Small scale puzzles
[and their solution]

Justin I. Read

Matthew Walker, Pascal Steger, Oscar Agertz, Michelle Collins, Denis Erkal, Giuliano Iorio, Filippo Fraternali, Alexandra Gregory

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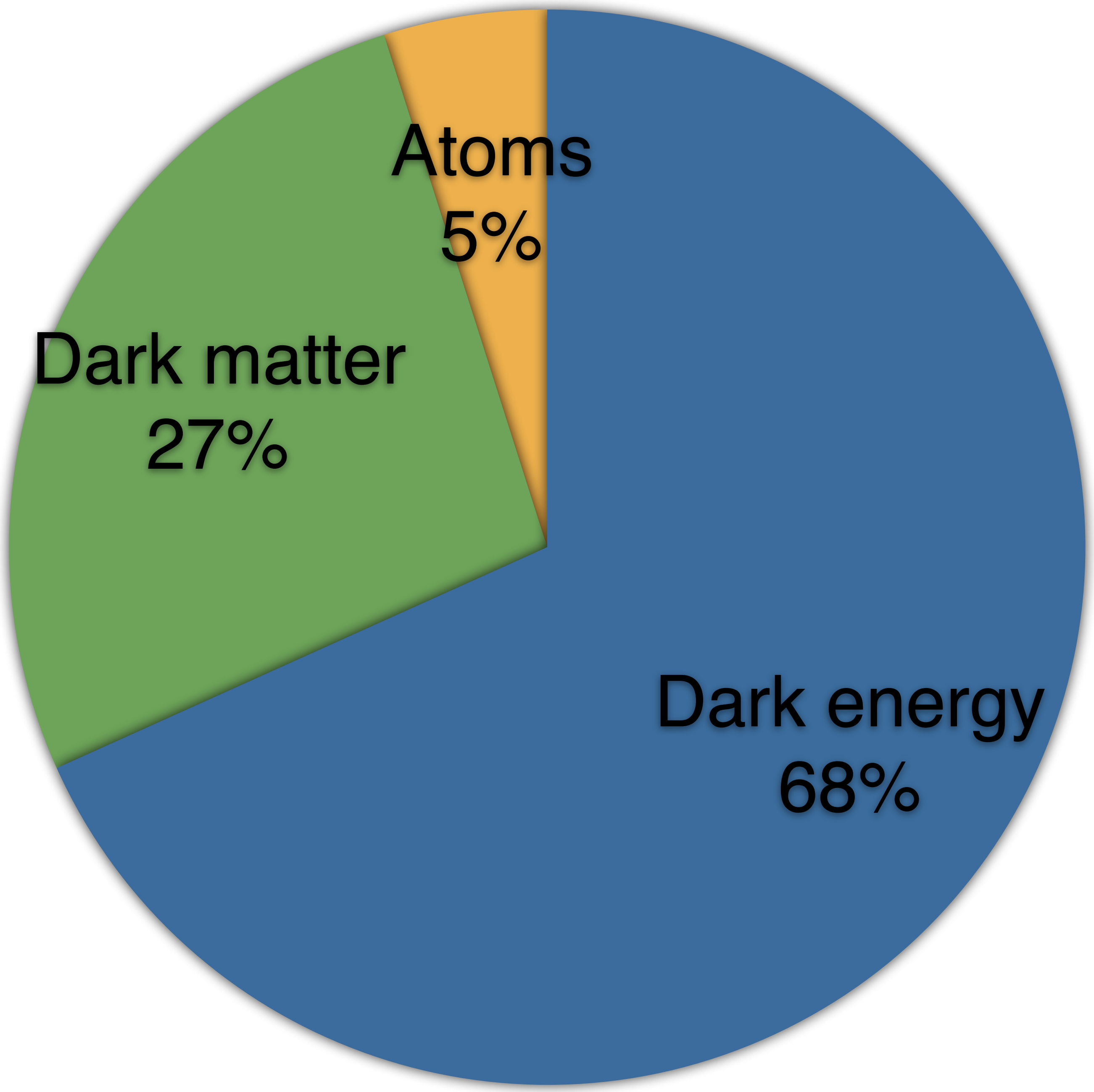
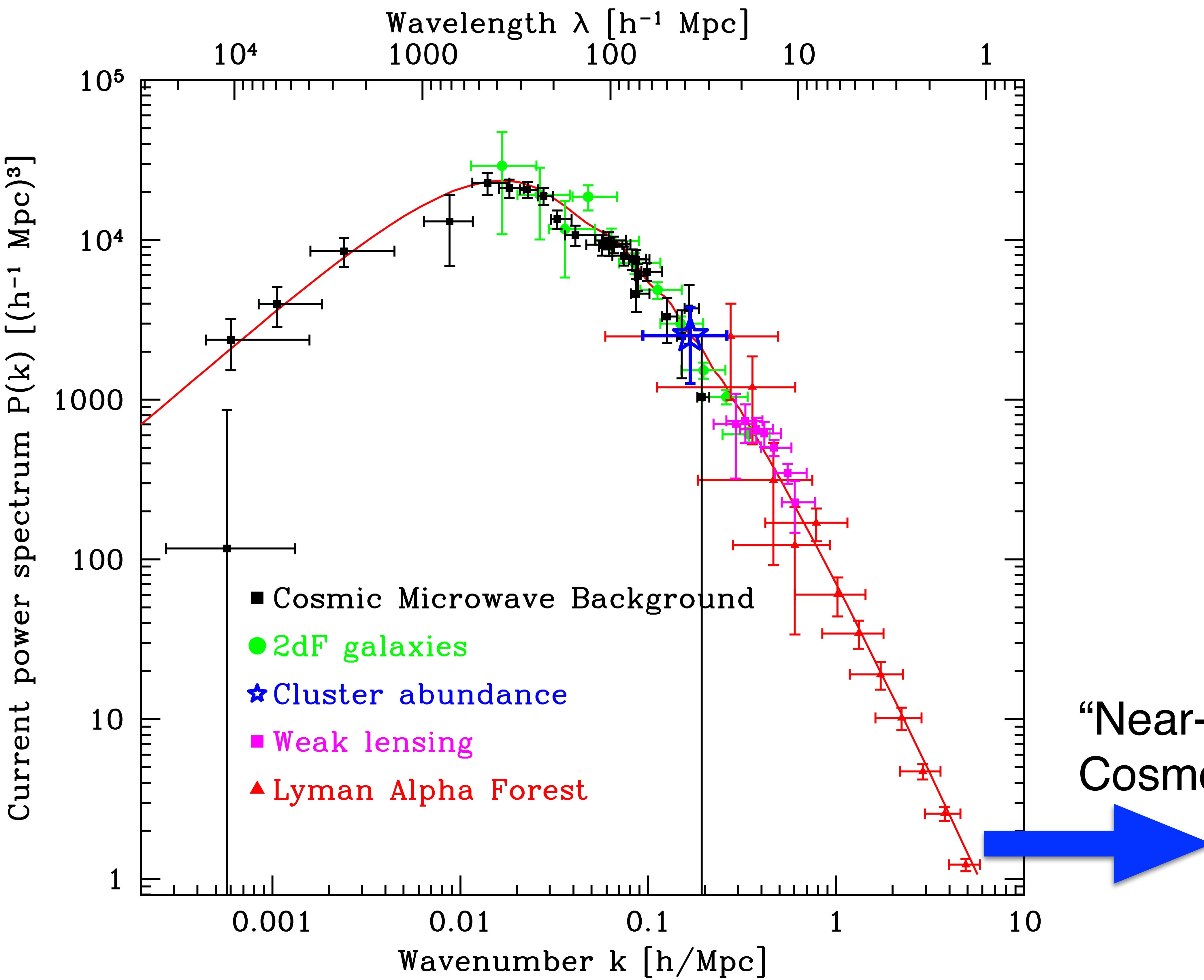
The Standard Cosmological Model

The standard cosmological model



Planck 2015

The standard cosmological model



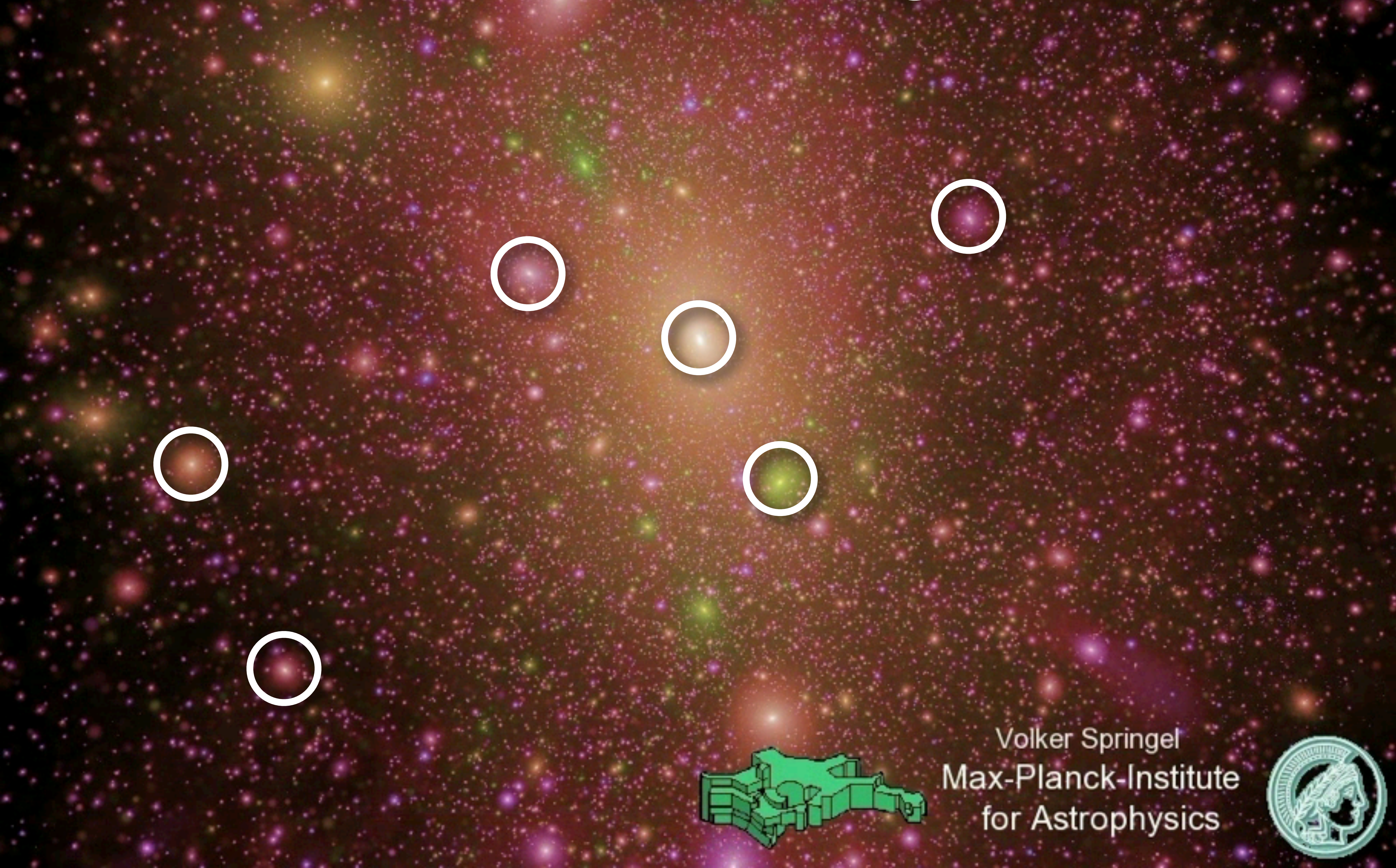
Tegmark & Zaldarriaga 2002

Small scale puzzles

“Aquarius” pure dark matter
simulation of structure formation in an
LCDM cosmology
[Springel et al. 2008]

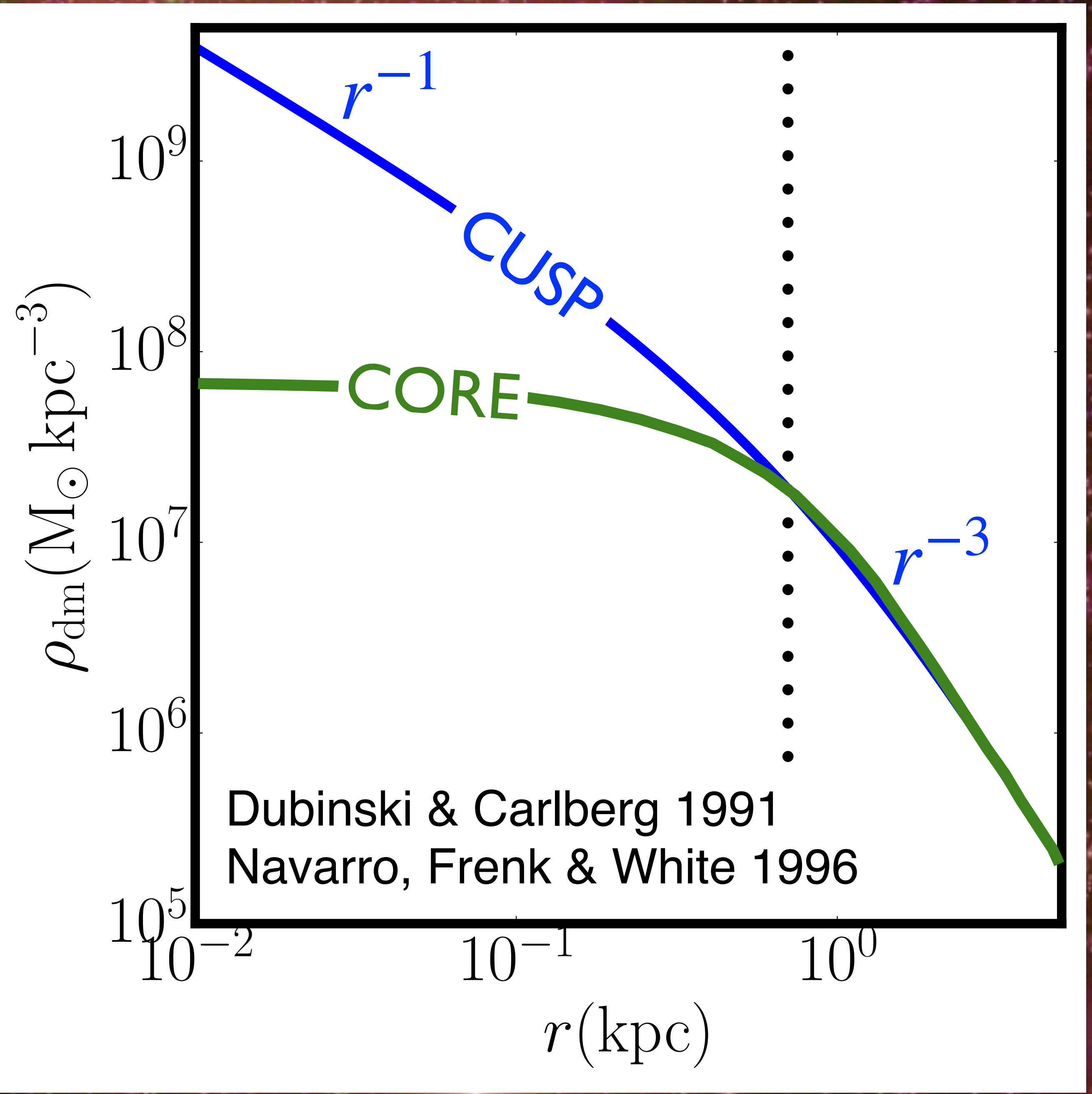
#1 : “Missing satellites” problem

[Klypin et al. 1999; Moore et al. 1999]



#2 : "Cusp-core" problem

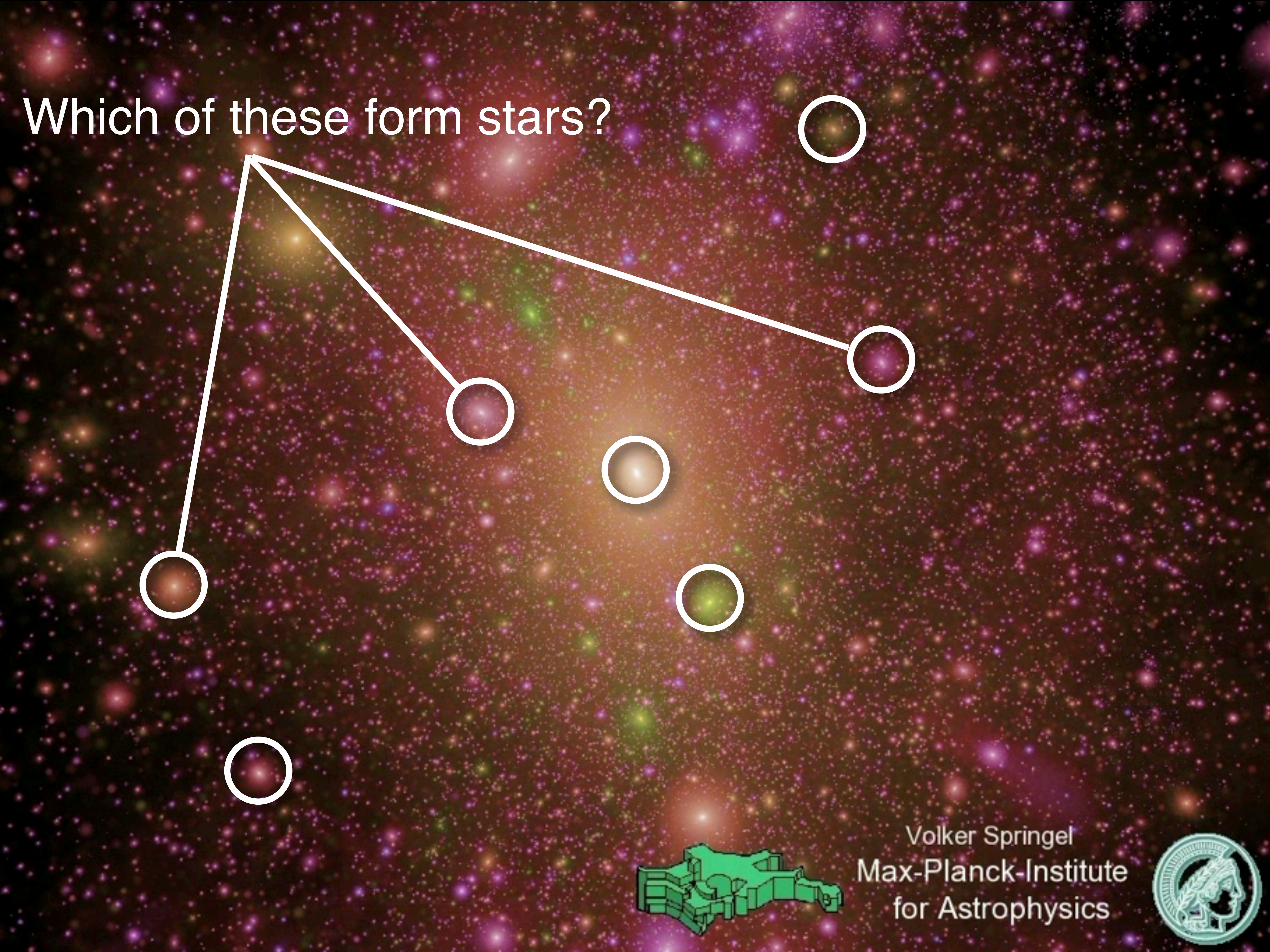
[Flores et al. 1994; Moore 1994]



Volker Springel
Max-Planck-Institute
for Astrophysics

Pure Dark Matter
Simulations

Observed Universe


Which of these form stars?
Volker Springel
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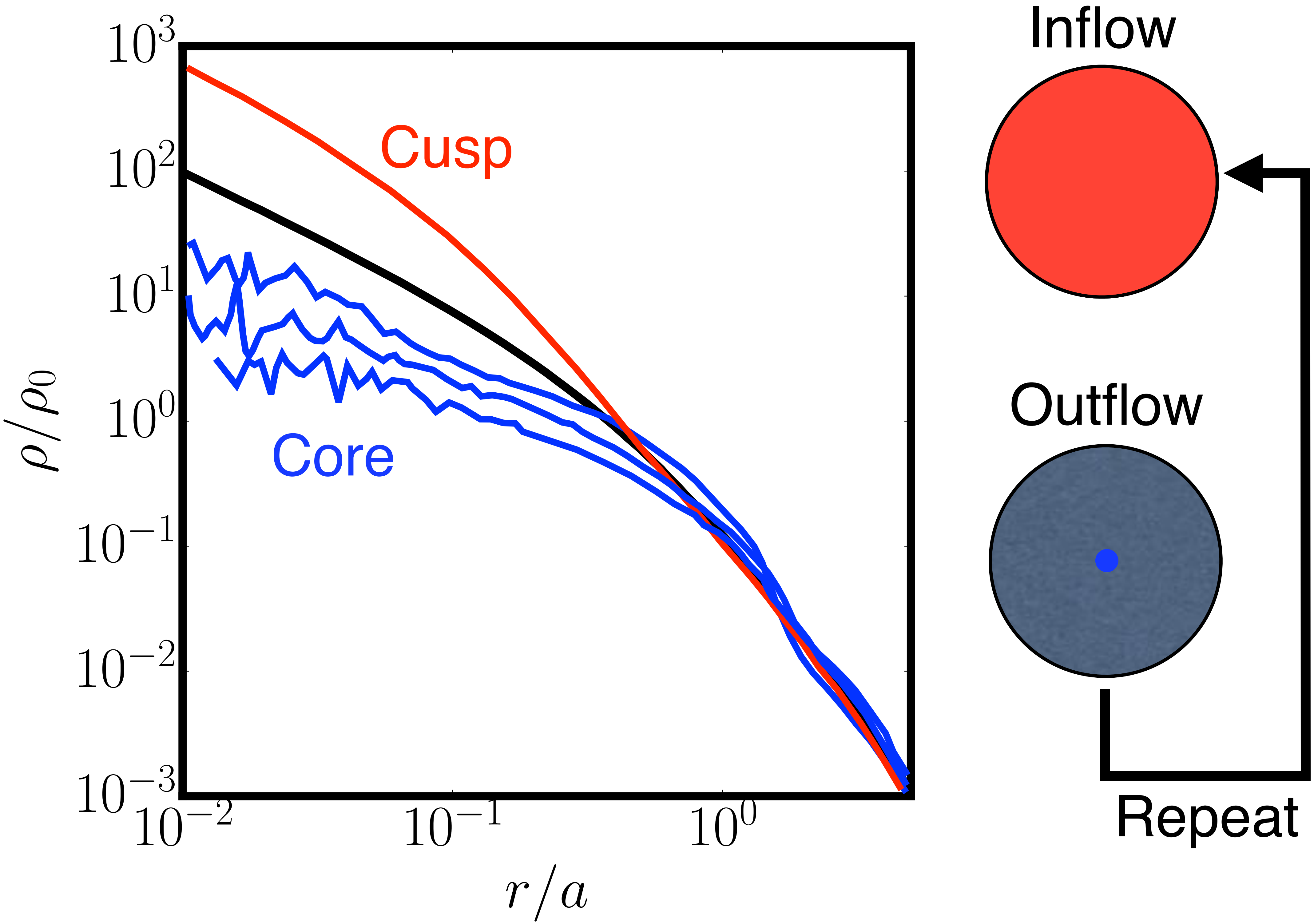
for Astrophysics

Dark Matter Heating

The physics of dark matter heating



Navarro et al. 1996; Gnedin & Zhao 2002; Read & Gilmore 2005 Pontzen & Governato 2012

