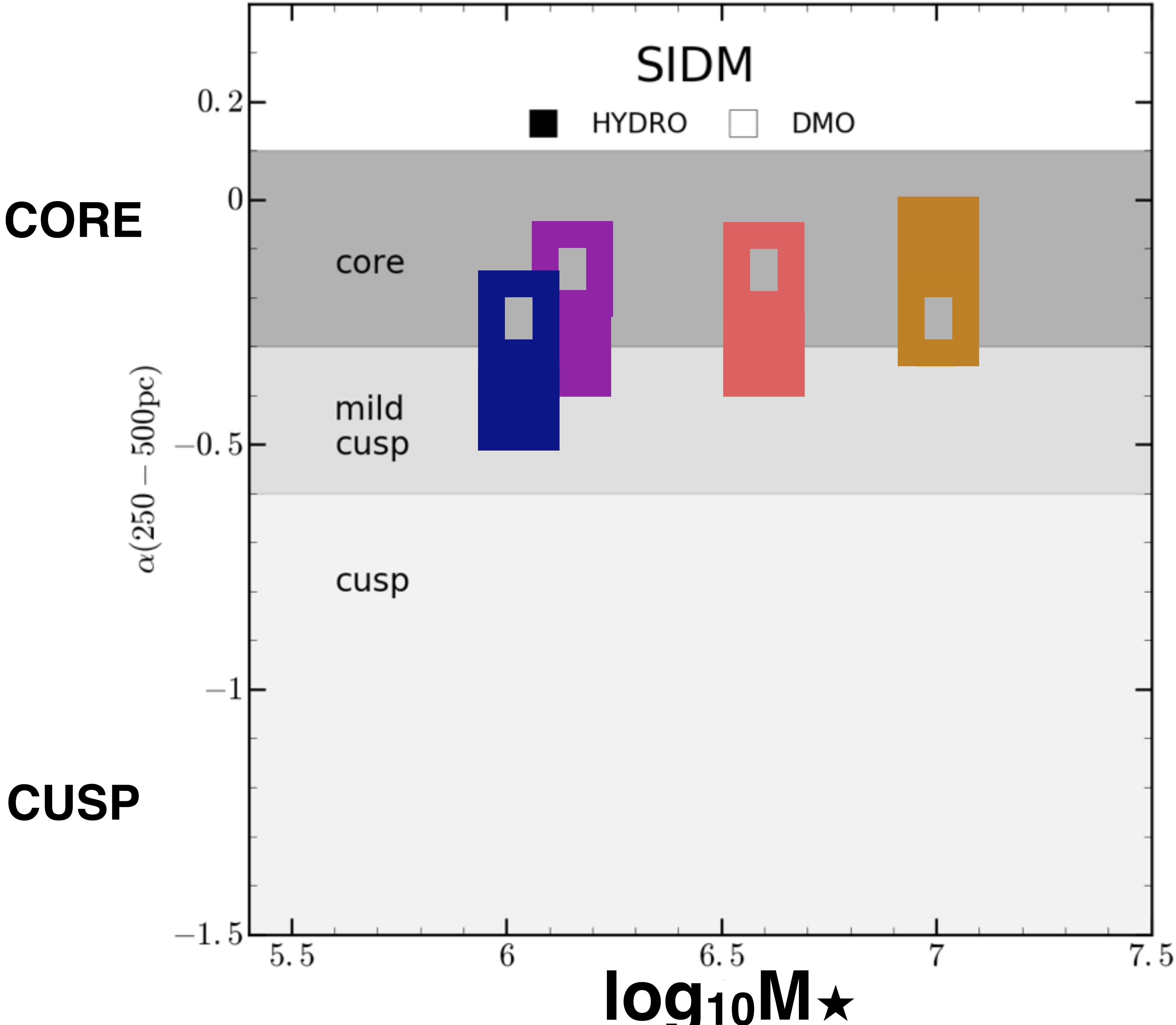
$\log_{10} M_\star$

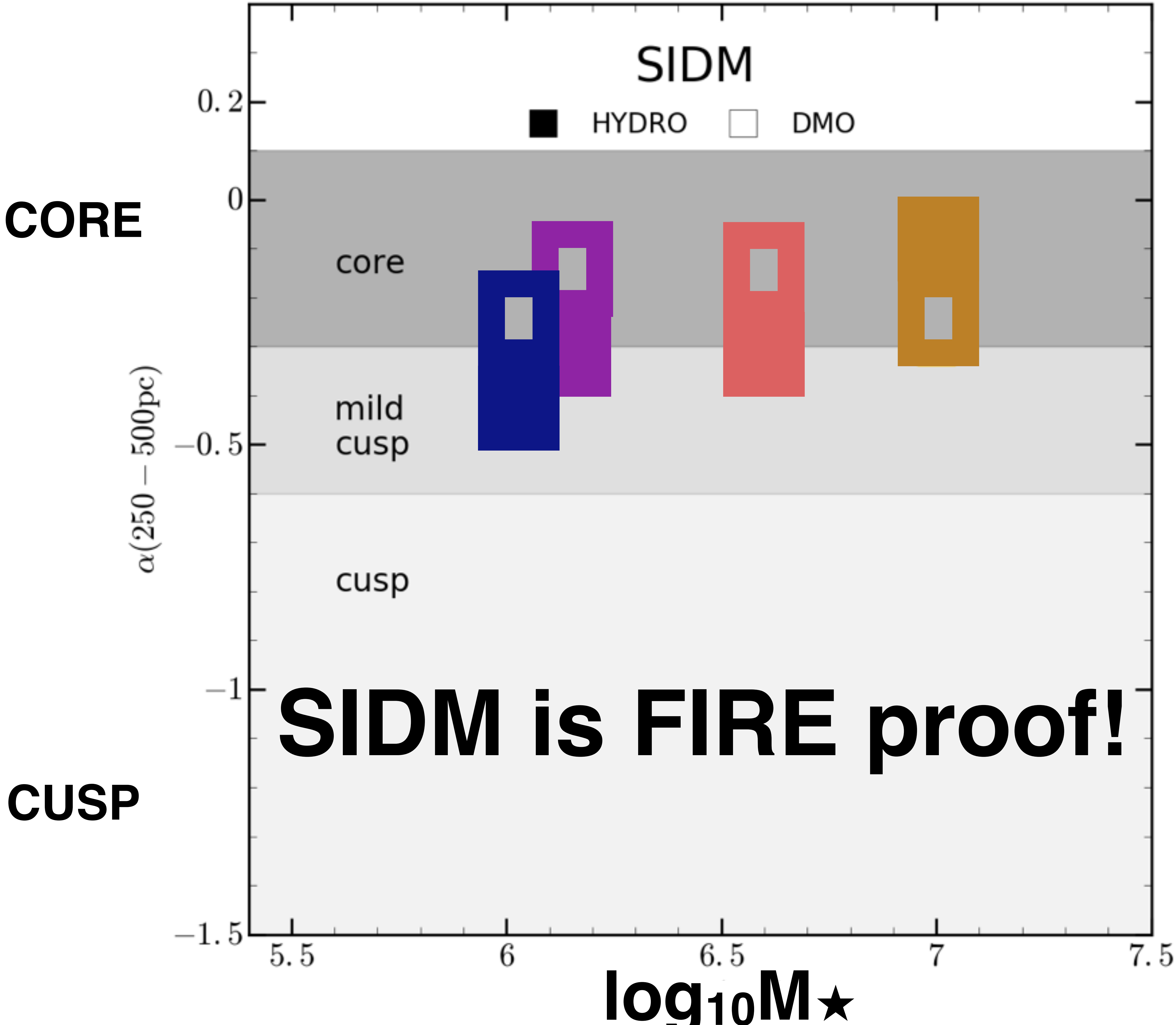




cdm only
cdm hydro
sidm only
sidm hydro
CDM
SIDM
$M_{*,cdm} = 1.58 \times 10^6 M_\odot$
$M_{*,sidm} = 1.37 \times 10^6 M_\odot$
$r_{*,1/2}^{cdm}$
$r_{*,1/2}^{sidm}$
$\rho\,(\mathrm{M_\odot/pc^3})$
r (pc)
1
0.1
0.01
0.001
0.0001
200
300
500
1000
5000


CDM
HYDRO
DMO
CORE
core
mild
cusp
cusp
feedback
CUSP
0.2
0
−0.5
−1
−1.5
α(250 − 500pc)
5.5
6
6.5
7
7.5
log10M★