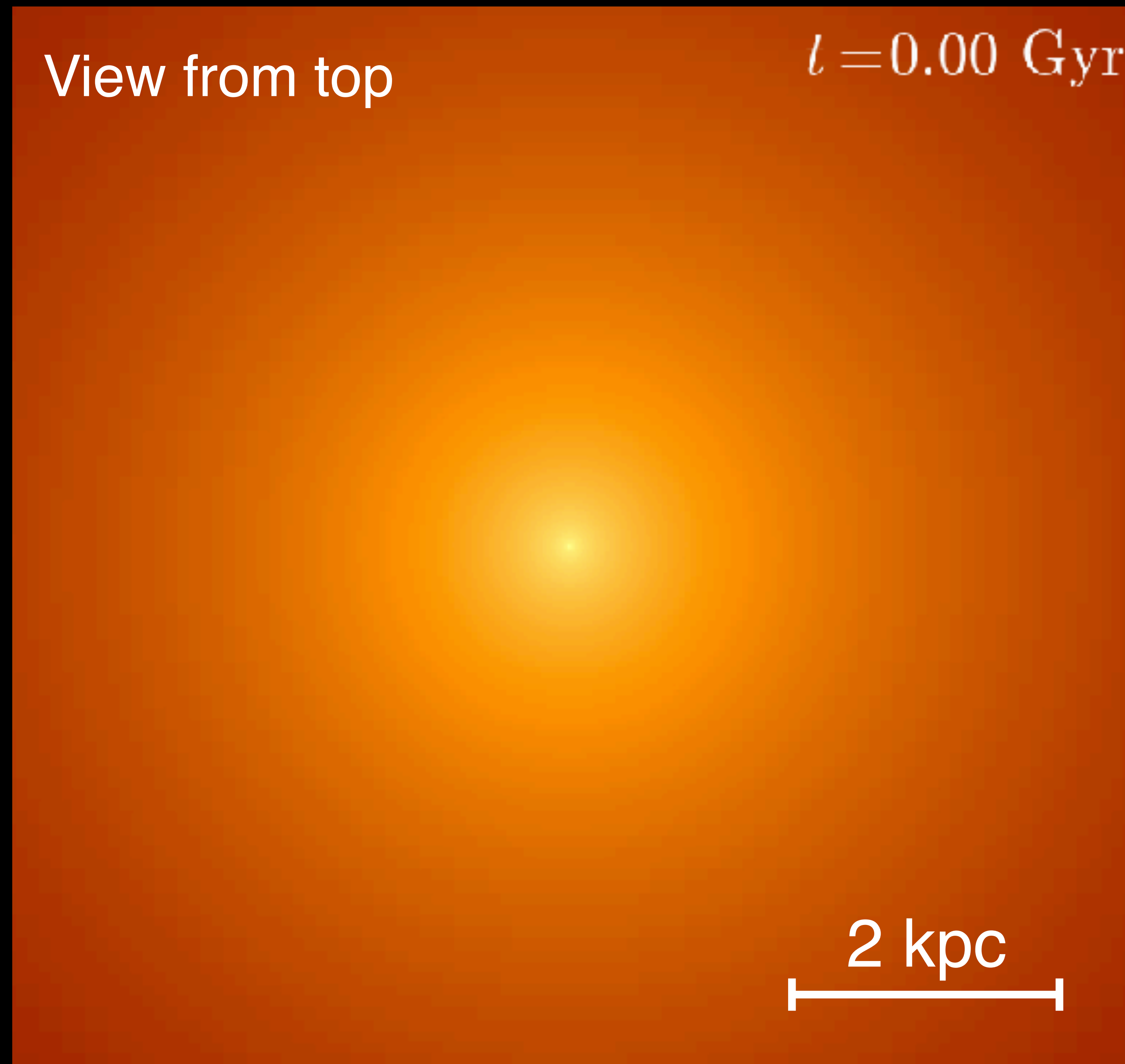
Simulations | Resolving stellar feedback

$\Delta x = 4\,\mathrm{pc}$

$M_{\mathrm{res}} = 300\,\mathrm{M}_{\odot}$

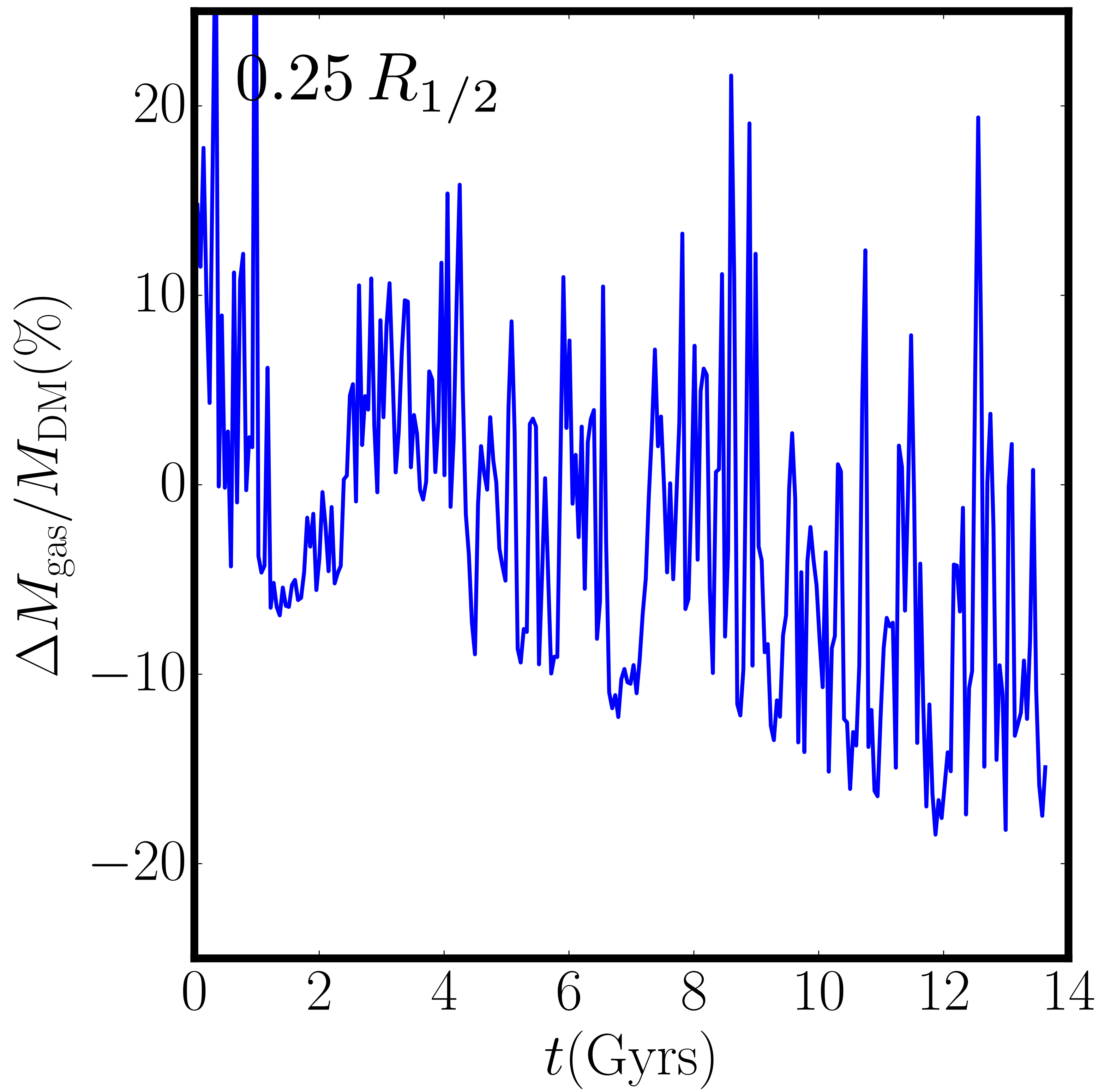
$\rho_{\mathrm{th}} = 300\,\mathrm{atoms/cc}$

$T_{\mathrm{gas,min}} = 100\,\mathrm{K}$



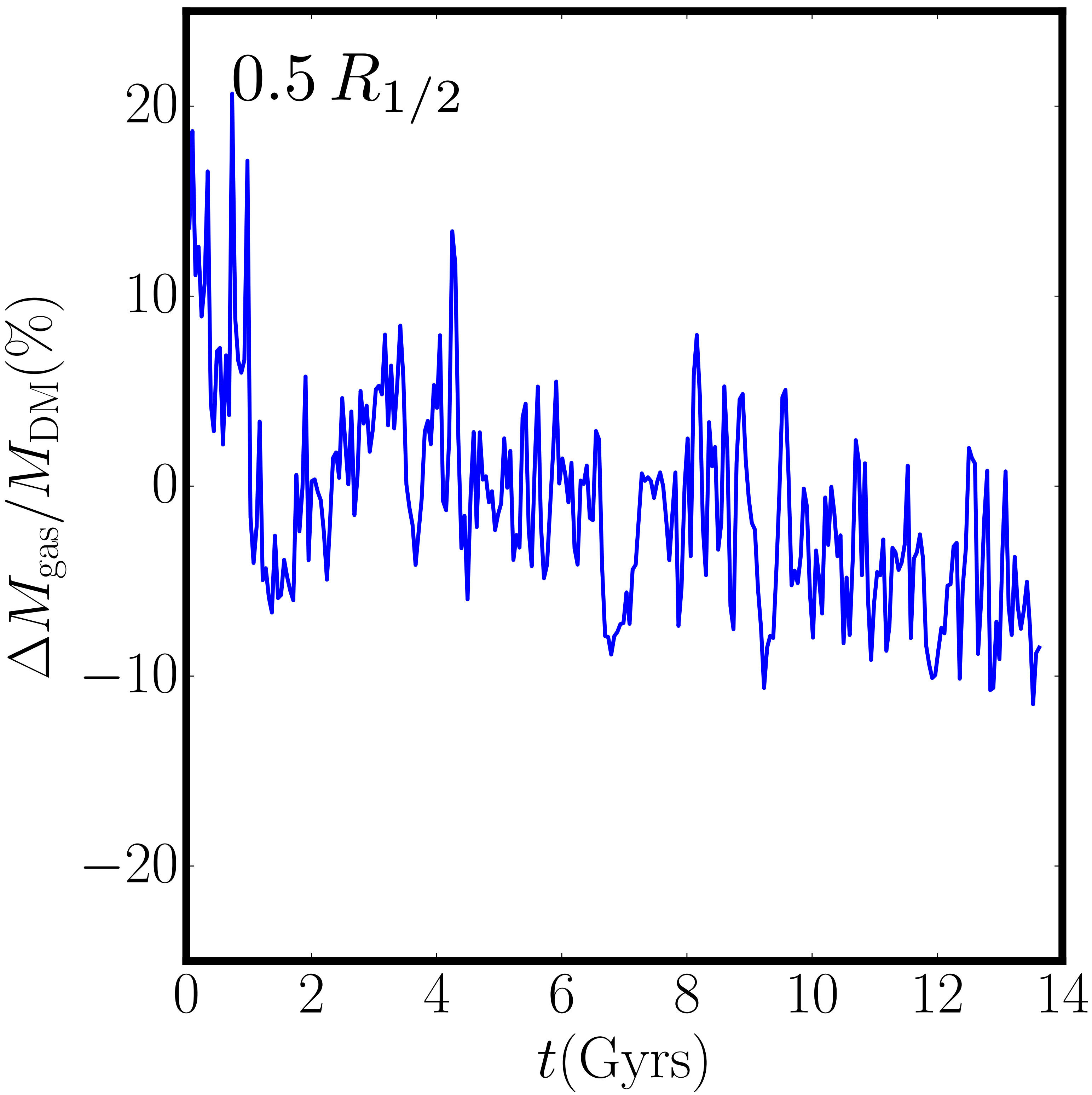
Read et al. 2016

Simulations I Resolving gas flows



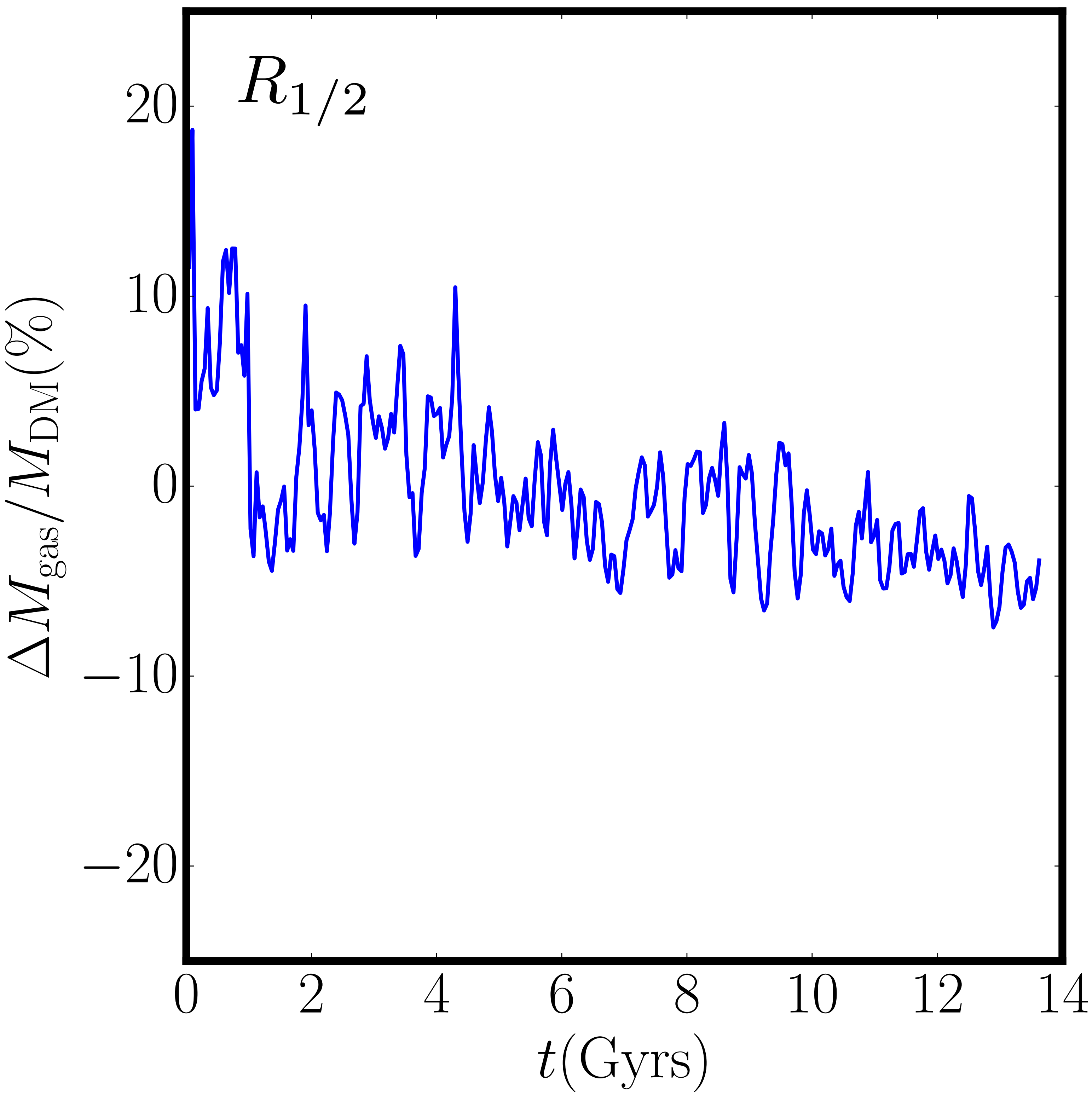
Read et al. 2016

Simulations | Resolving gas flows



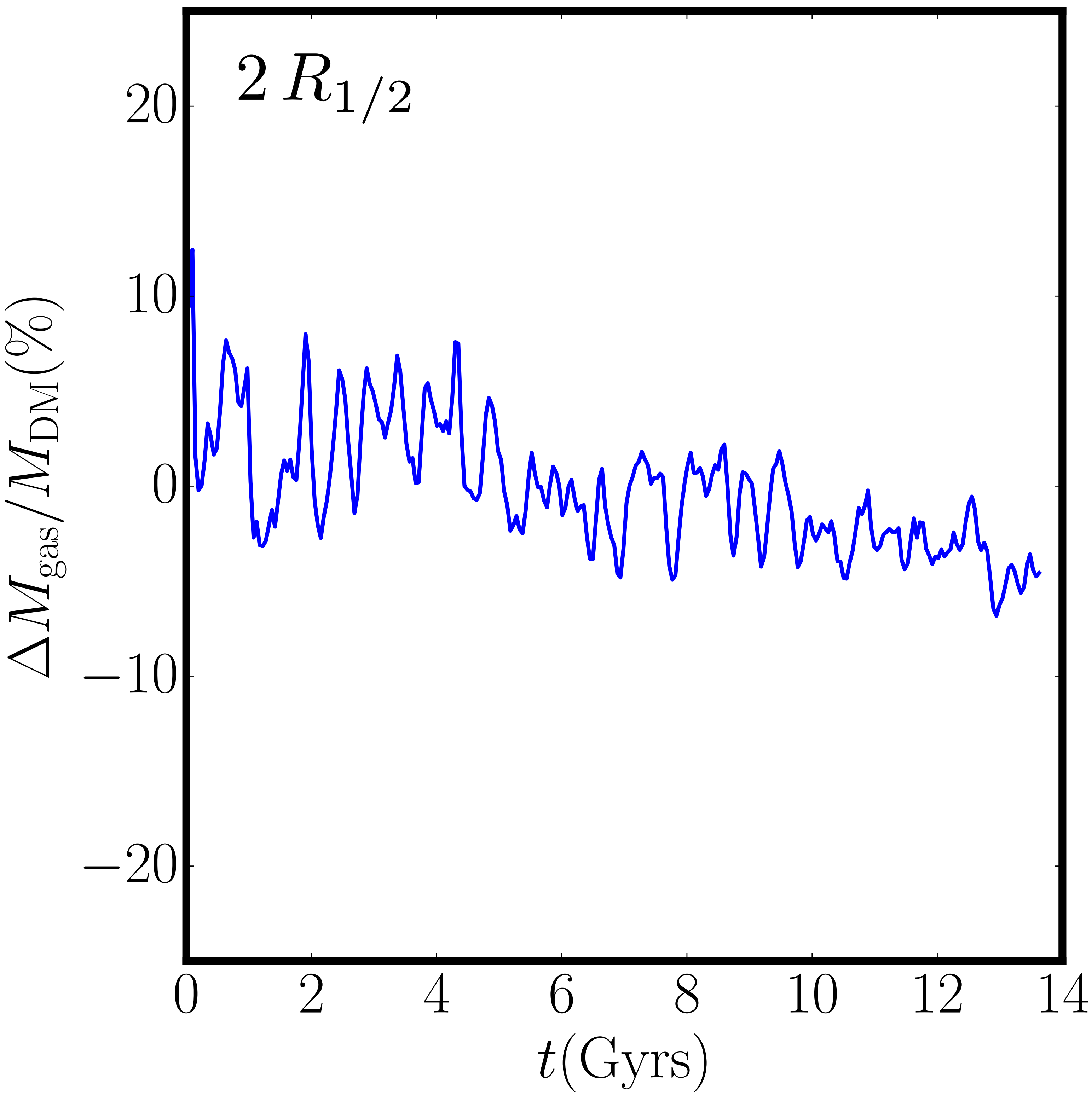
Read et al. 2016

Simulations I Resolving gas flows



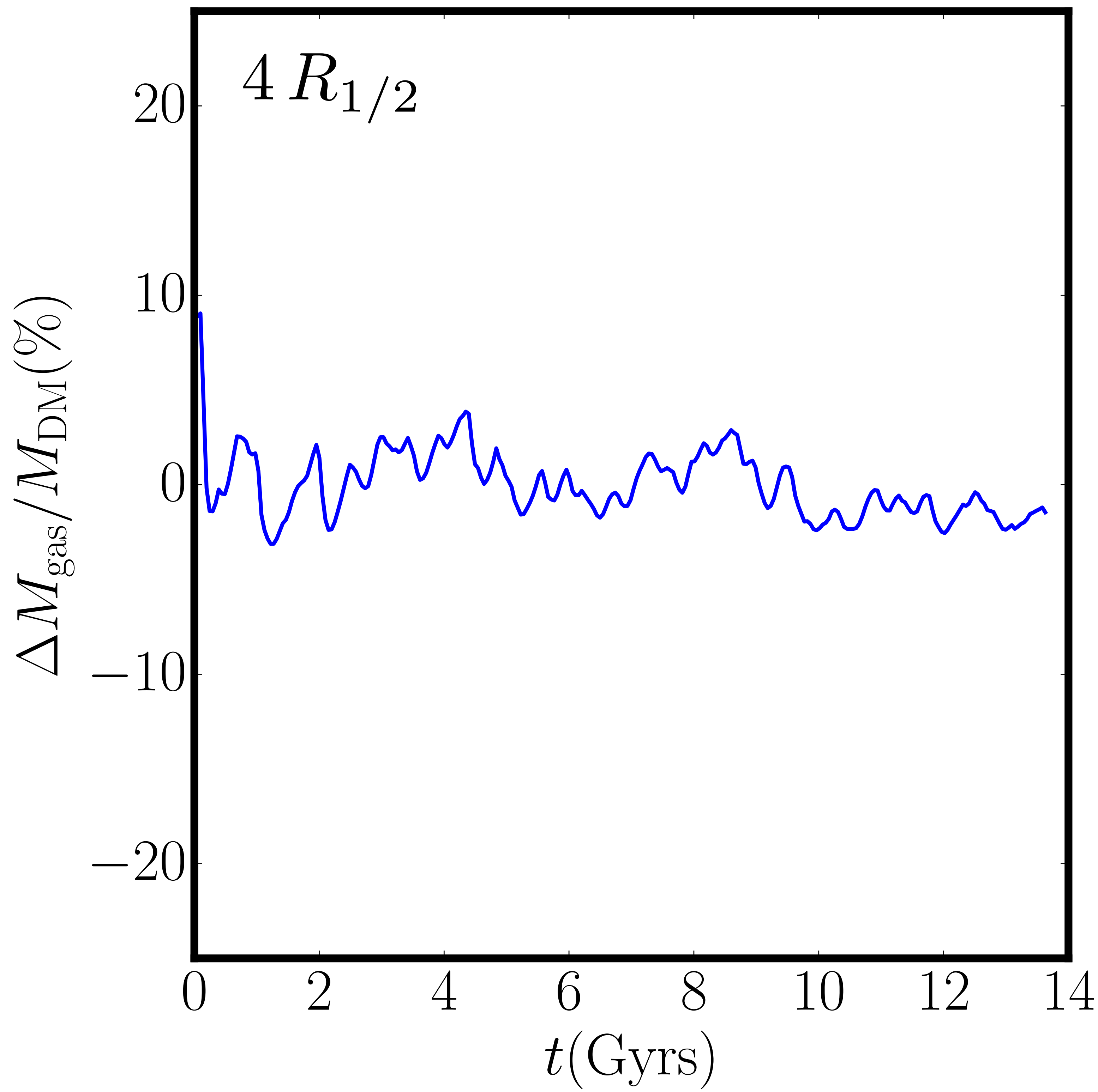
Read et al. 2016

Simulations I Resolving gas flows



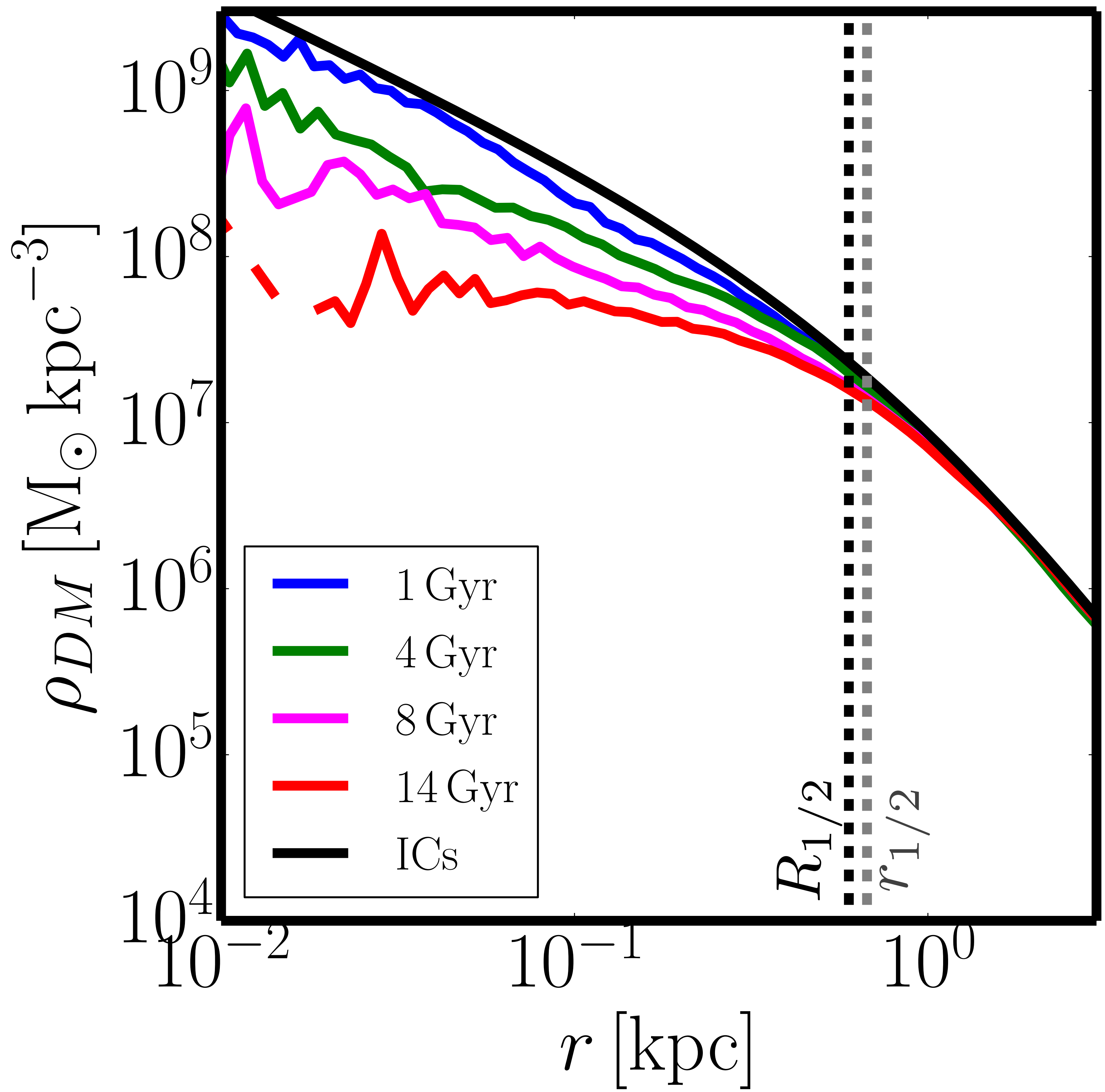
Read et al. 2016

Simulations I Resolving gas flows



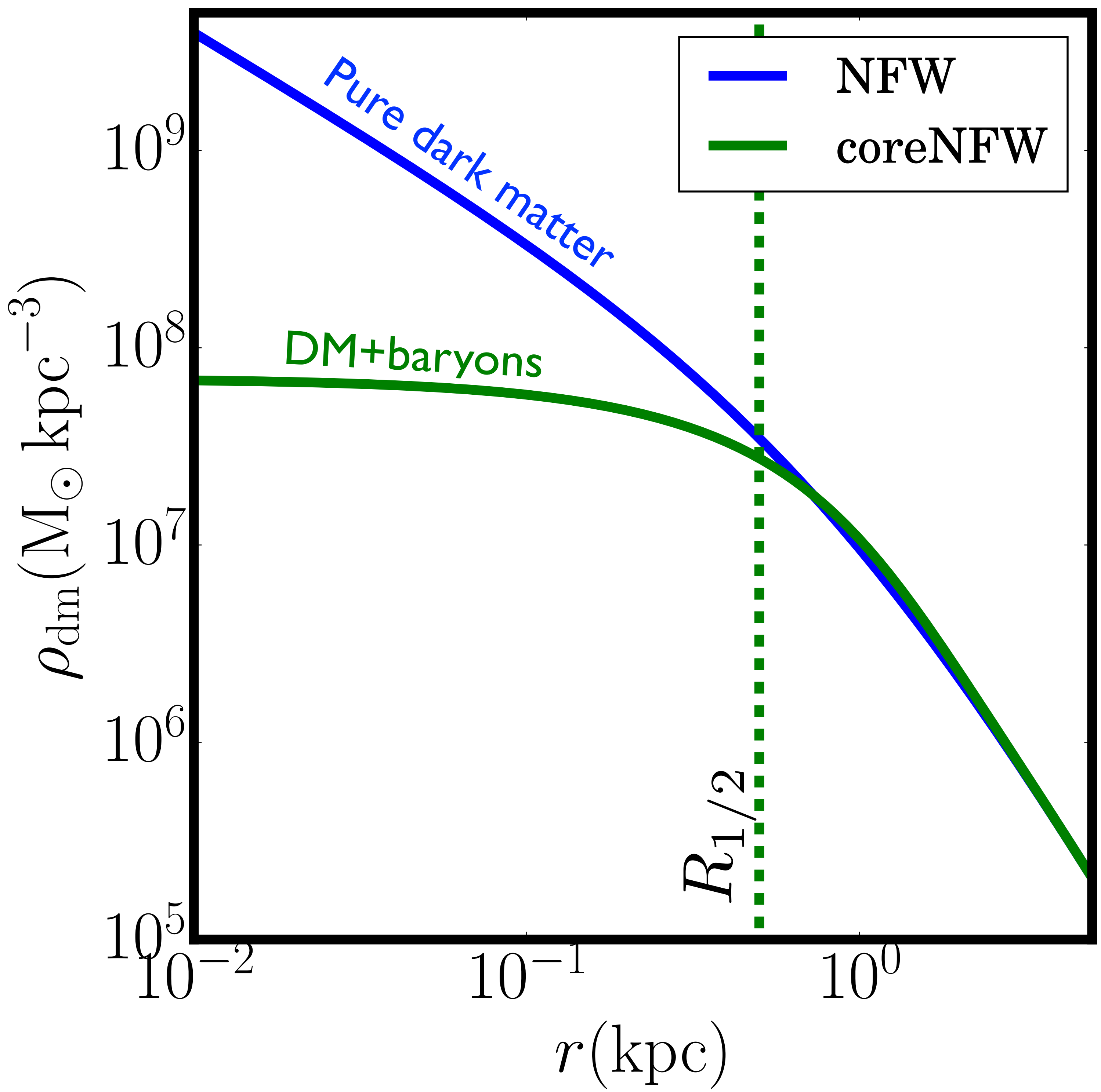
Read et al. 2016

Simulations I Cusp-core transformations



Read et al. 2016

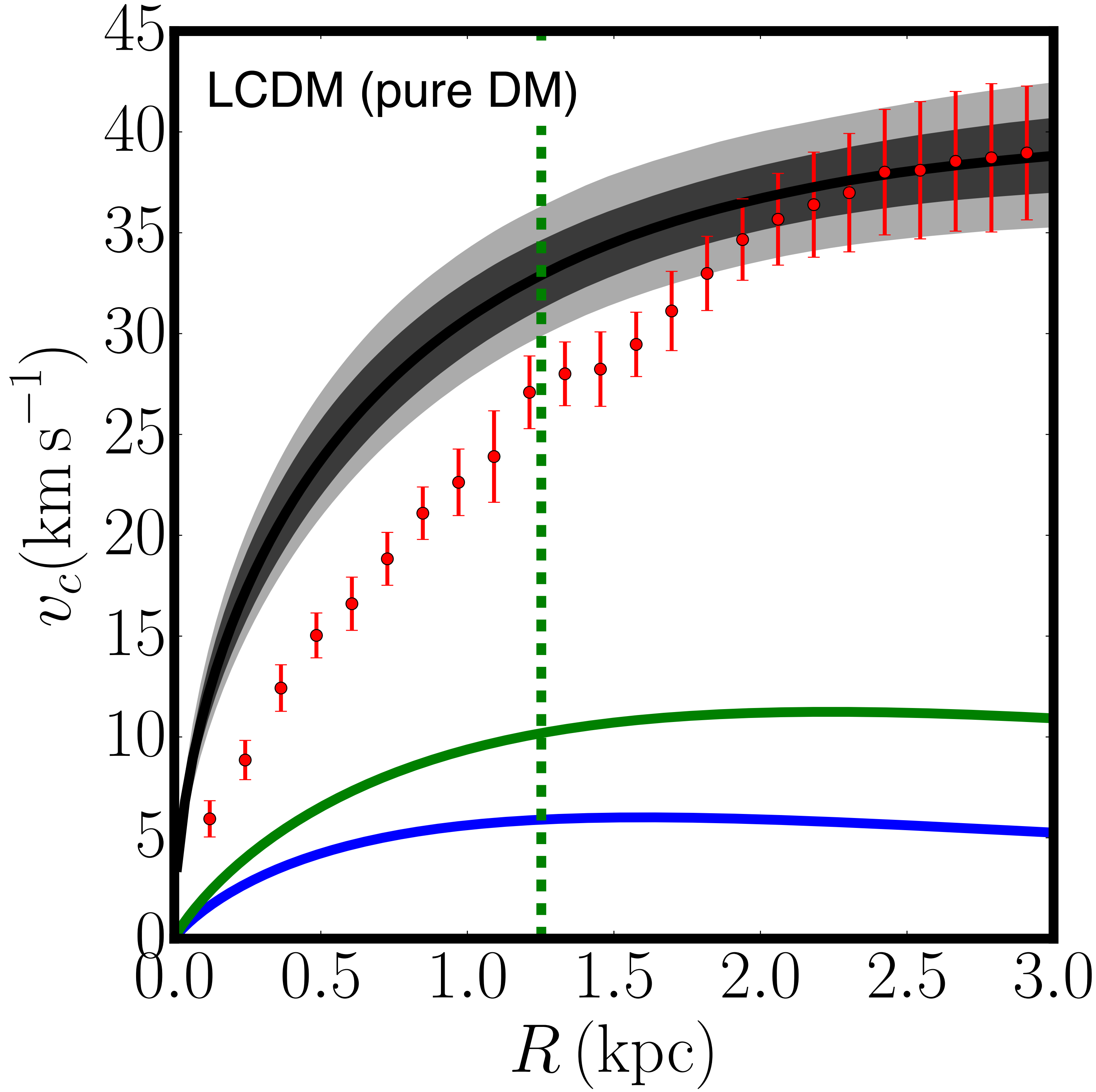
Simulations | Cusp-core transformations



Read et al. 2016

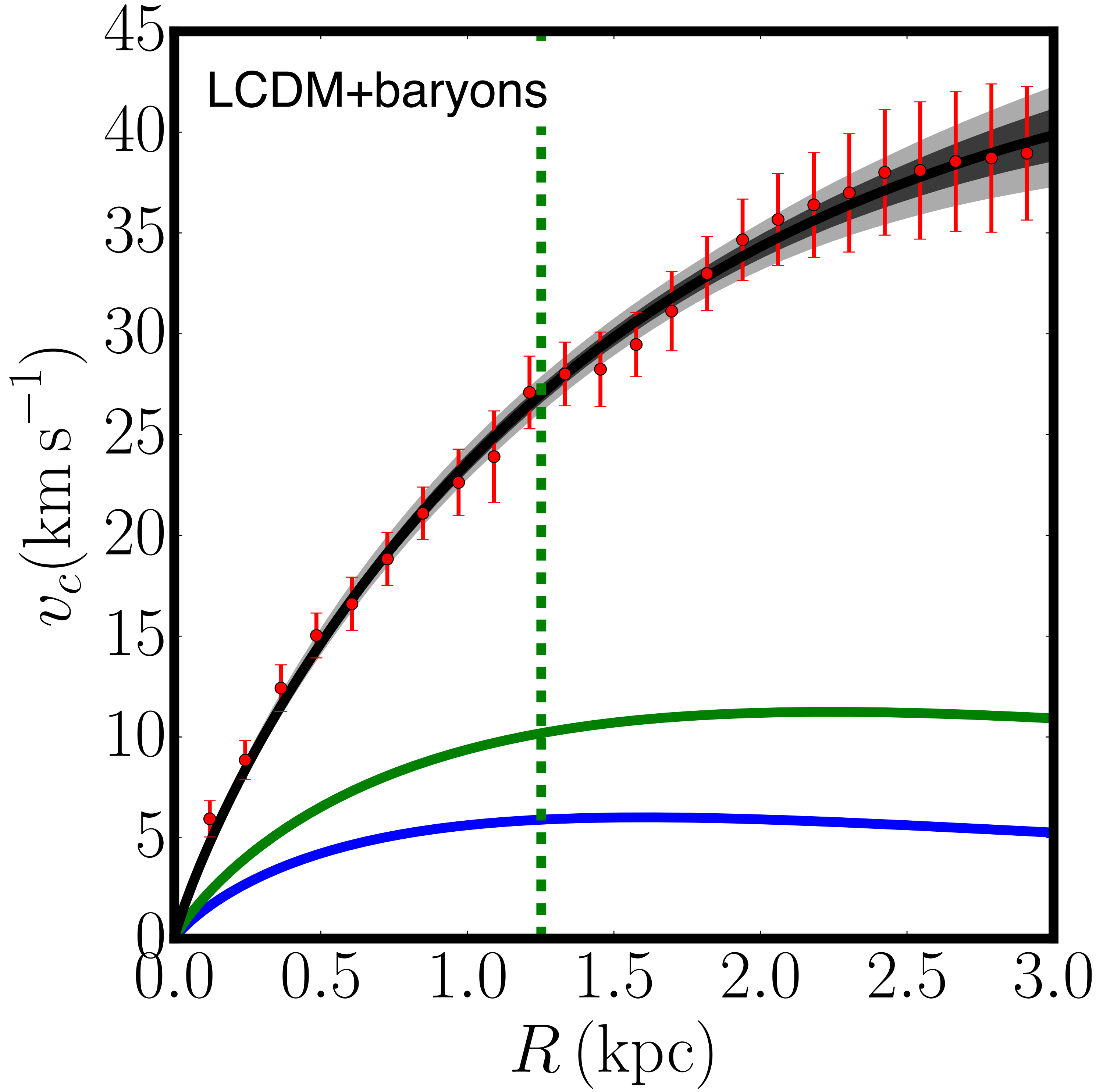
The Cusp-Core Problem Revisited

Measurement | Rotation cuves

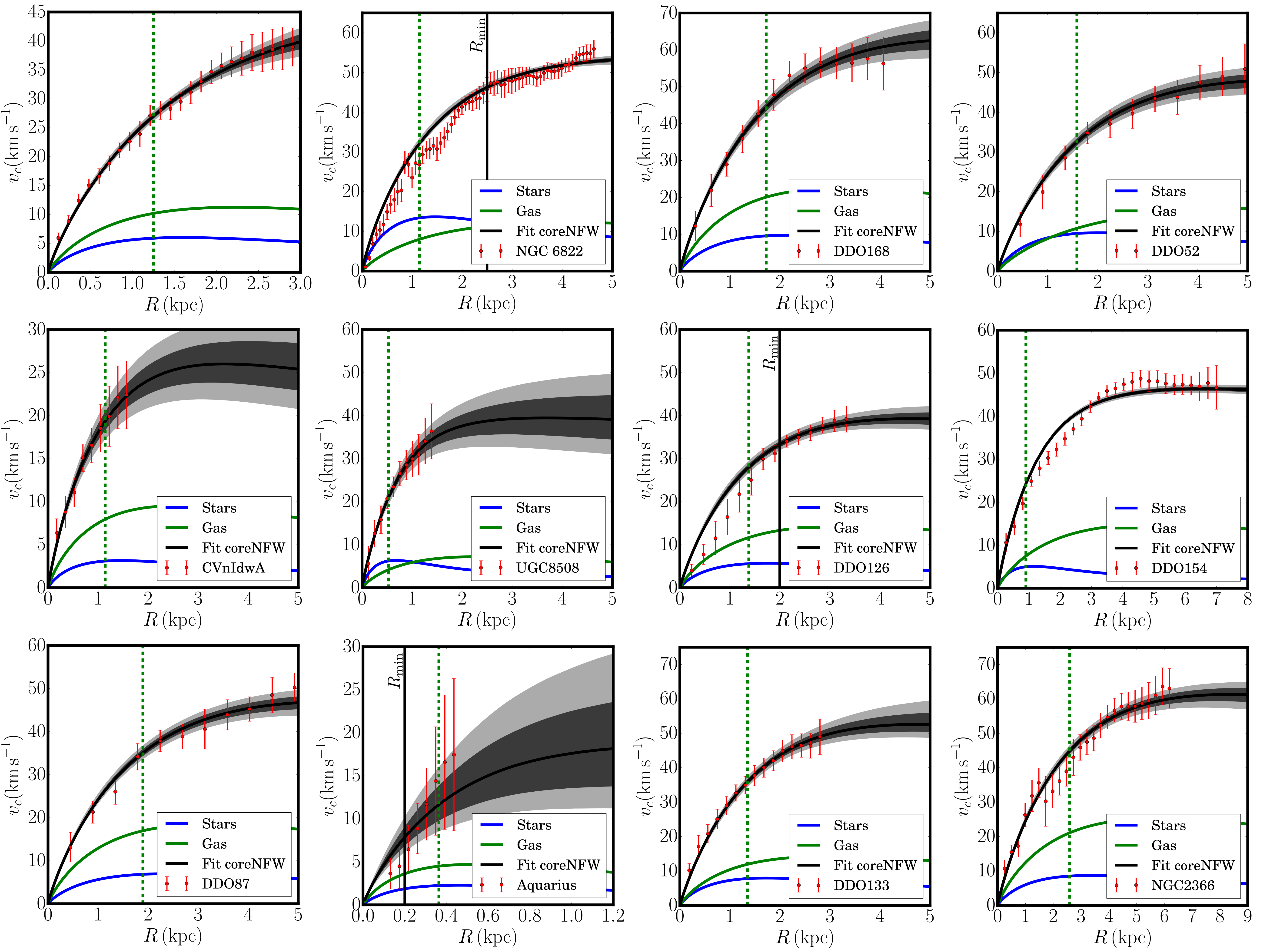


Read et al. 2016b,2017

Measurement | Rotation cuves

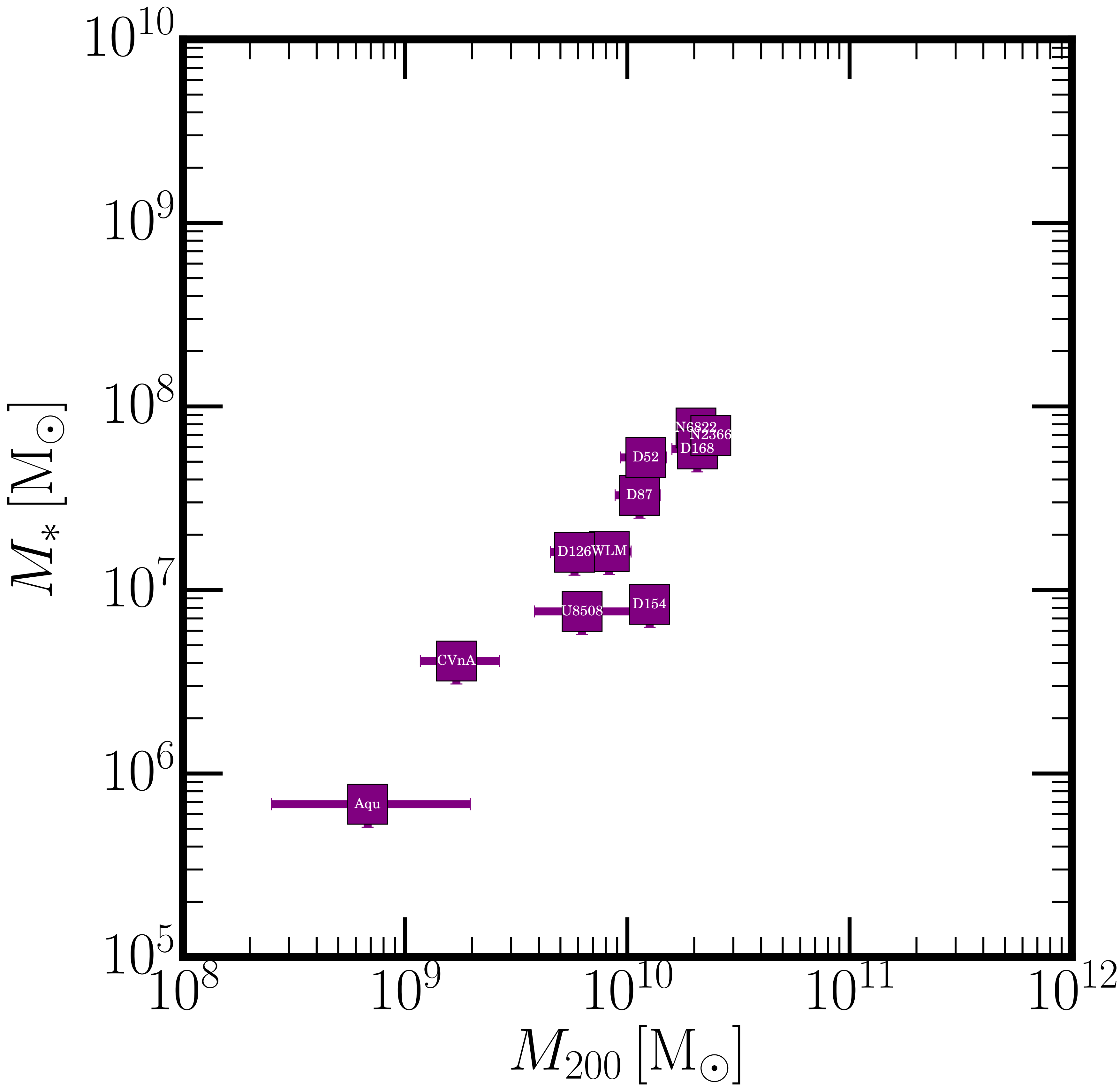


Read et al. 2016b,2017


$v_c\,(\mathrm{km\,s^{-1}})$
$R\,(\mathrm{kpc})$
$R_{\rm min}$
Stars
Gas
Fit coreNFW
NGC 6822
DDO168
DDO52
CVnIdwA
UGC8508
DDO126
DDO154
DDO87
Aquarius
DDO133
NGC2366