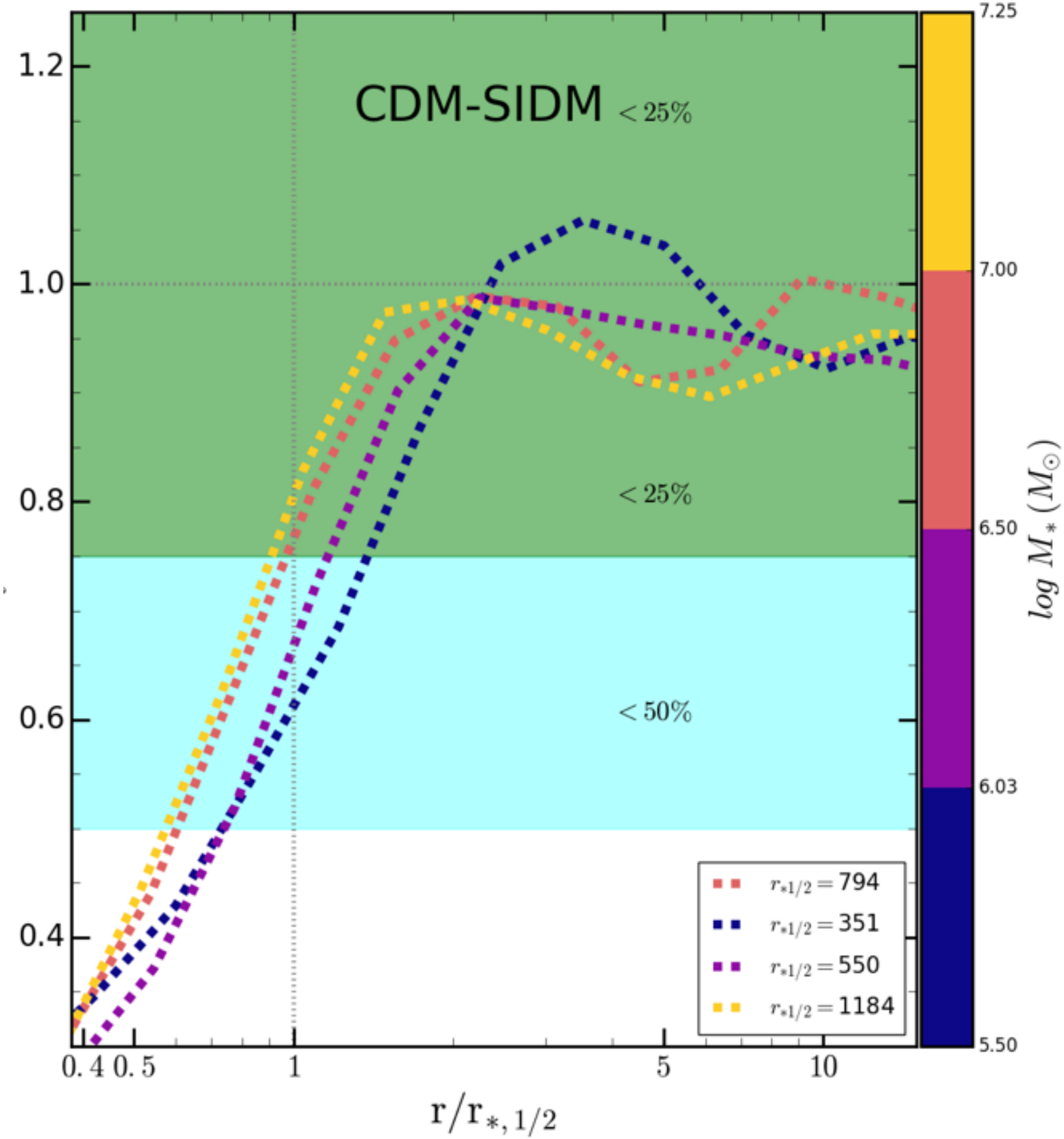

CORE
CUSP
SIDM
HYDRO
DMO
core
mild
cusp
cusp
0.2
0
−0.5
−1
−1.5
5.5
6
6.5
7
7.5
α(250 − 500pc)
log10M★



CORE
CUSP
SIDM
HYDRO
DMO
core
mild
cusp
cusp
0.2
0
−0.5
−1
−1.5
$\alpha(250-500\mathrm{pc})$
5.5
6
6.5
7
7.5
SIDM is FIRE proof!
$\log_{10}M_\star$

FIRE HYDRO SIMS

Density ratio SIDM/CDM



Conclusions

- ★ **Astrophysics can plausibly solve small-halo abundance problem, but this demands a specific relationship M_{halo} vs. M_{star}**
  - ☆ **Too big to fail:** densities of small galaxies are too low compared to standard relation.

- ★ **Feedback** can make cores if galaxies have enough stars:
  - ☆ $M_\star > 3.10^6 M_\odot$ **needed for cores.**
  - ☆ **Most MW satellites are smaller than this.**

SIDM

★ Small-scale problems alleviated for

- ☆ **σ/m ~ 1 cm² /g** [on v~10km/s scale] of dwarfs

★ Clusters: **σ/m < 0.2 cm² /g** [v~1000 km/s]

- ☆ Based on density alone (better than bullet cluster)

★ Tight conspiracy between SIDM distribution and baryon distribution.

- ☆ Observational consequences @ v~100 km/s?

★ SIDM is more resilient to feedback than CDM.

- ☆ **Predictions much less sensitive to feedback**