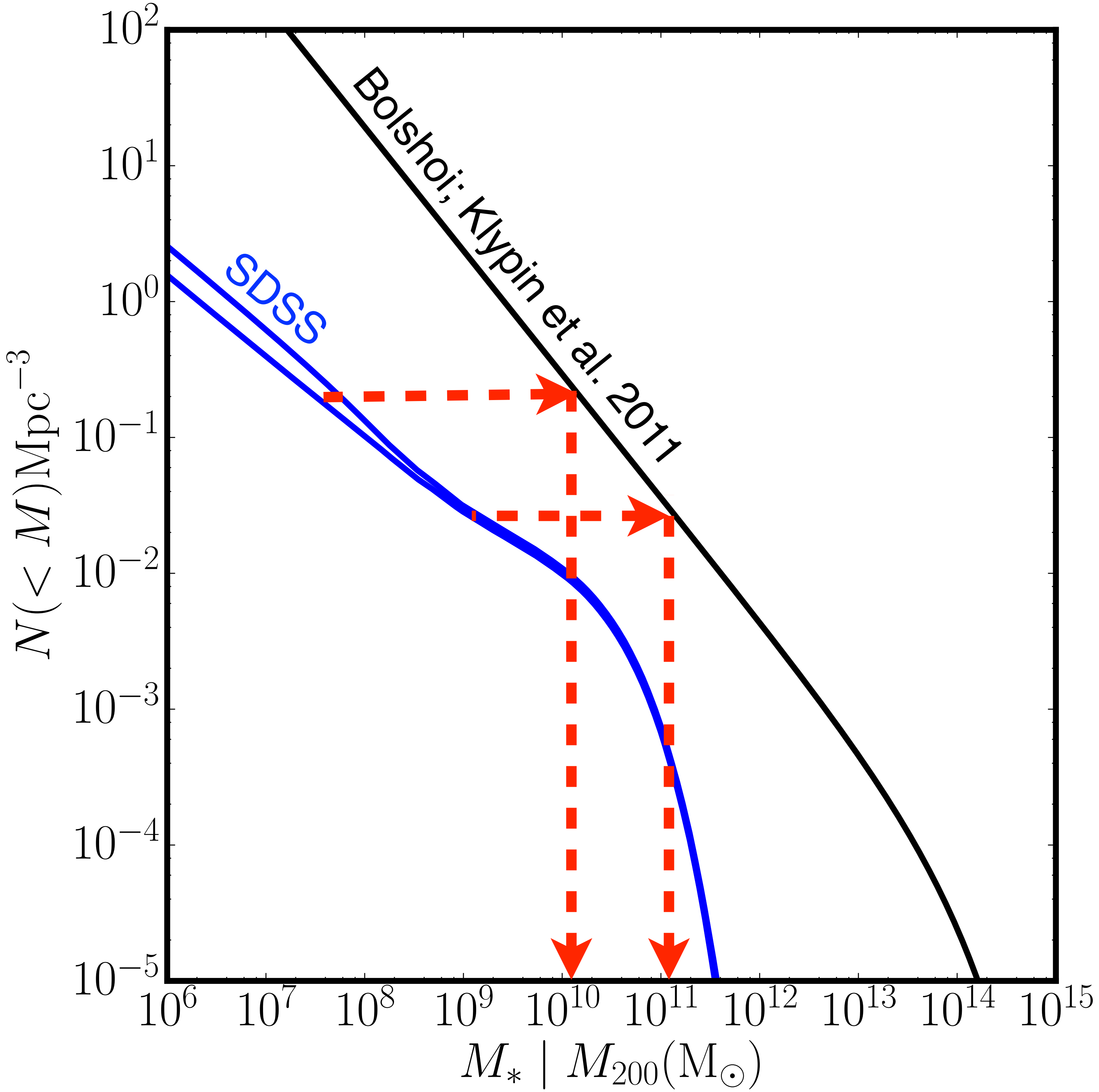
Missing Satellites Revisited

Missing satellites | Isolated gas rich dwarfs



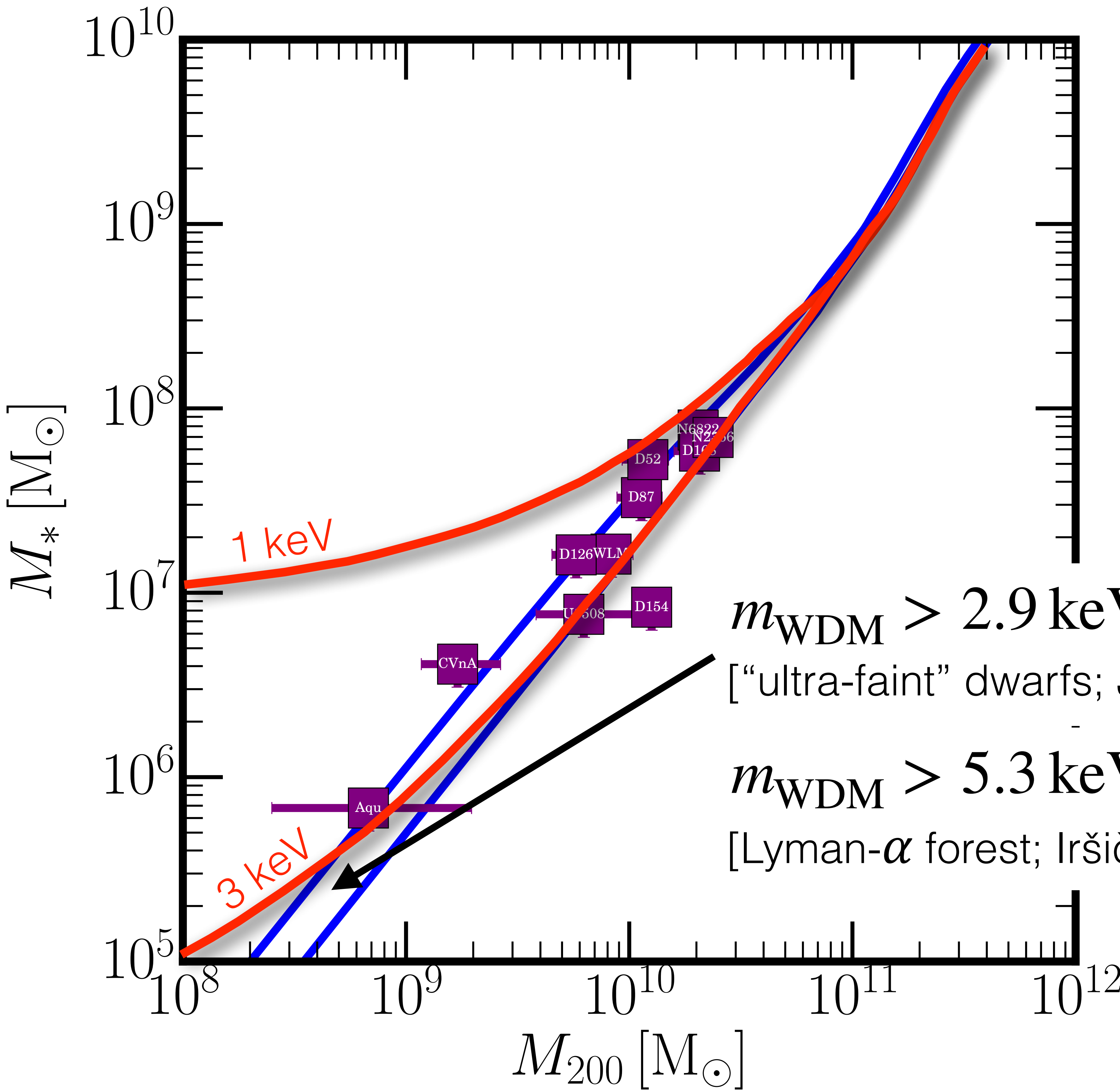
Read et al. 2017; and see Katz et al. 2017

Missing satellites | Isolated gas rich dwarfs



Read et al. 2017

Missing satellites | Isolated gas rich dwarfs



$m_{\mathrm{WDM}} > 2.9\,\mathrm{keV}\,(95\%)$

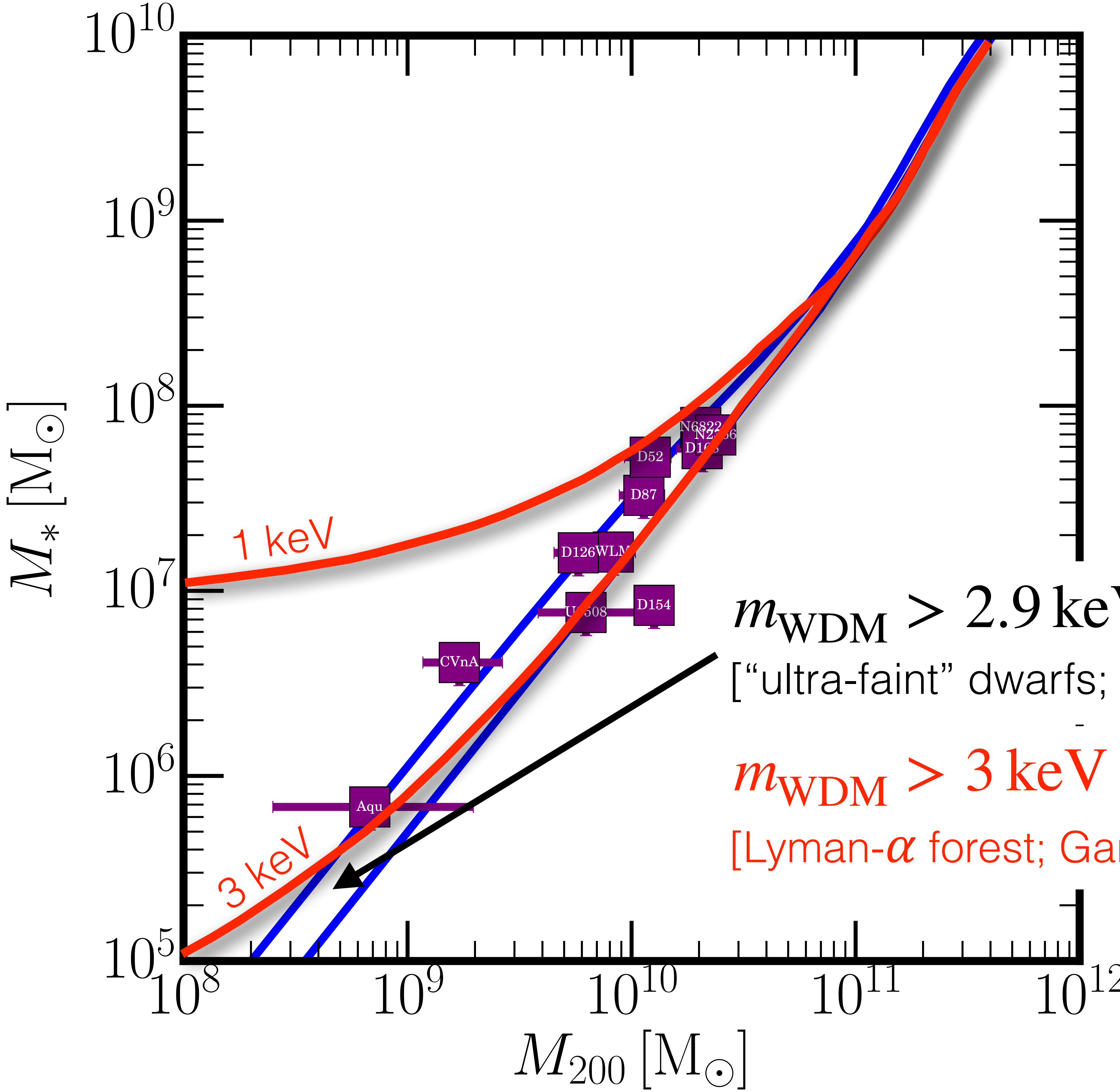
[“ultra-faint” dwarfs; Jethwa et al. 2018]

$m_{\mathrm{WDM}} > 5.3\,\mathrm{keV}\,(95\%)$

[Lyman-α forest; Iršič et al. 2017]

Read et al. 2017

Missing satellites | Isolated gas rich dwarfs



$m_{\rm WDM} > 2.9\,{\rm keV}\,(95\%)$

["ultra-faint" dwarfs; Jethwa et al. 2018]

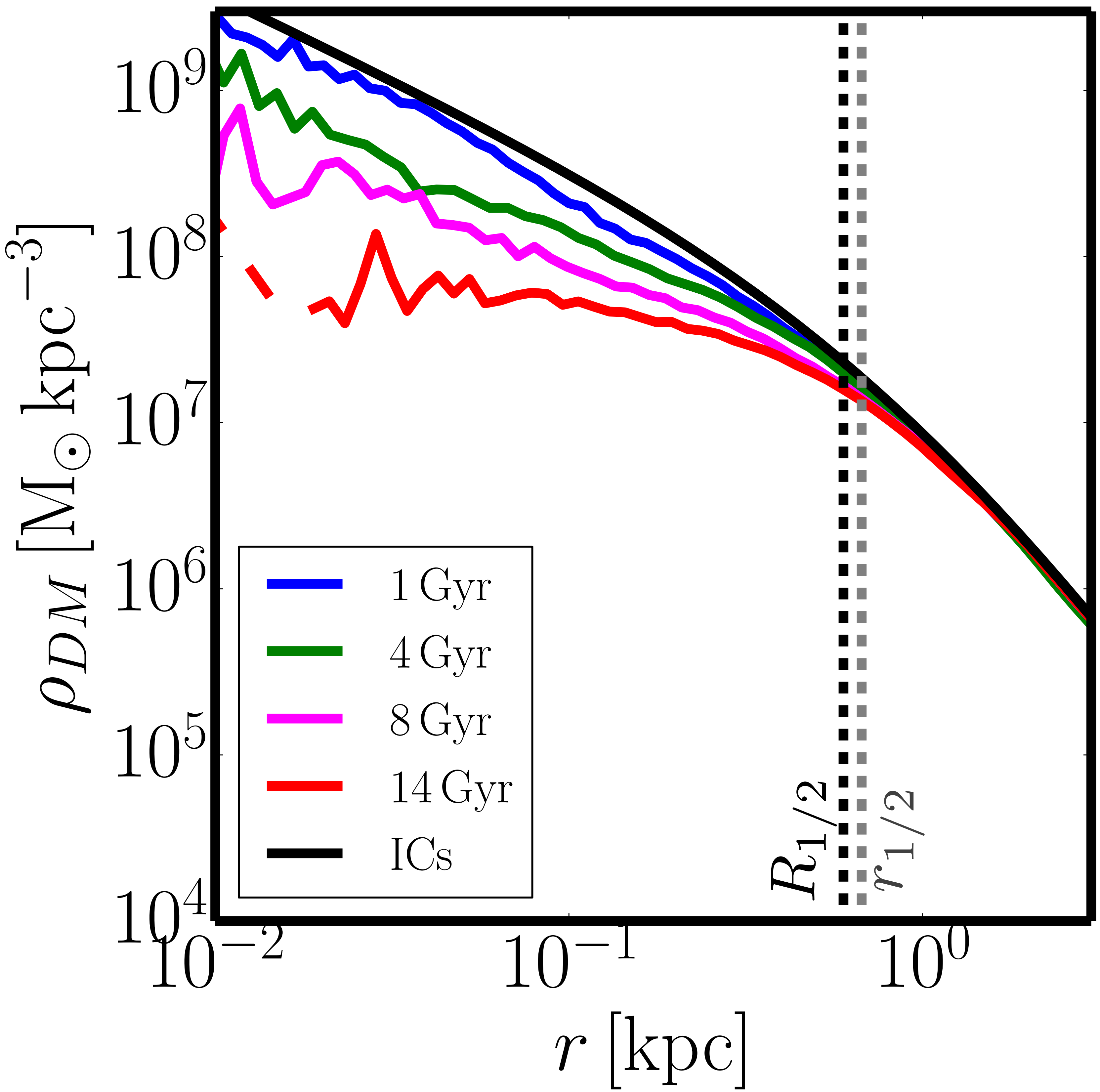
$m_{\rm WDM} > 3\,{\rm keV}$

[Lyman-α forest; Garzilli et al. 2018]

Read et al. 2017

“Smoking gun” evidence for DM heating

Less star formation ⇒ more cusp



Read et al. 2016

Less star formation ⇒ more cusp

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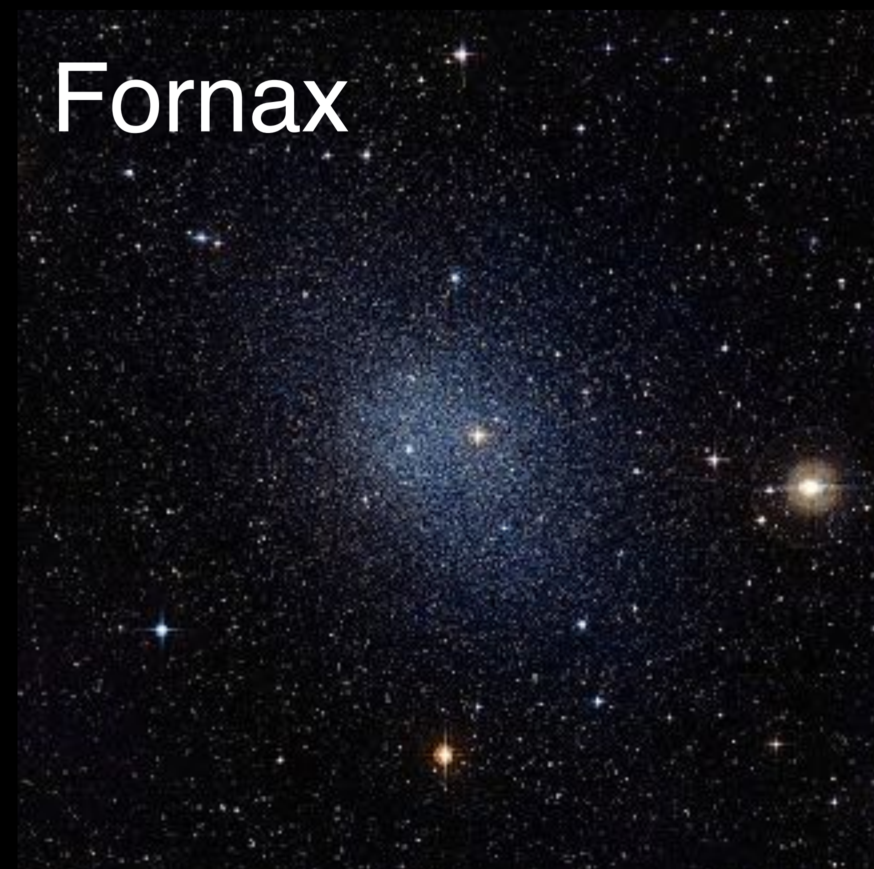
Leroy, Nature 2015

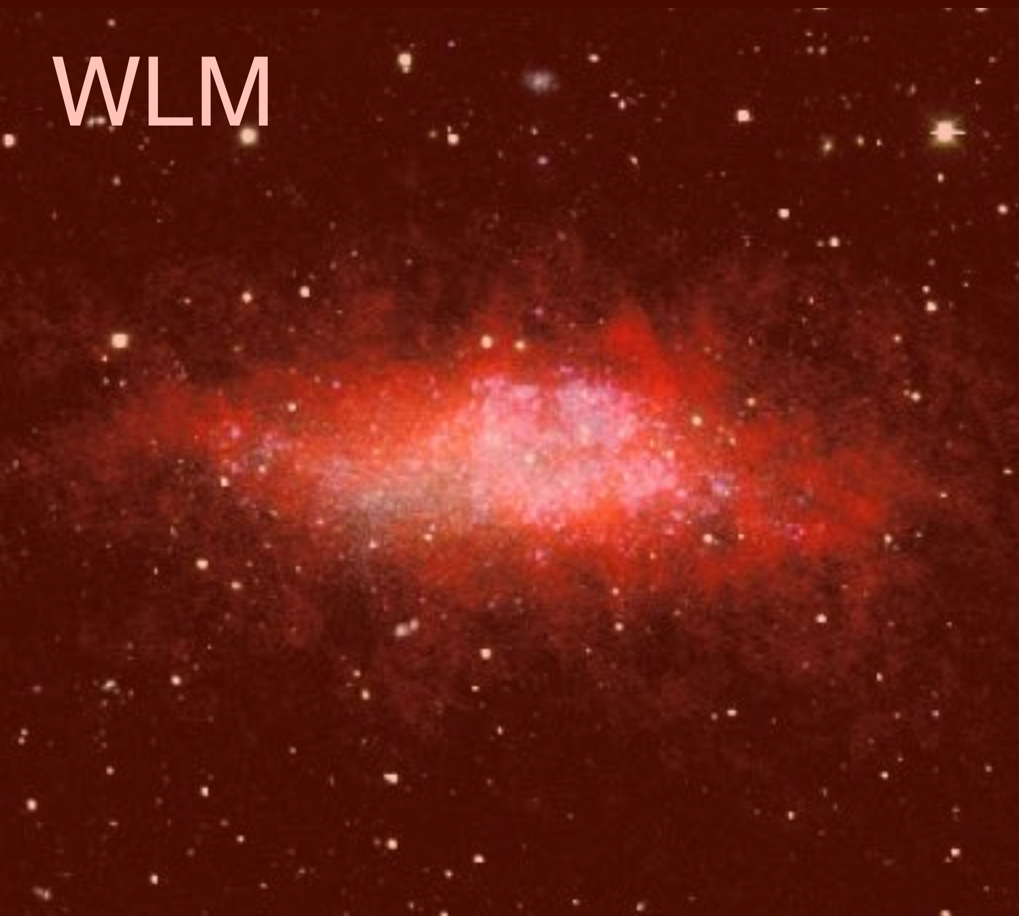


ESO/Digitized Sky Survey 2

Robert Lupton & SDSS

Decreasing star formation
⇒
More DM cusp!

Less star formation ⇒ more cusp



Leroy, Nature 2015

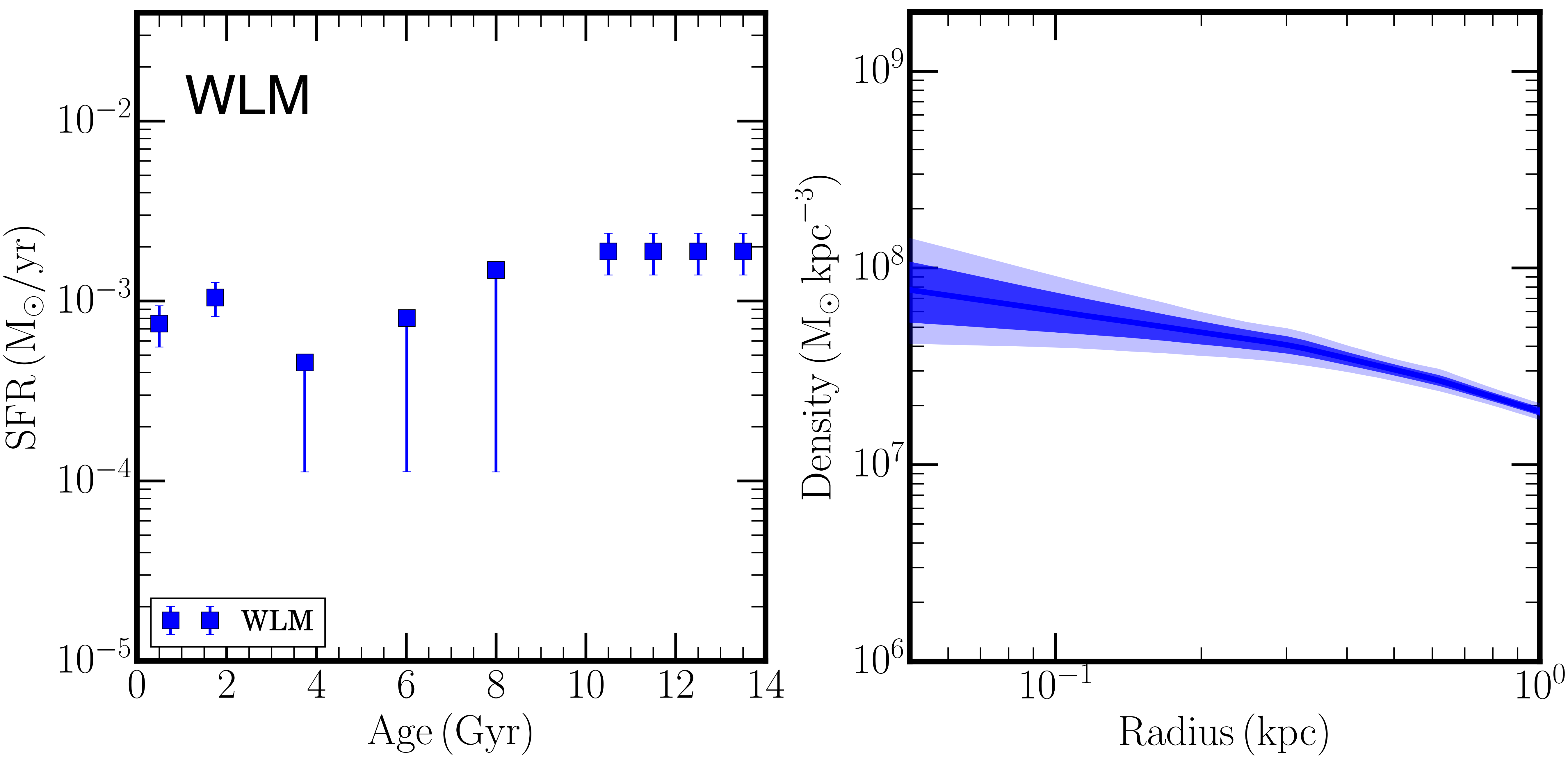
ESO/Digitized Sky Survey 2

Robert Lupton & SDSS

Rotation curves

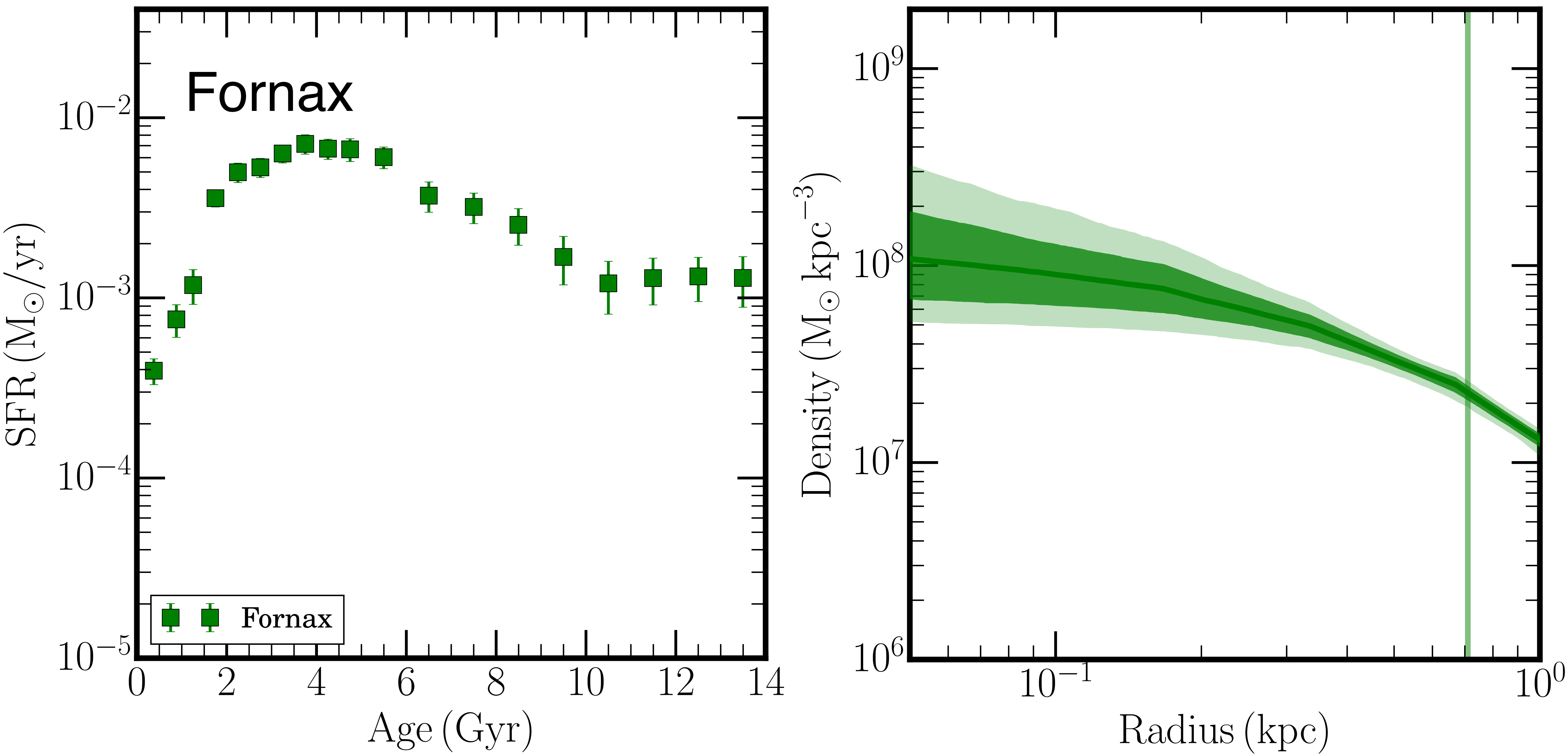
Stellar kinematics

Less star formation ⇒ more cusp



Read et al. 2018a,b,c: arXiv:1805.06934; arXiv:1807.07093; arXiv:1808.06634

Less star formation ⇒ more cusp



Read et al. 2018a,b,c: arXiv:1805.06934; arXiv:1807.07093; arXiv:1808.06634

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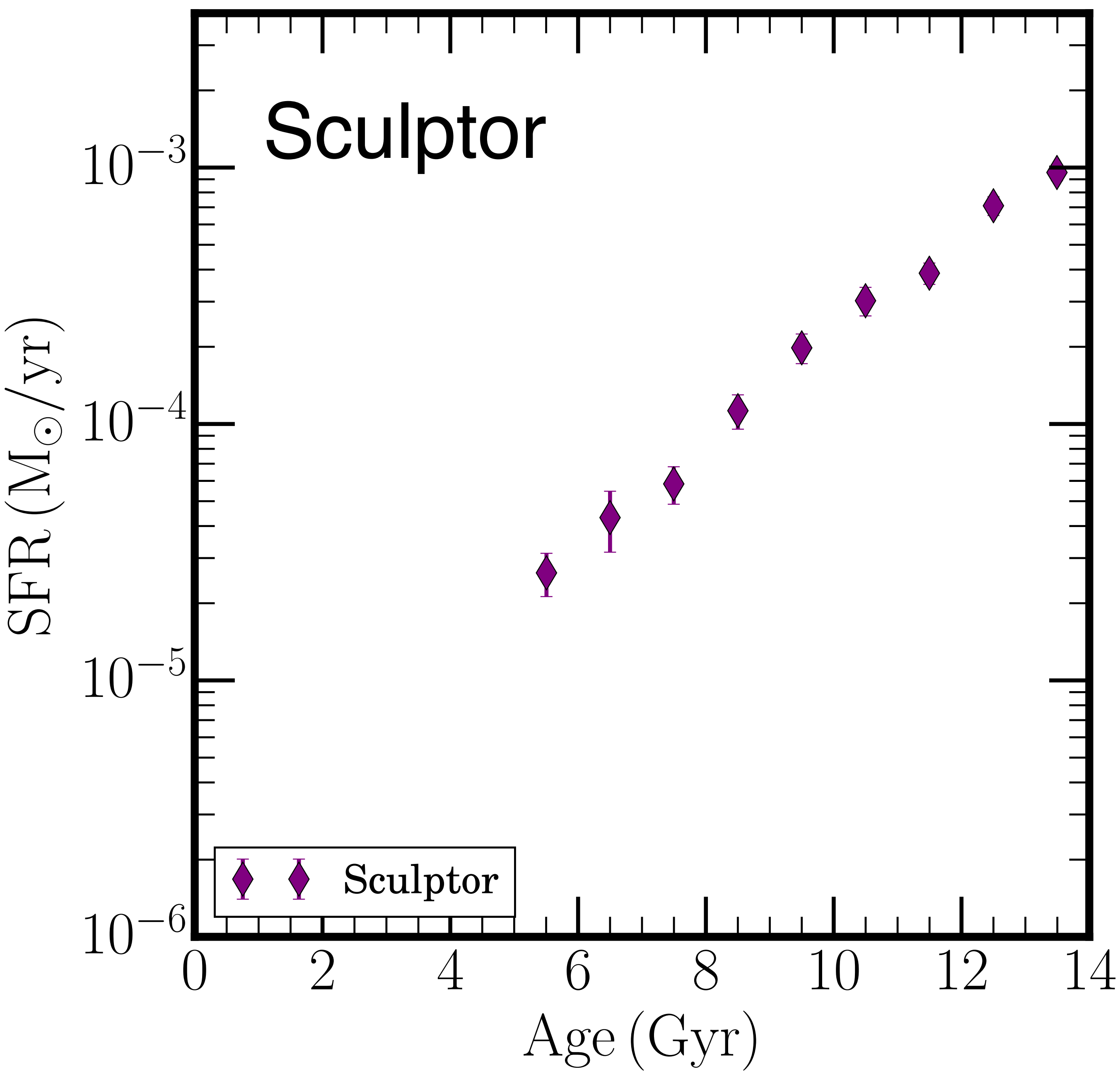

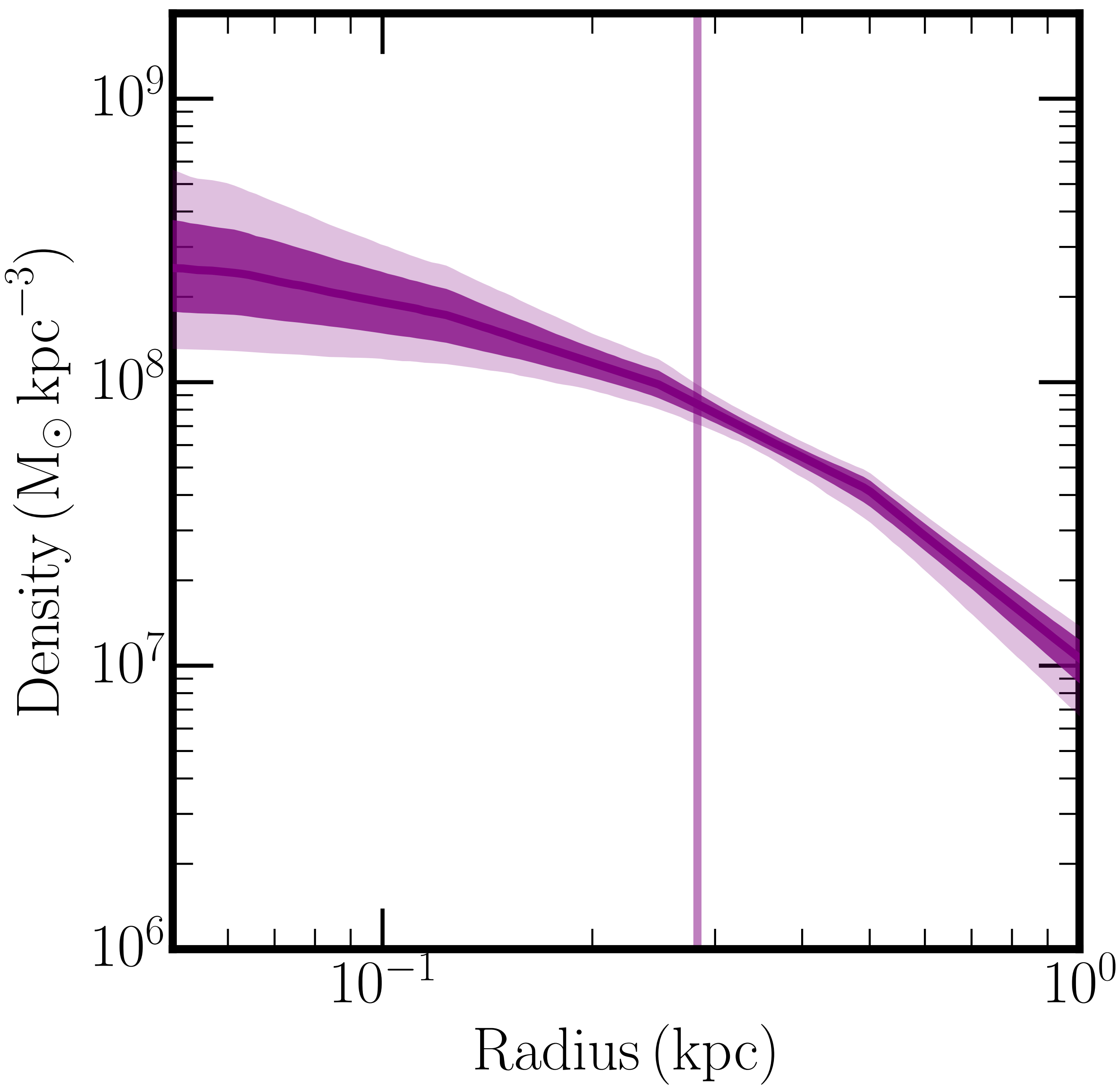

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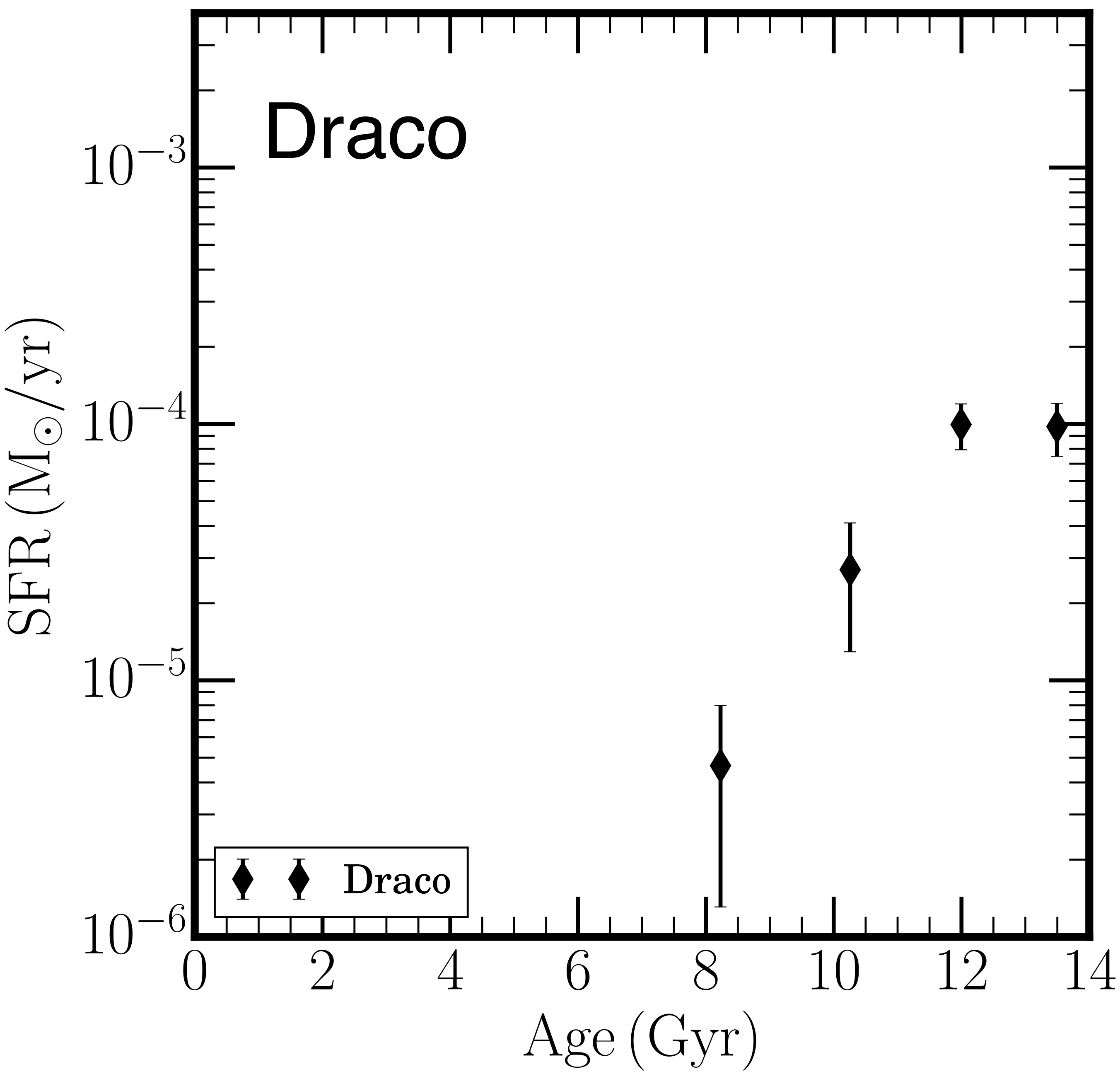

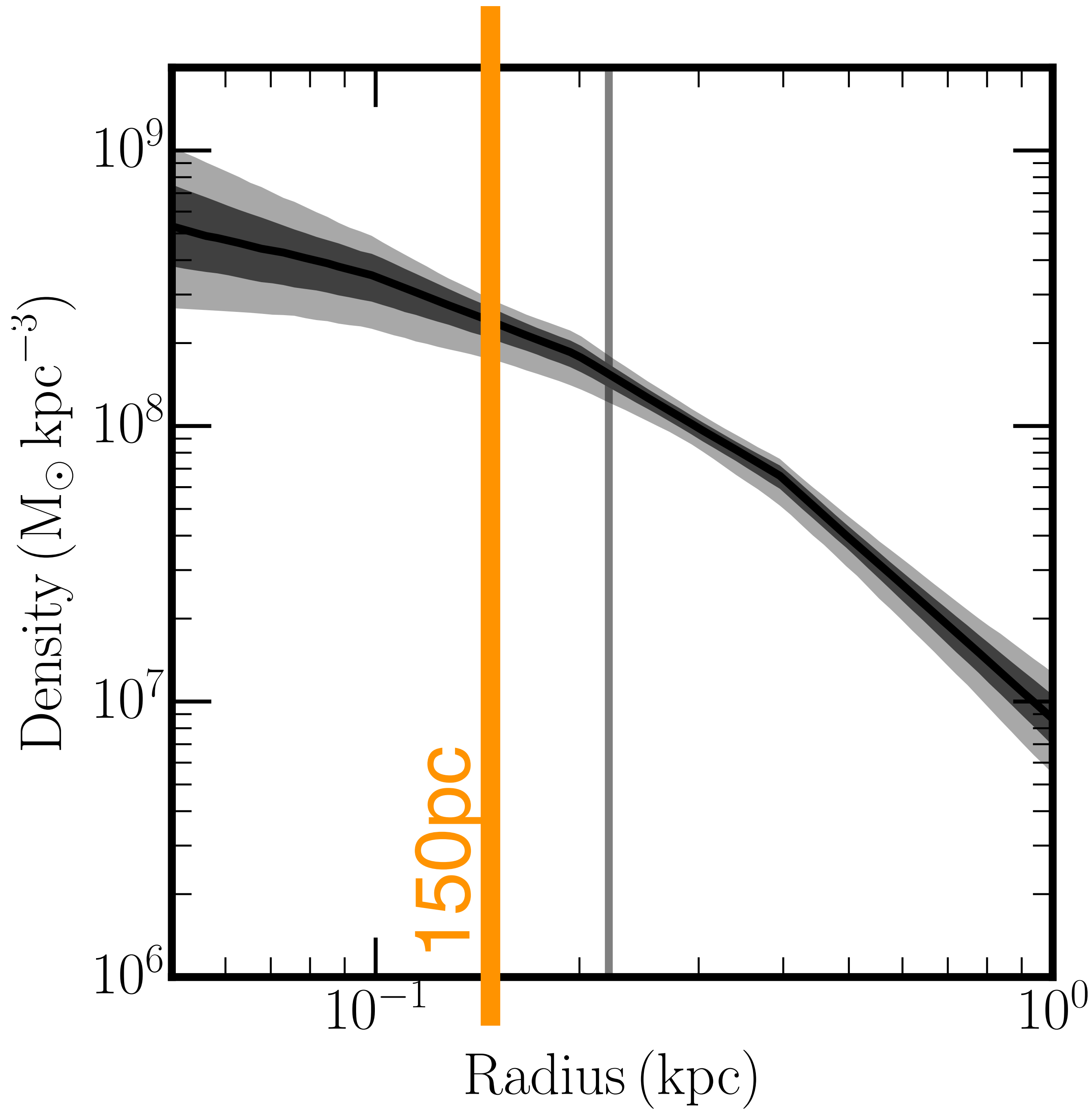

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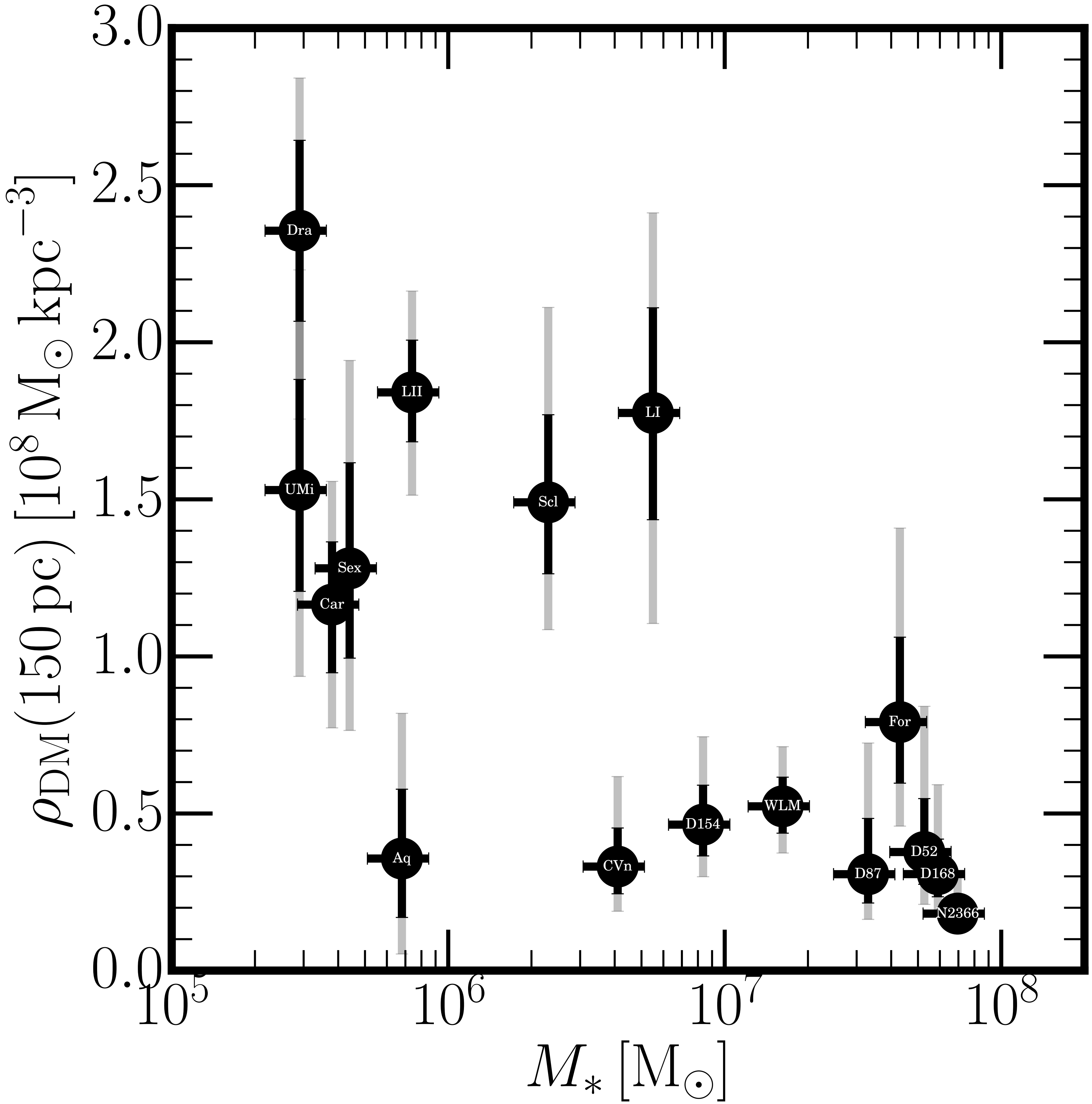

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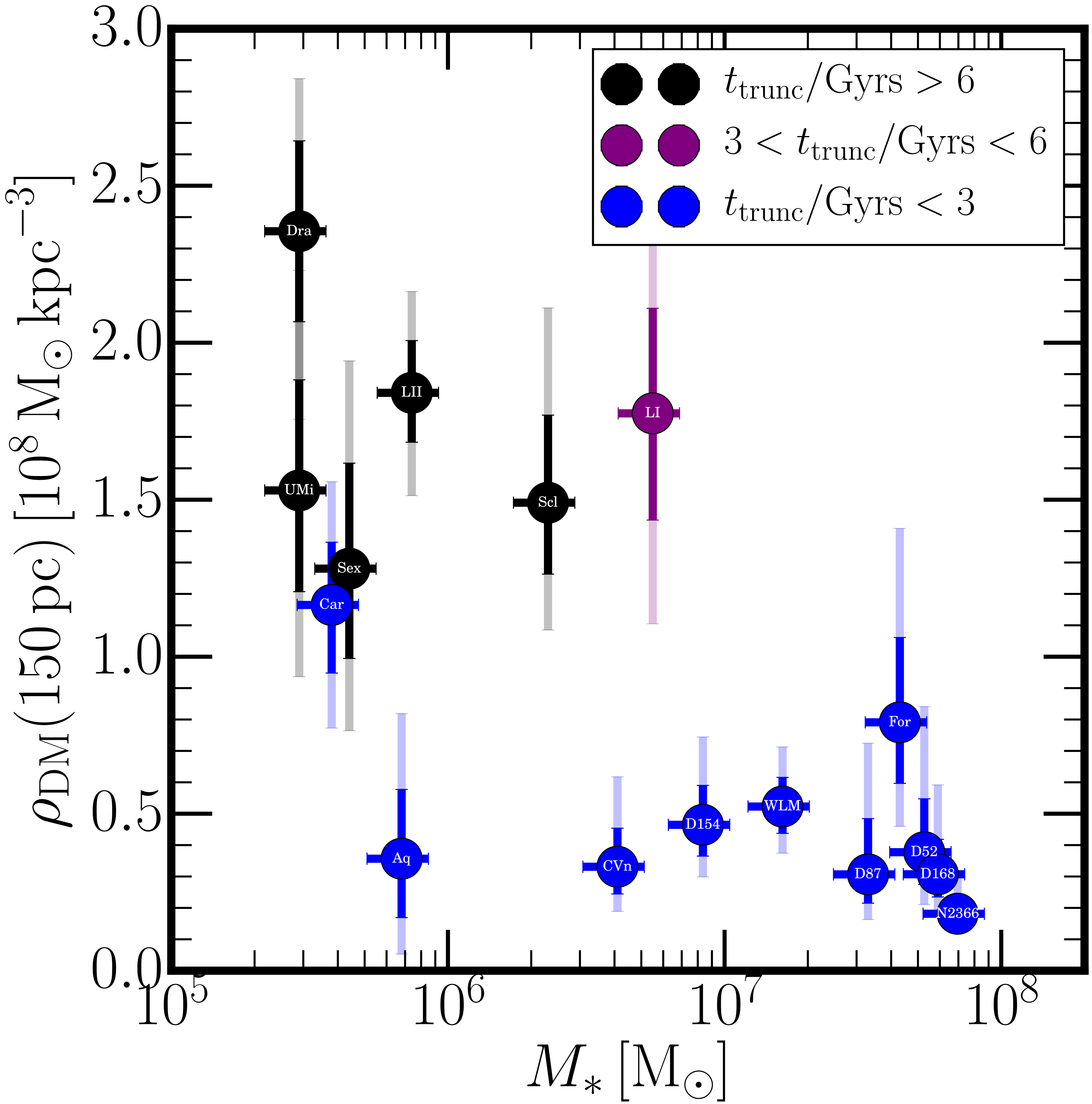
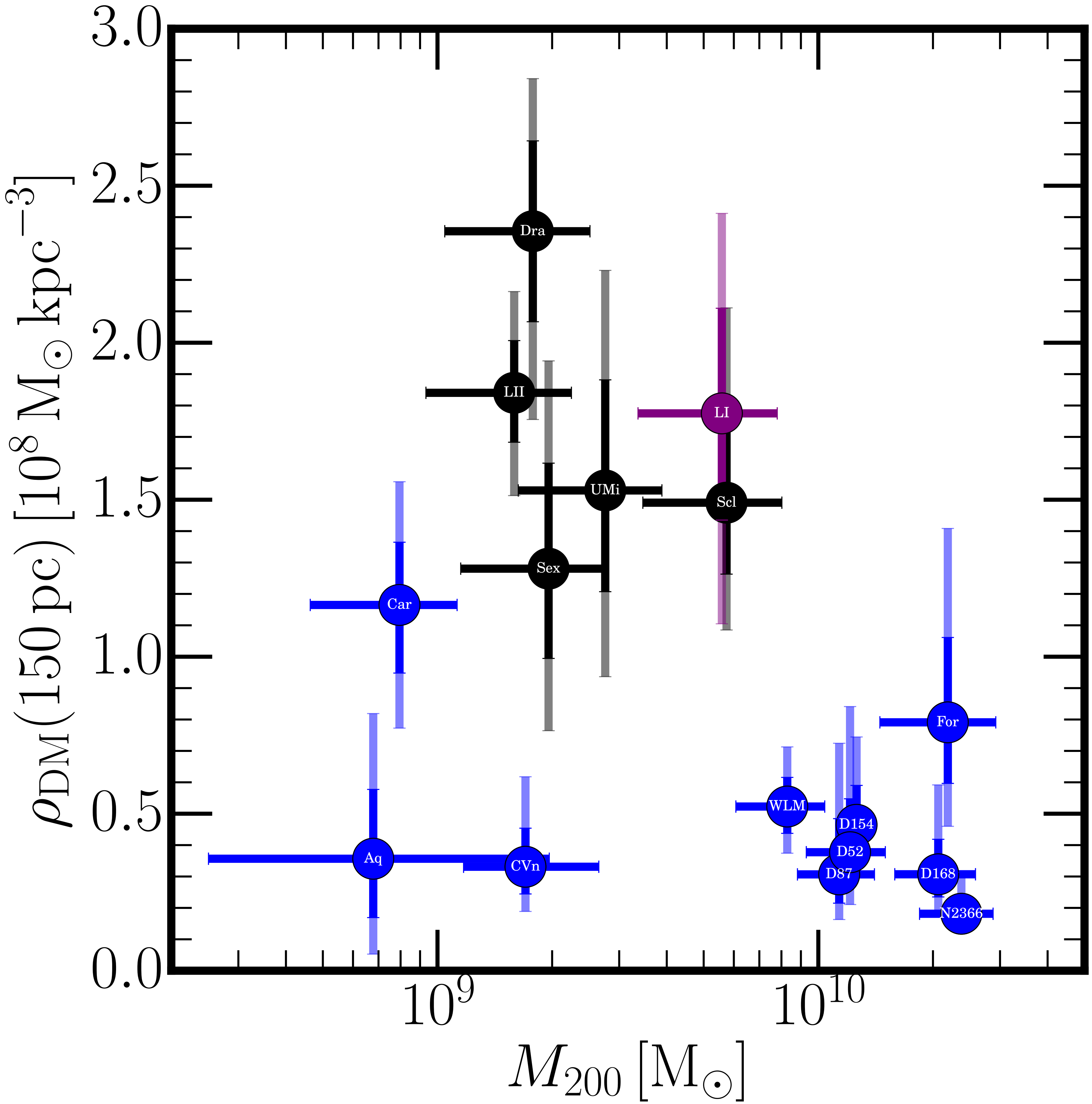


Read et al. 2018a,b,c: arXiv:1805.06934; arXiv:1807.07093; arXiv:1808.06634



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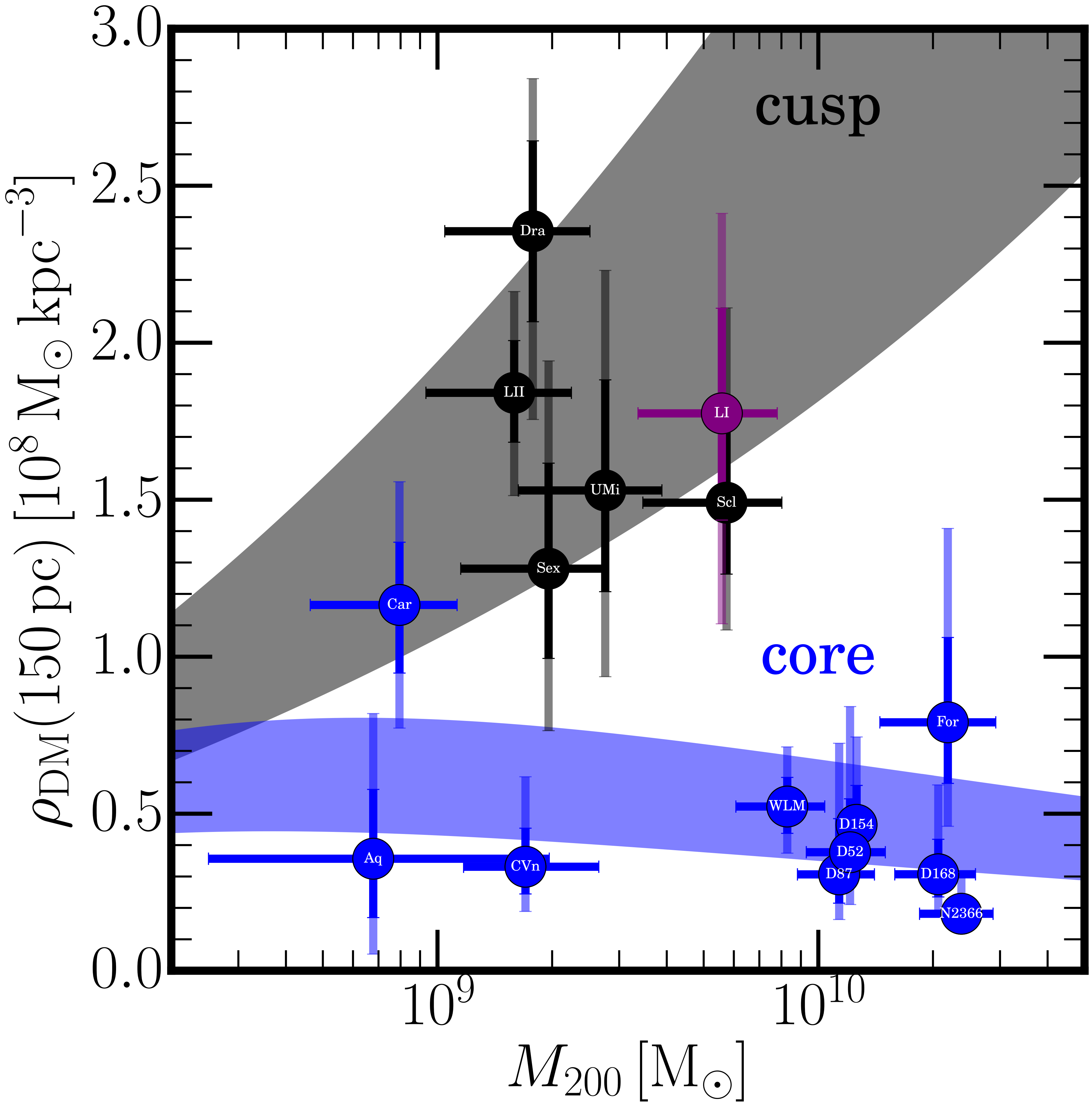
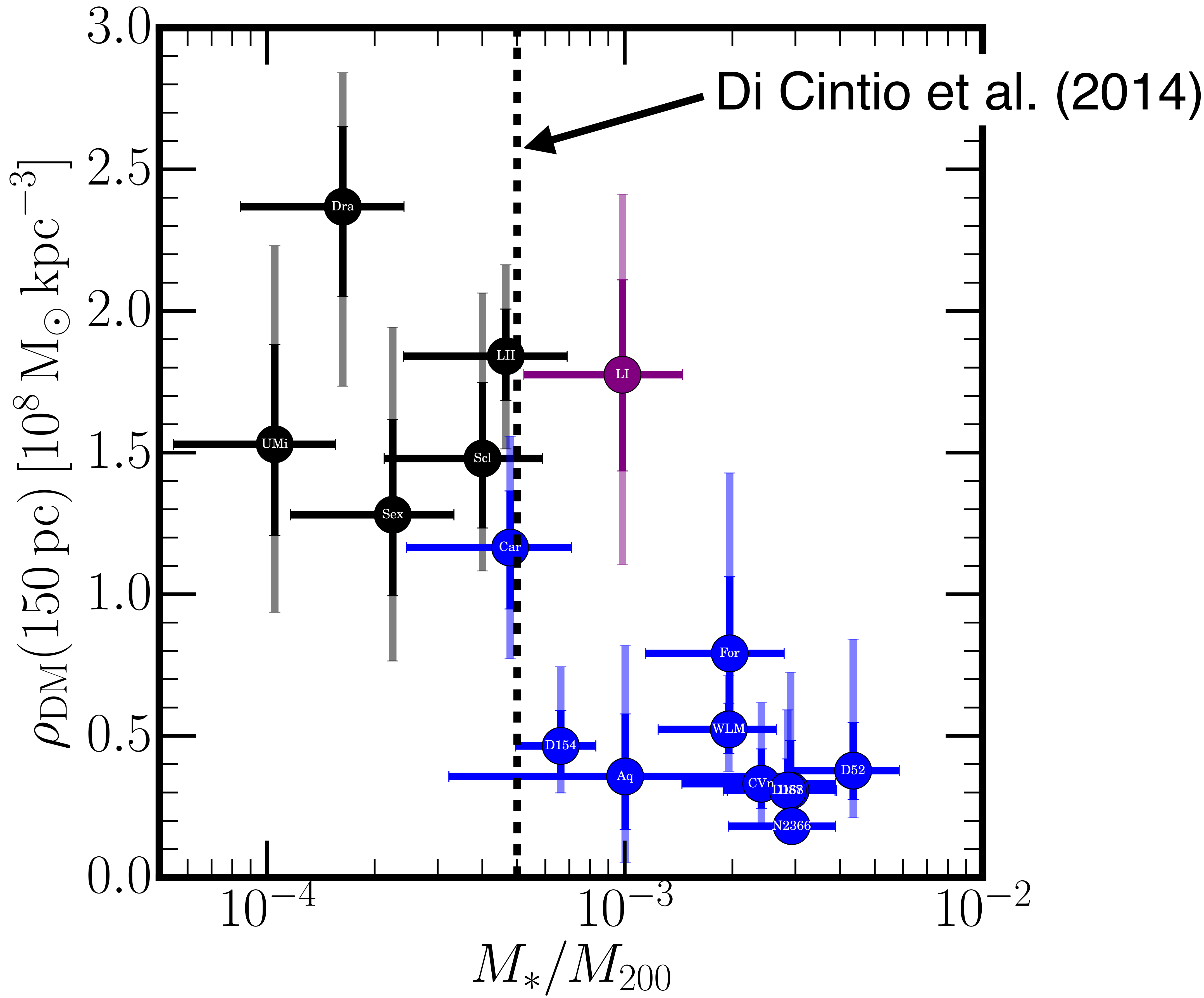


Read et al. 2018a,b,c: arXiv:1805.06934; arXiv:1807.07093; arXiv:1808.06634



Read et al. 2018a,b,c: arXiv:1805.06934; arXiv:1807.07093; arXiv:1808.06634

Conclusions

Conclusions

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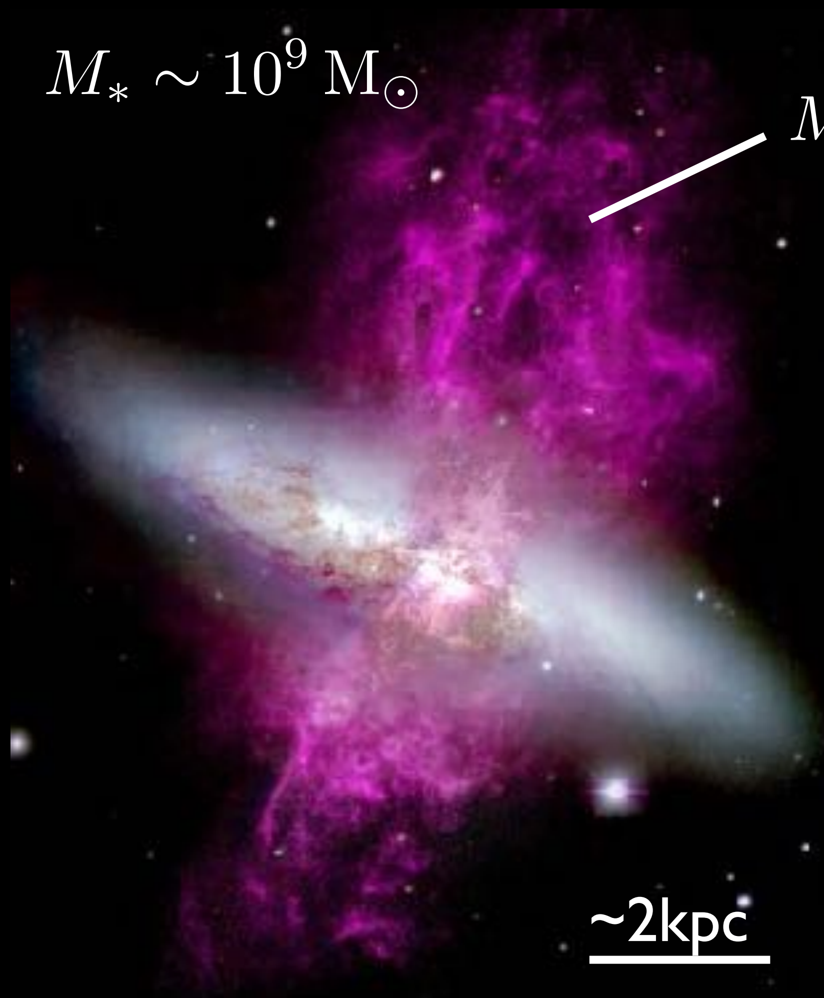
- Accounting for the observed stellar mass-halo mass relation, there is **no missing satellites problem**
- Accounting for **dark matter heating**, there is no cusp-core problem.
- We have found “smoking gun” evidence for dark matter heating: dwarf galaxies with more star formation have lower central dark matter densities.
- Dark matter appears to be a cold, collisionless fluid that can be heated up and moved around.

Justin I. Read

EXTRA SLIDES

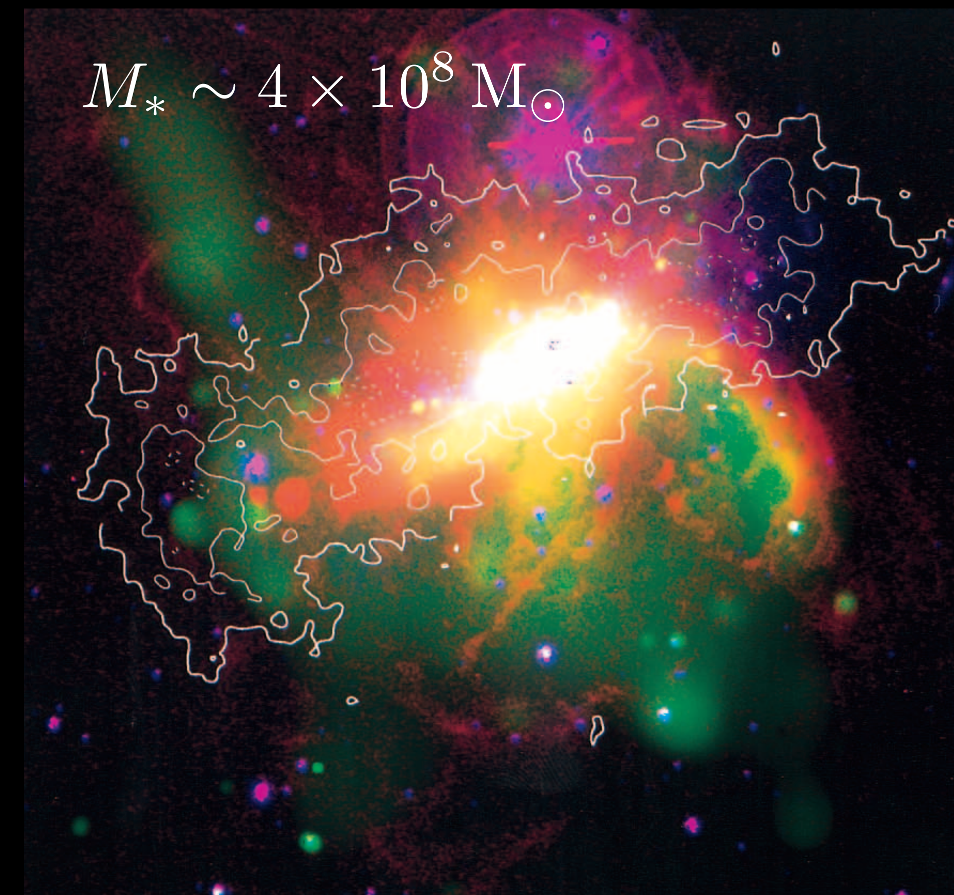
Stellar feedback

Stellar feedback & galactic winds



M82 | Westmoquette et al. 2009

NGC1482 | Veilleux et al. 2002



NGC1569 | Martin et al. 2002

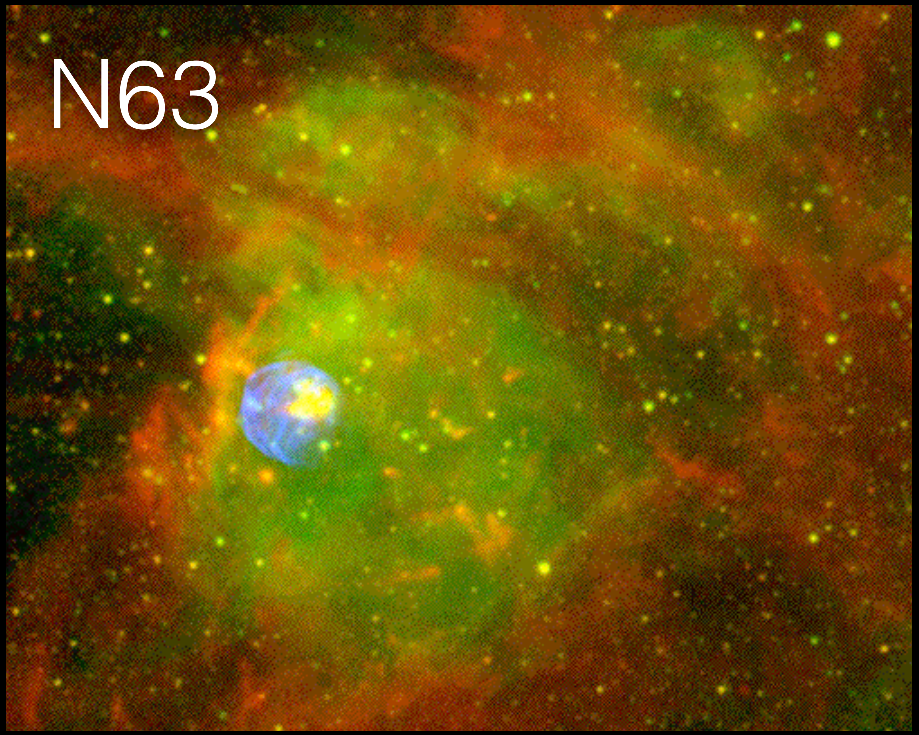
and see Strickland & Heckman 2009; McQuinn et al. 2018

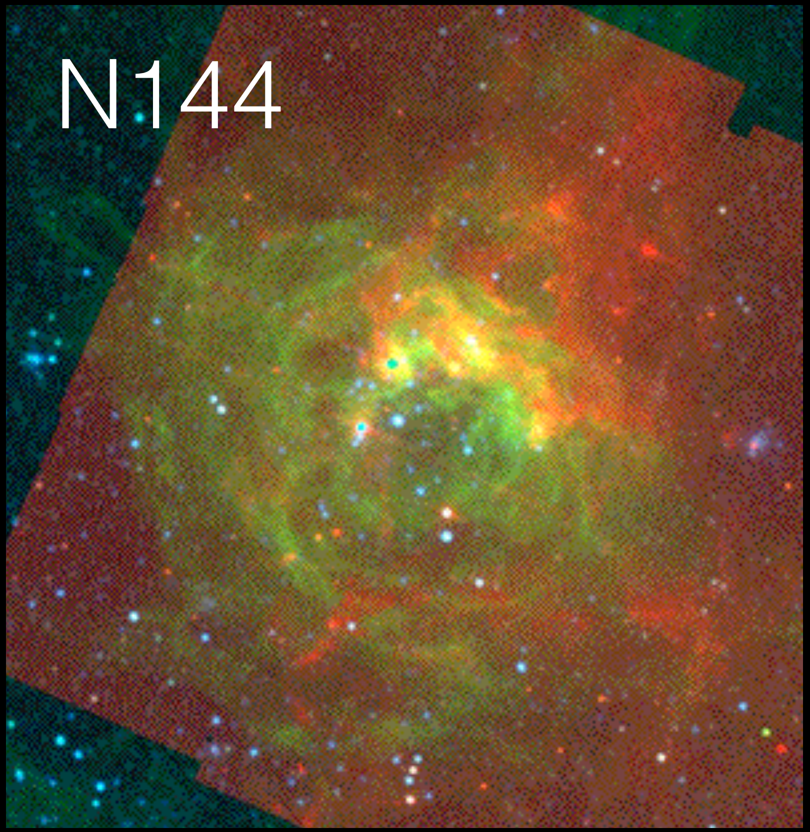
Stellar feedback & galactic winds

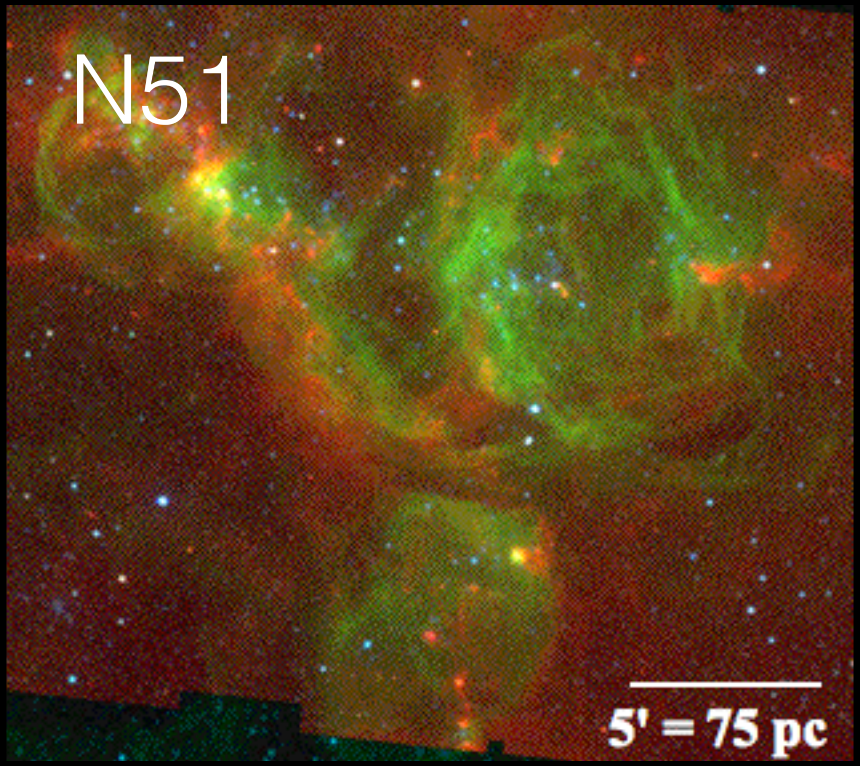
X-ray

H-alpha

8-μm







Chu et al. 2005

Simulation requirements

Stellar feedback & galactic winds

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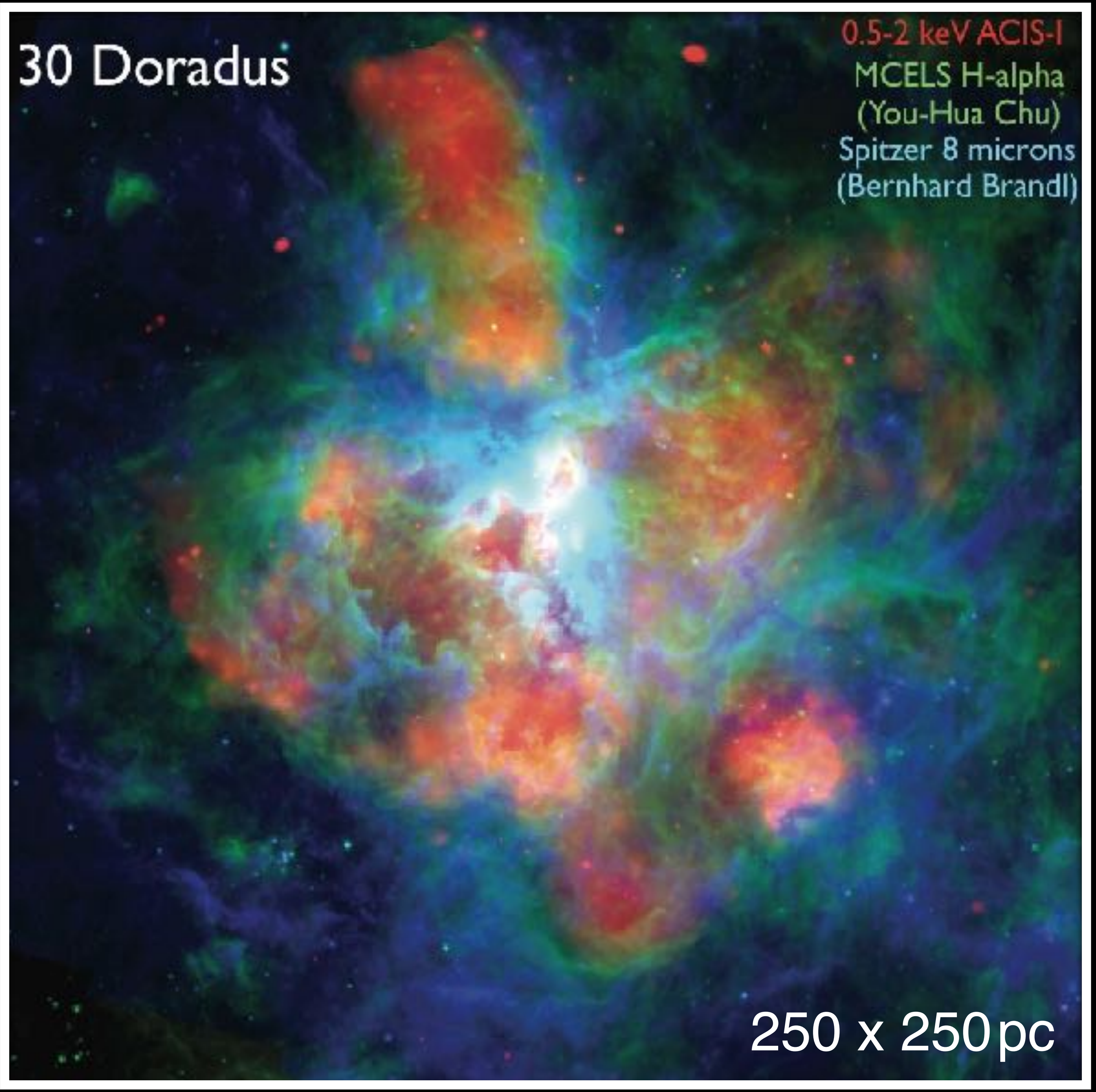

Image composite credit: Leisa Townsley et al. 2006

Stellar feedback & galactic winds

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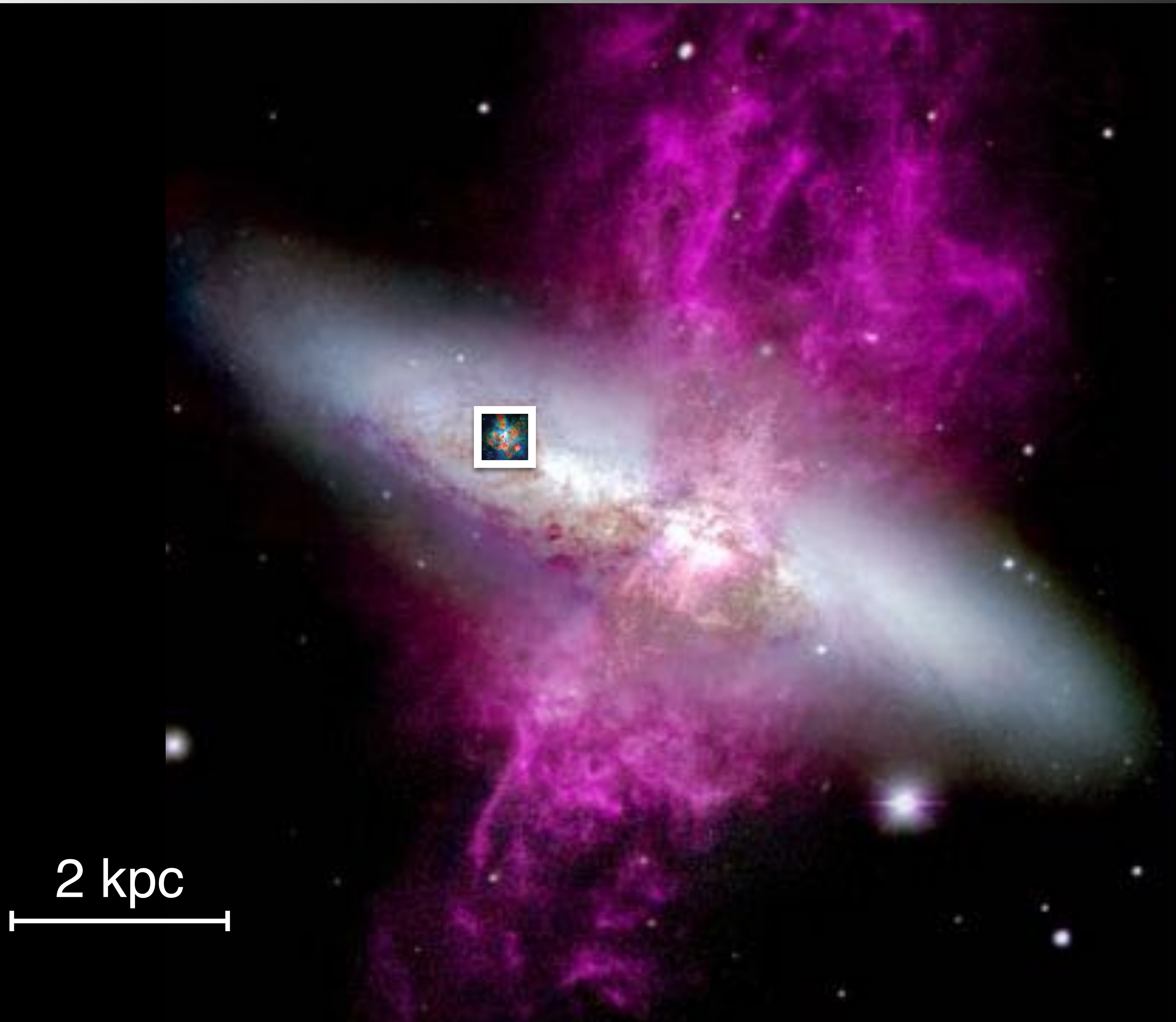

Westmoquette et al. 2009; and see Strickland & Heckman 2009; McQuinn et al. 2018

Stellar feedback | Simulation requirements

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$\Delta x < 50\,\mathrm{pc}$

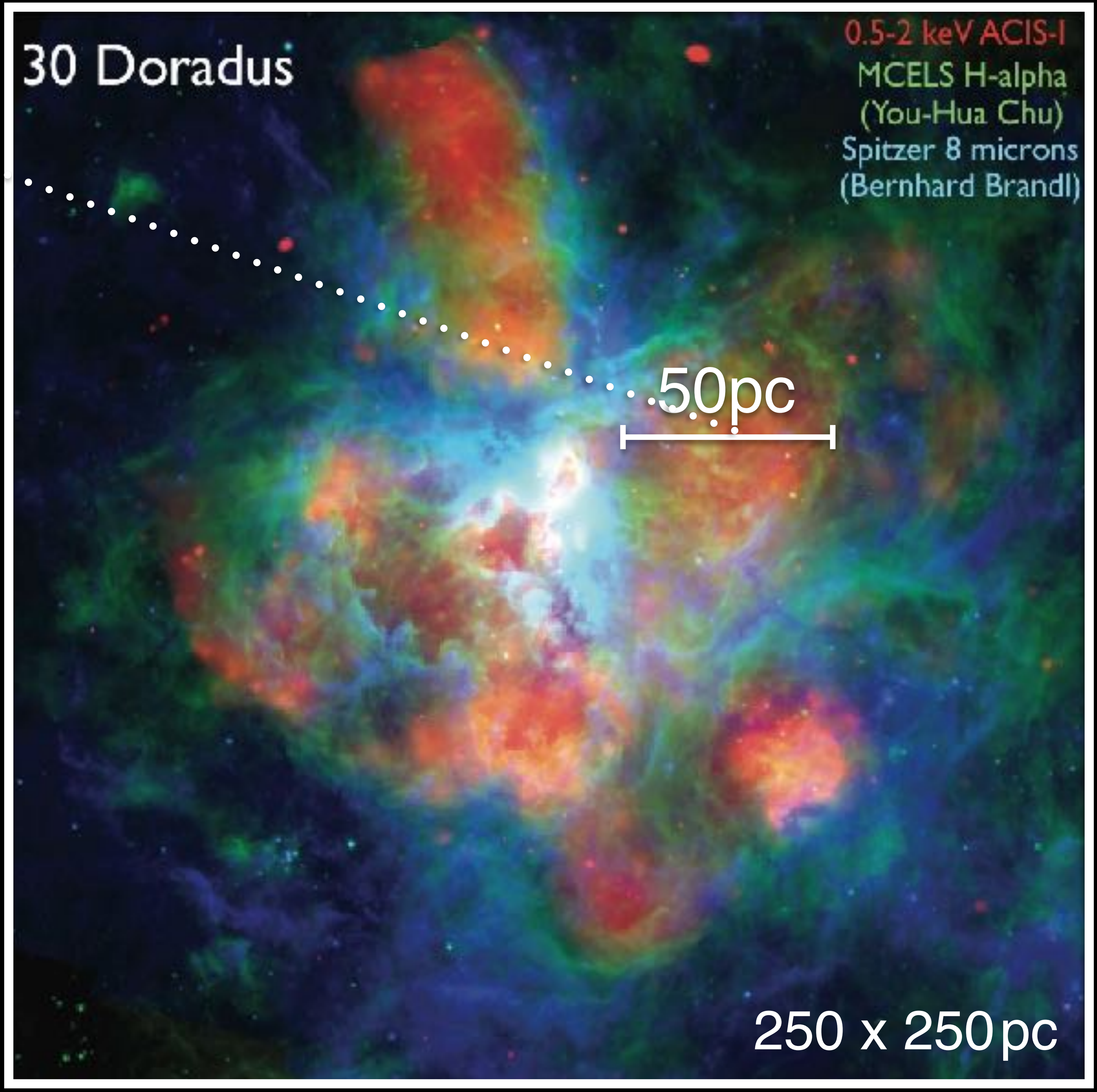
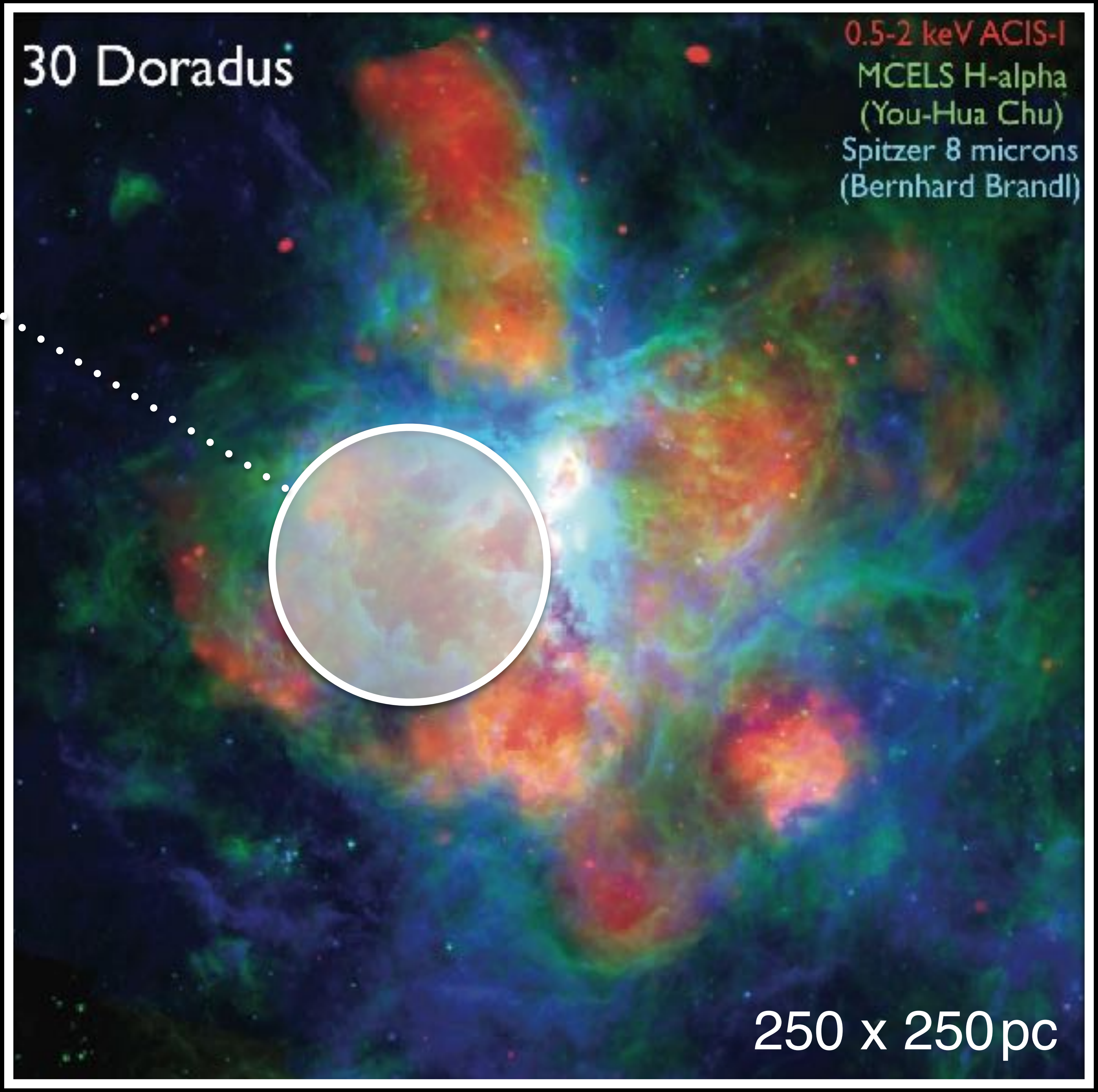


Image composite credit: Leisa Townsley et al. 2006

Stellar feedback I Simulation requirements

$\Delta x < 50\,\mathrm{pc}$

$M_{\mathrm{res}} < 1000\,\mathrm{M}_{\odot}$



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Stellar feedback | Simulation requirements

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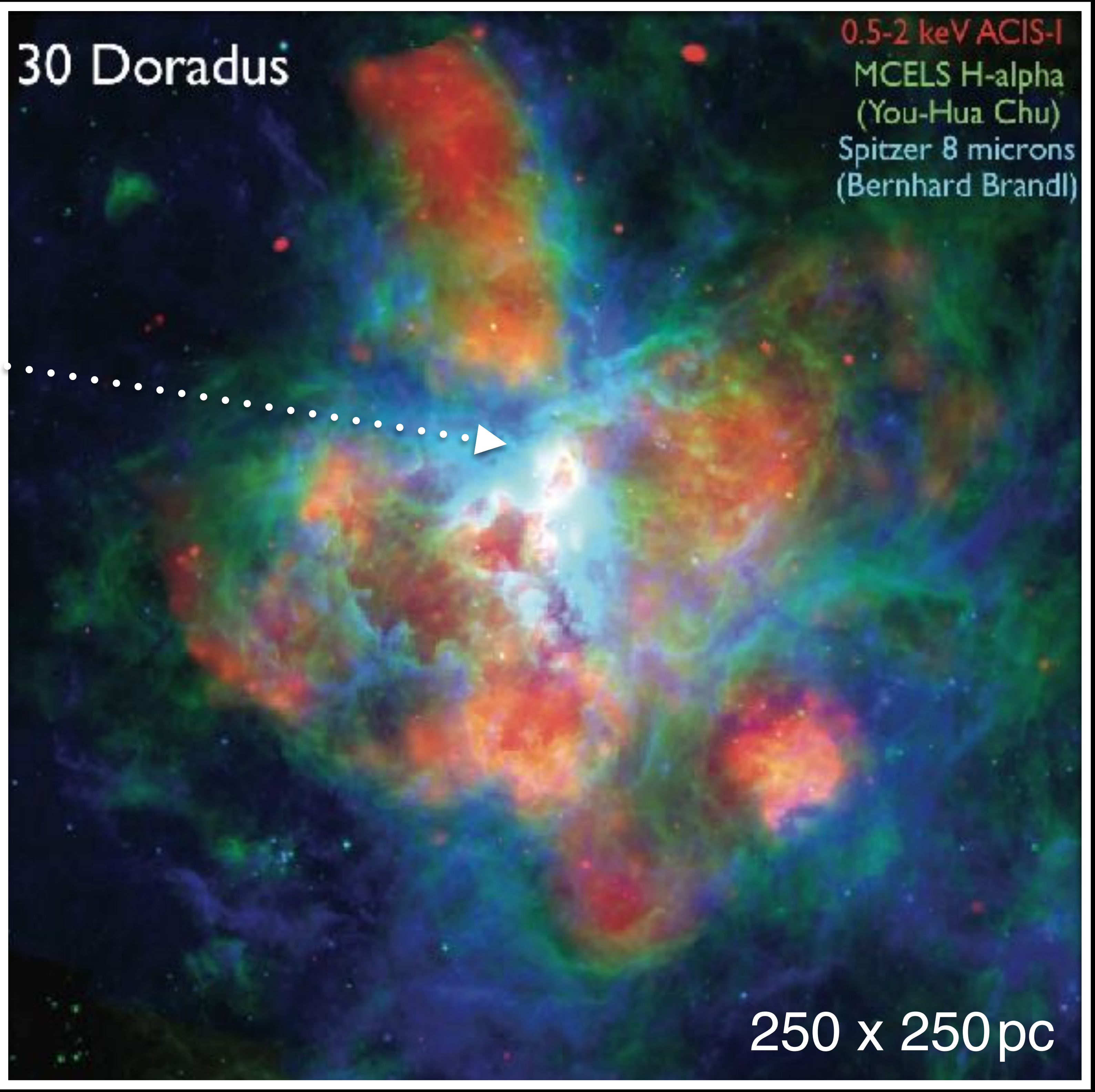
$\rho_{\mathrm{th}} > 100\,\mathrm{atoms/cc}$

$T_{\mathrm{gas,min}} < 100\,\mathrm{K}$



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Stellar feedback | Simulation requirements

$\Delta x < 50\,\mathrm{pc}$

$M_{\mathrm{res}} < 1000\,\mathrm{M}_{\odot}$

$\rho_{\mathrm{th}} > 100\,\mathrm{atoms/cc}$

$T_{\mathrm{gas,min}} < 100\,\mathrm{K}$

Simulations that do not meet these requirements will not resolve gas flows ➤ ***no cusp-core transformations***

Pontzen & Governato 2012; Read et al. 2016; Bose et al. 2018; Benitez-Llambay et al. 2018

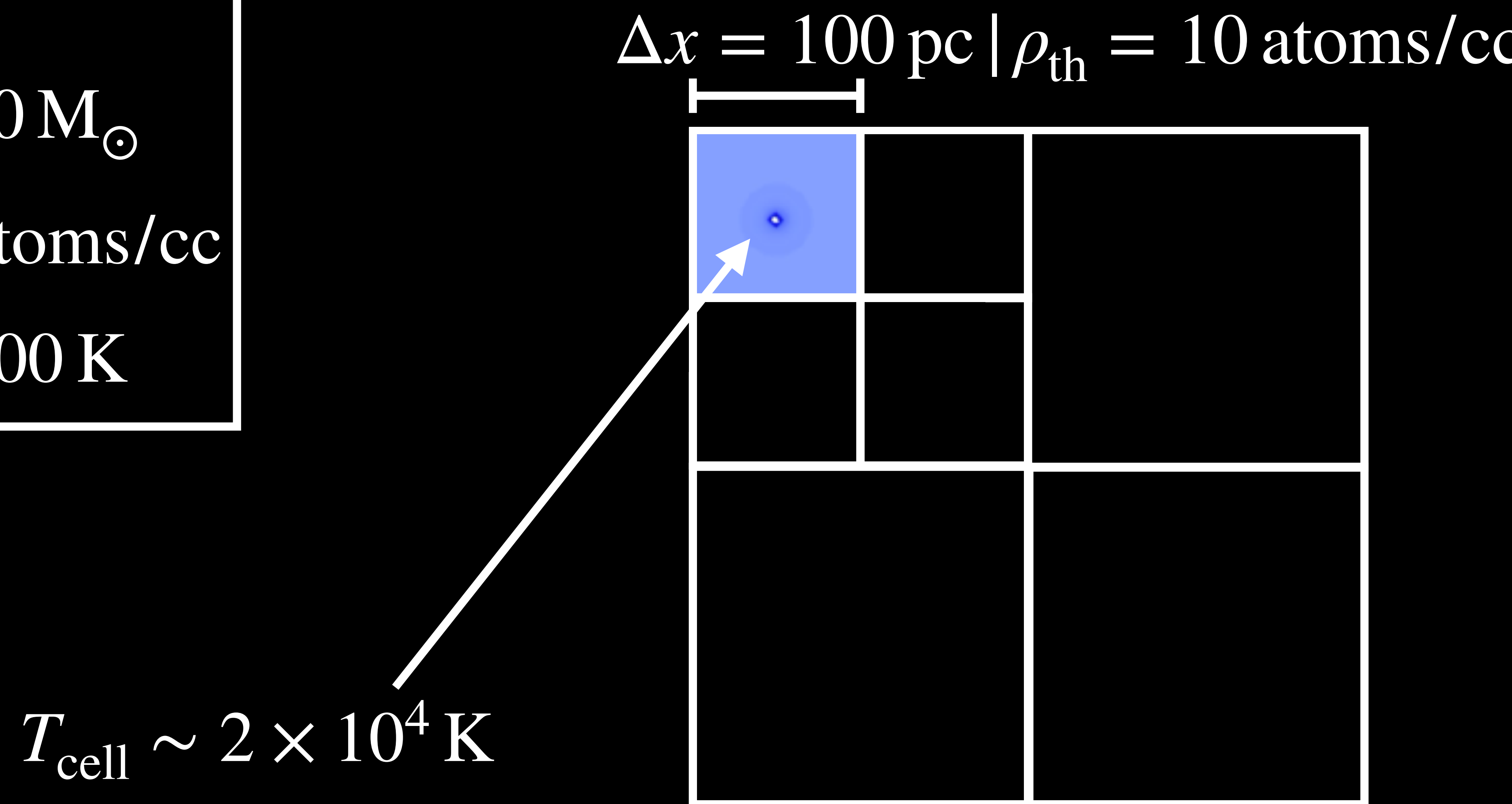
Stellar feedback | Overcooling

$\Delta x < 50\,\mathrm{pc}$

$M_{\mathrm{res}} < 1000\,\mathrm{M}_{\odot}$

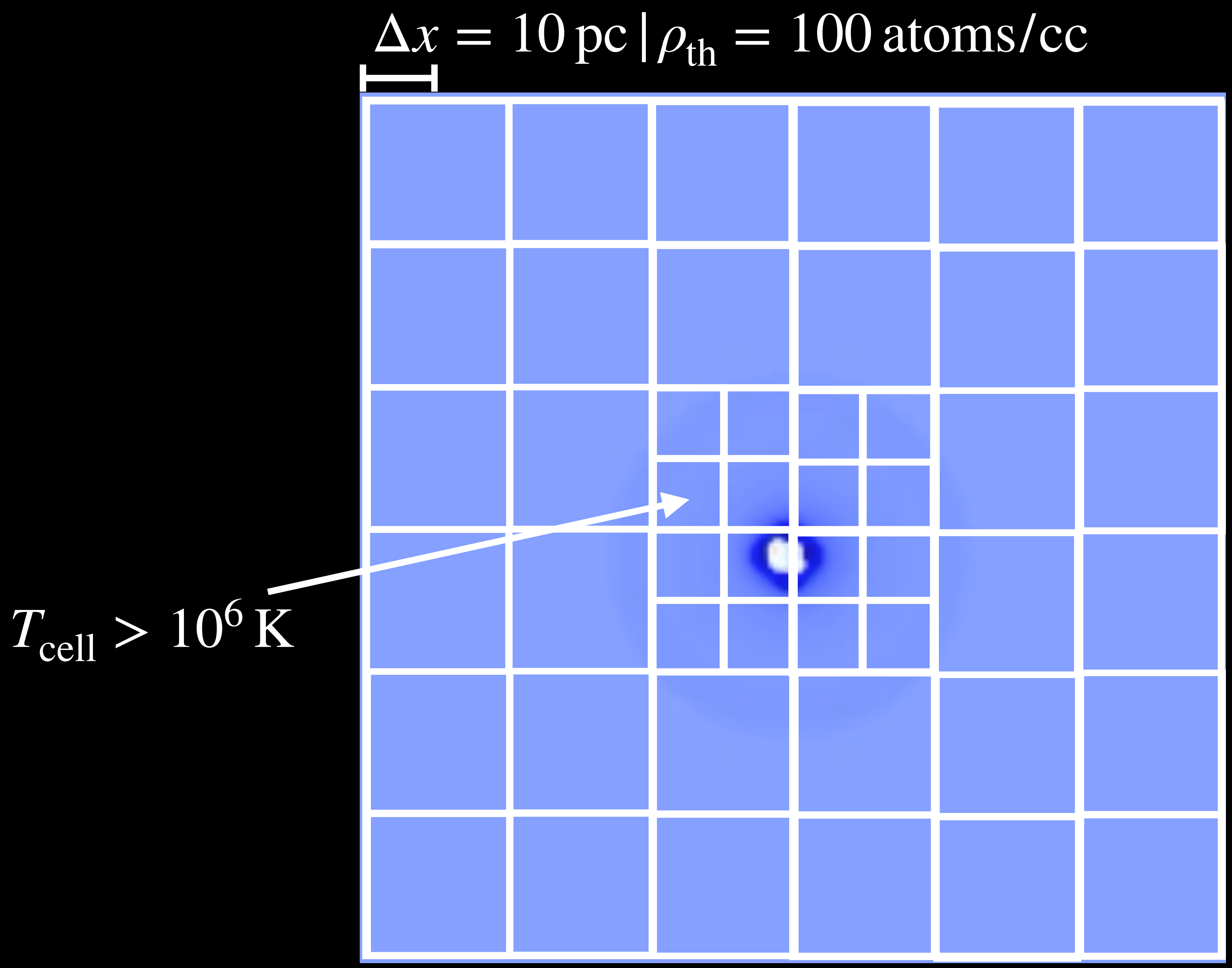
$\rho_{\mathrm{th}} > 100\,\mathrm{atoms/cc}$

$T_{\mathrm{gas,min}} < 100\,\mathrm{K}$



e.g. Agertz et al. 2013; Dalla Vecchia & Schaye 2008

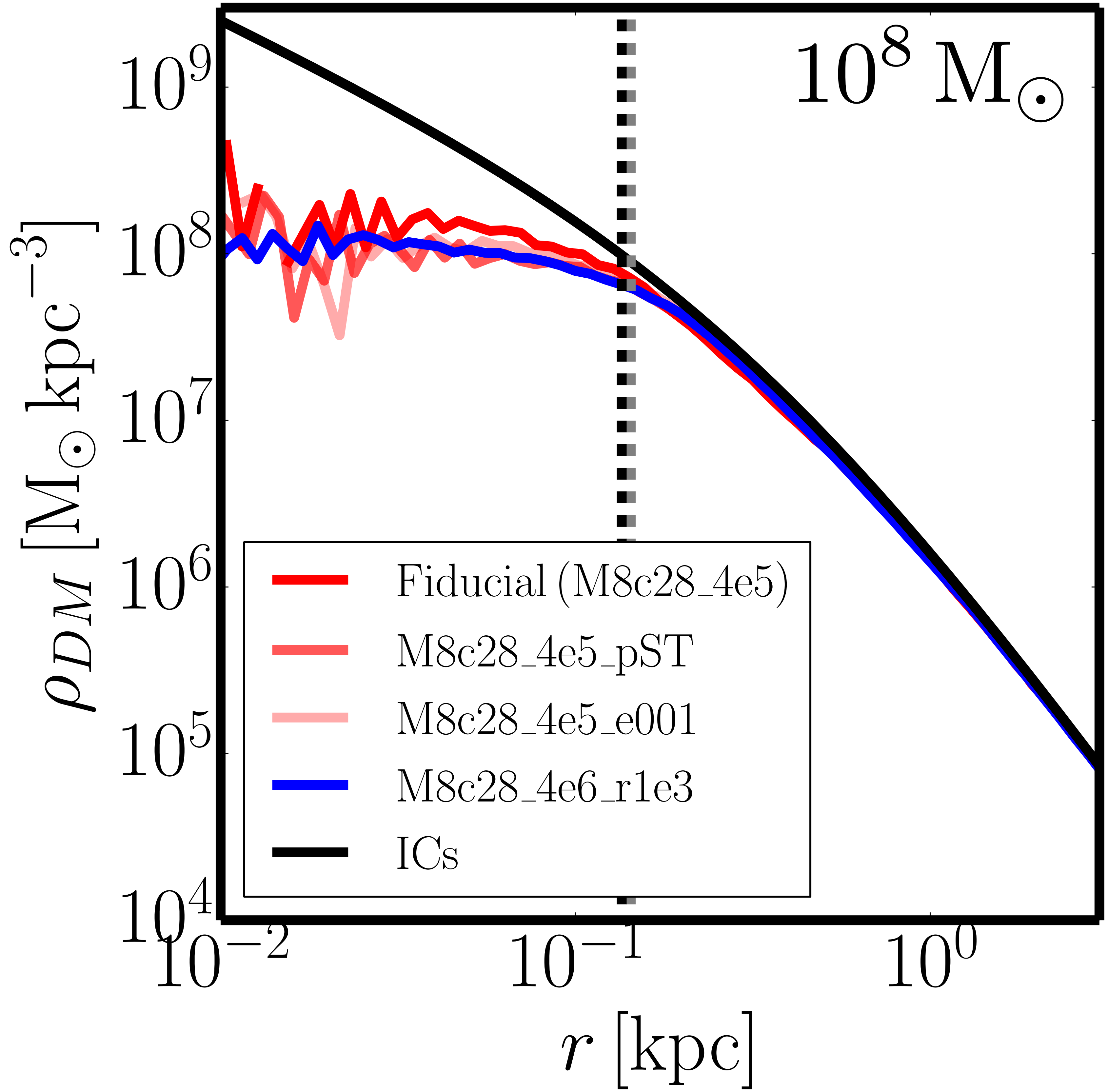
Stellar feedback | Overcooling



e.g. Agertz et al. 2013; Dalla Vecchia & Schaye 2008

Simulation robustness

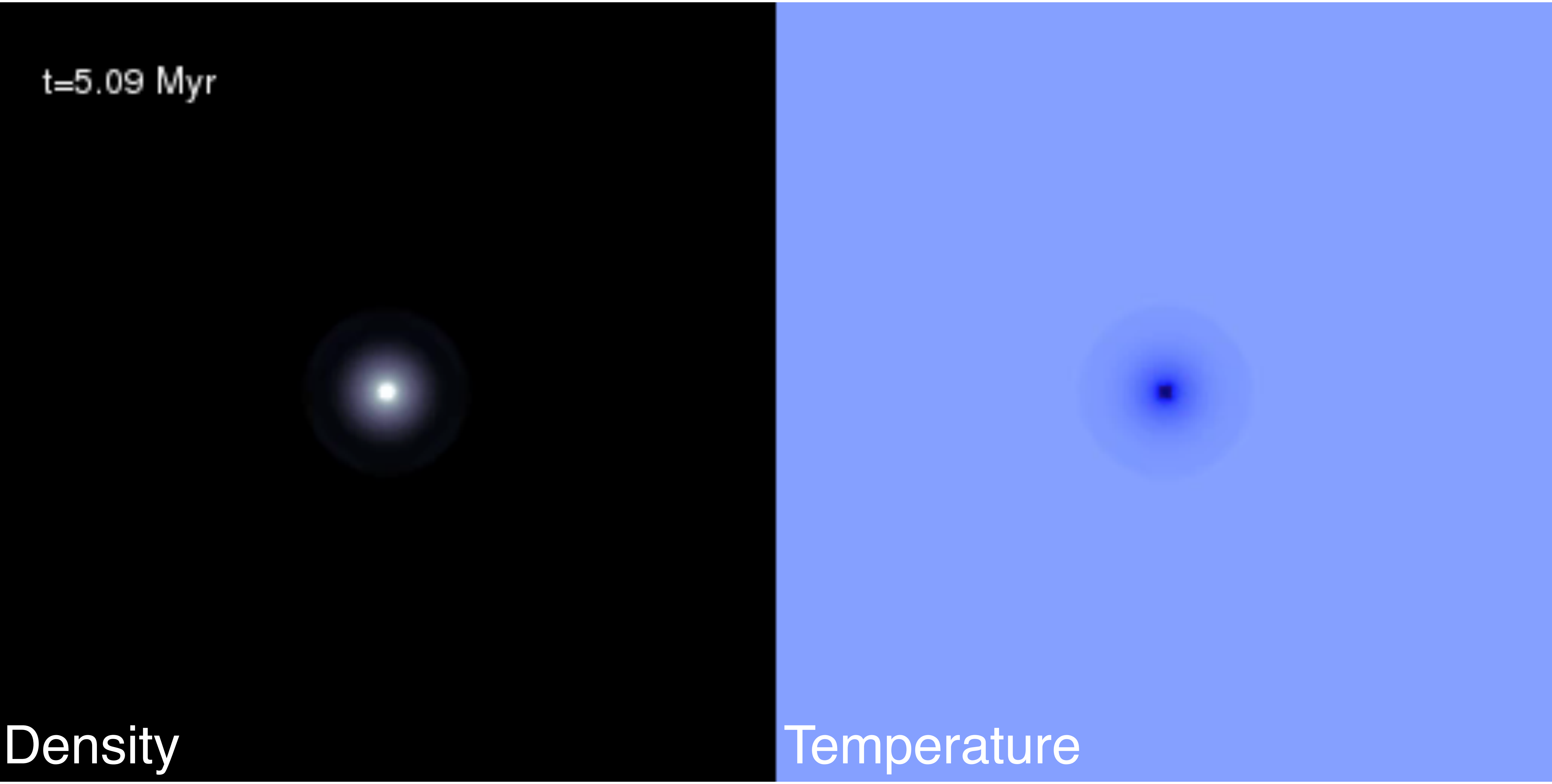
Simulations | Cusp-core transformations



Read et al. 2016

Modelling Super-bubbles

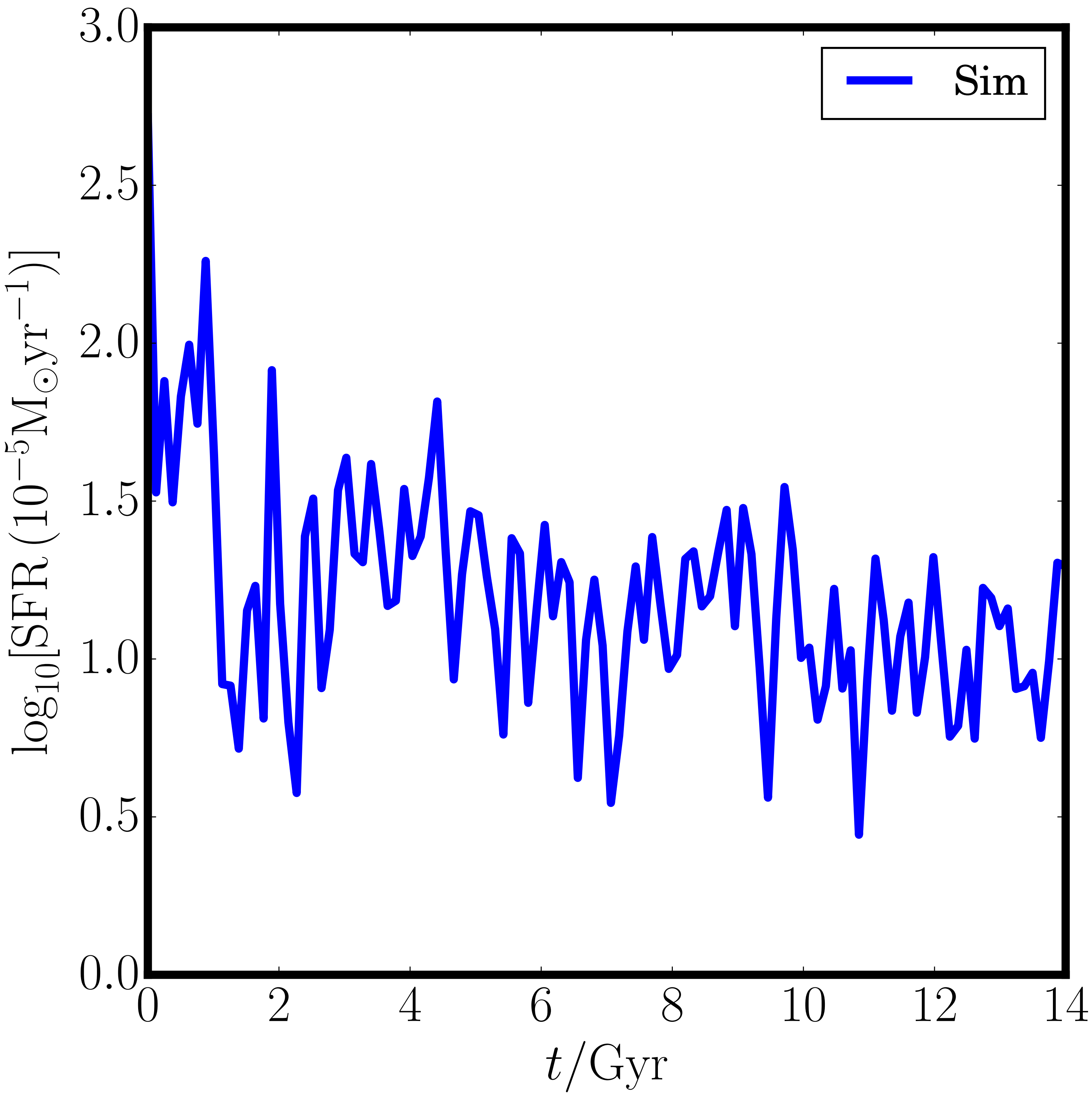
Simulations | Cusp-core transformations



Read et al. 2016

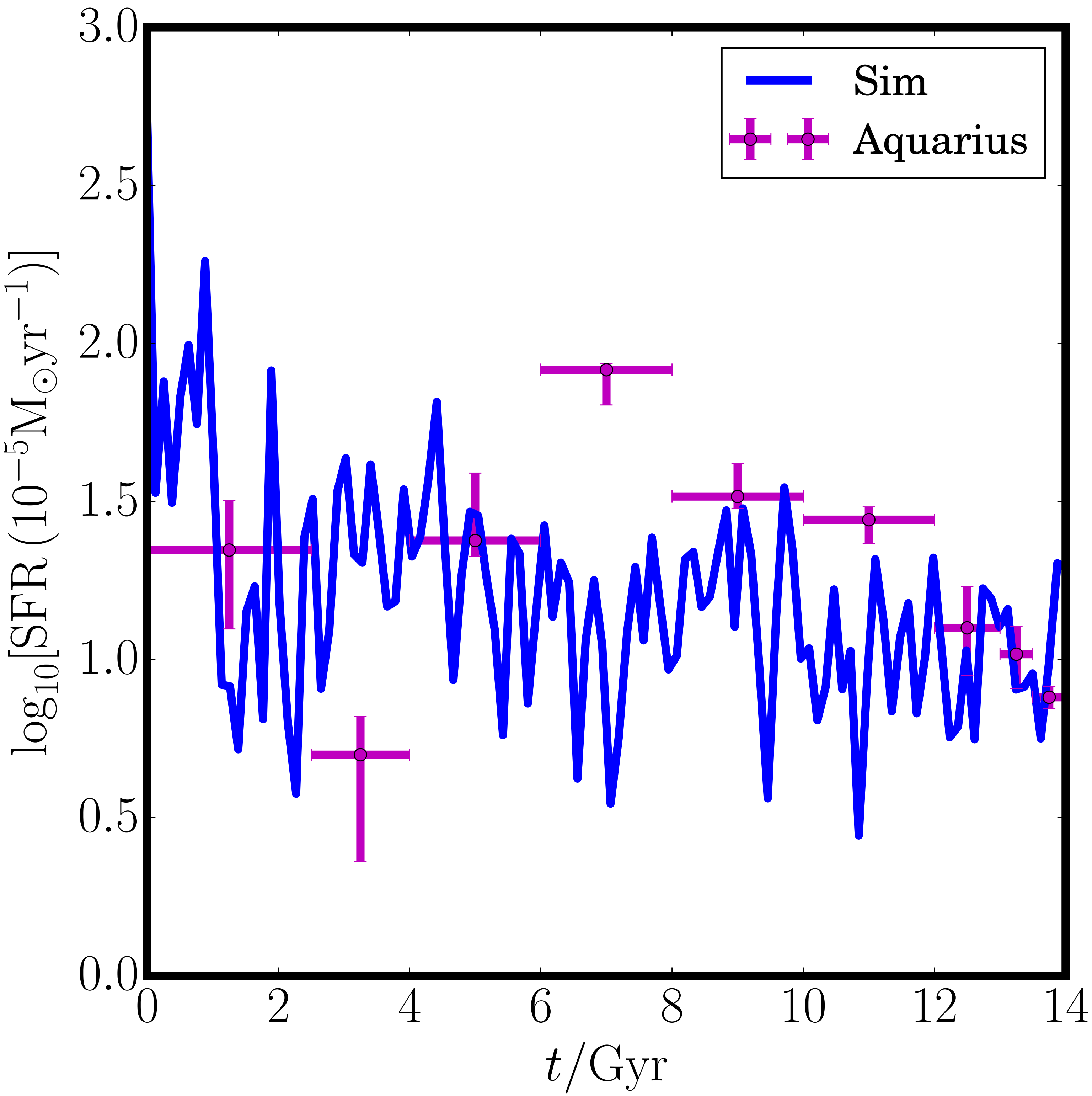
Observational tests of cusp-core forms

Predictions | Bursty star formation



Read et al. 2016; Teyssier et al. 2013; Pontzen & Governato 2011/2014; Kauffmann 2014

Predictions | Bursty star formation



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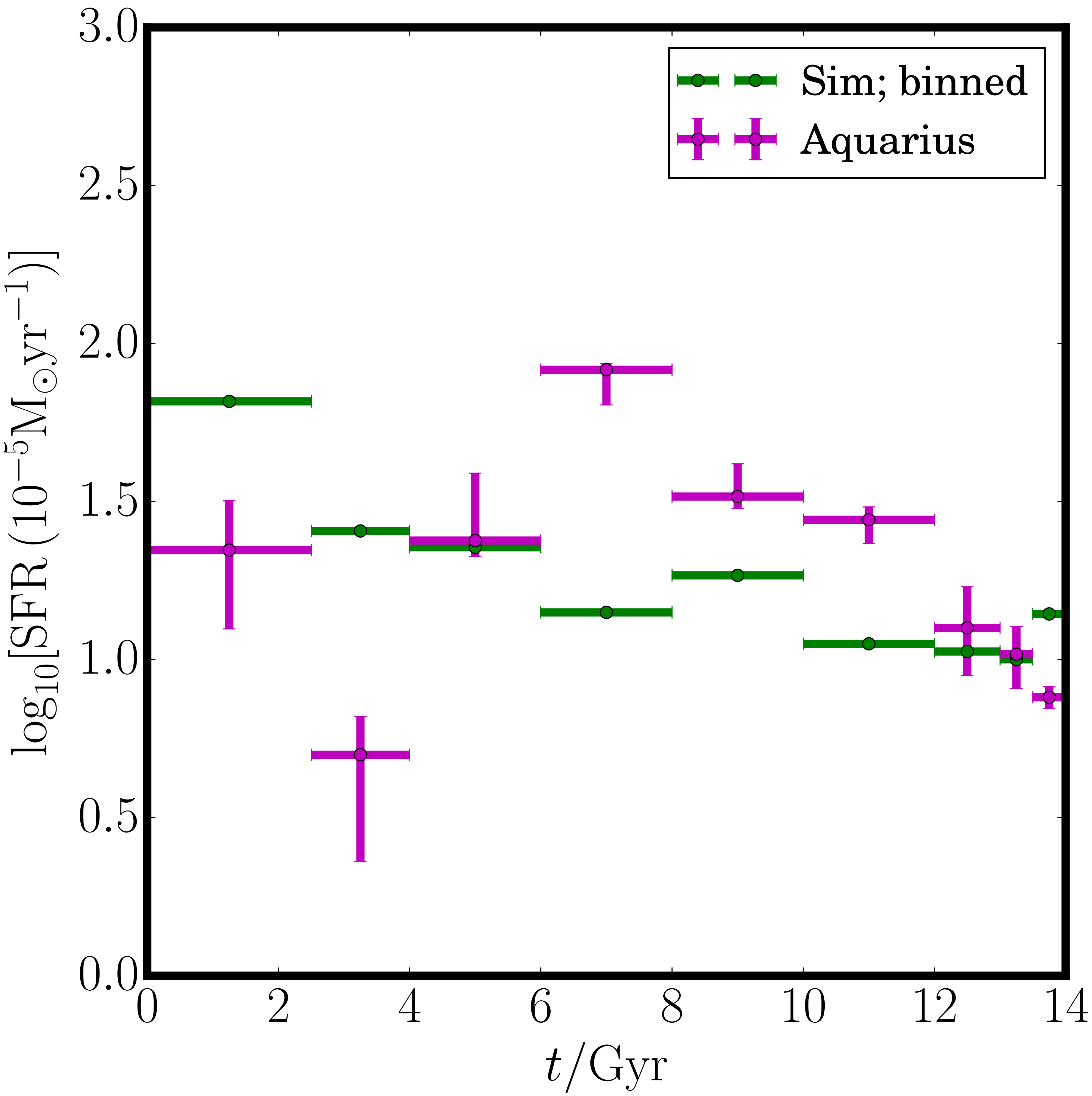
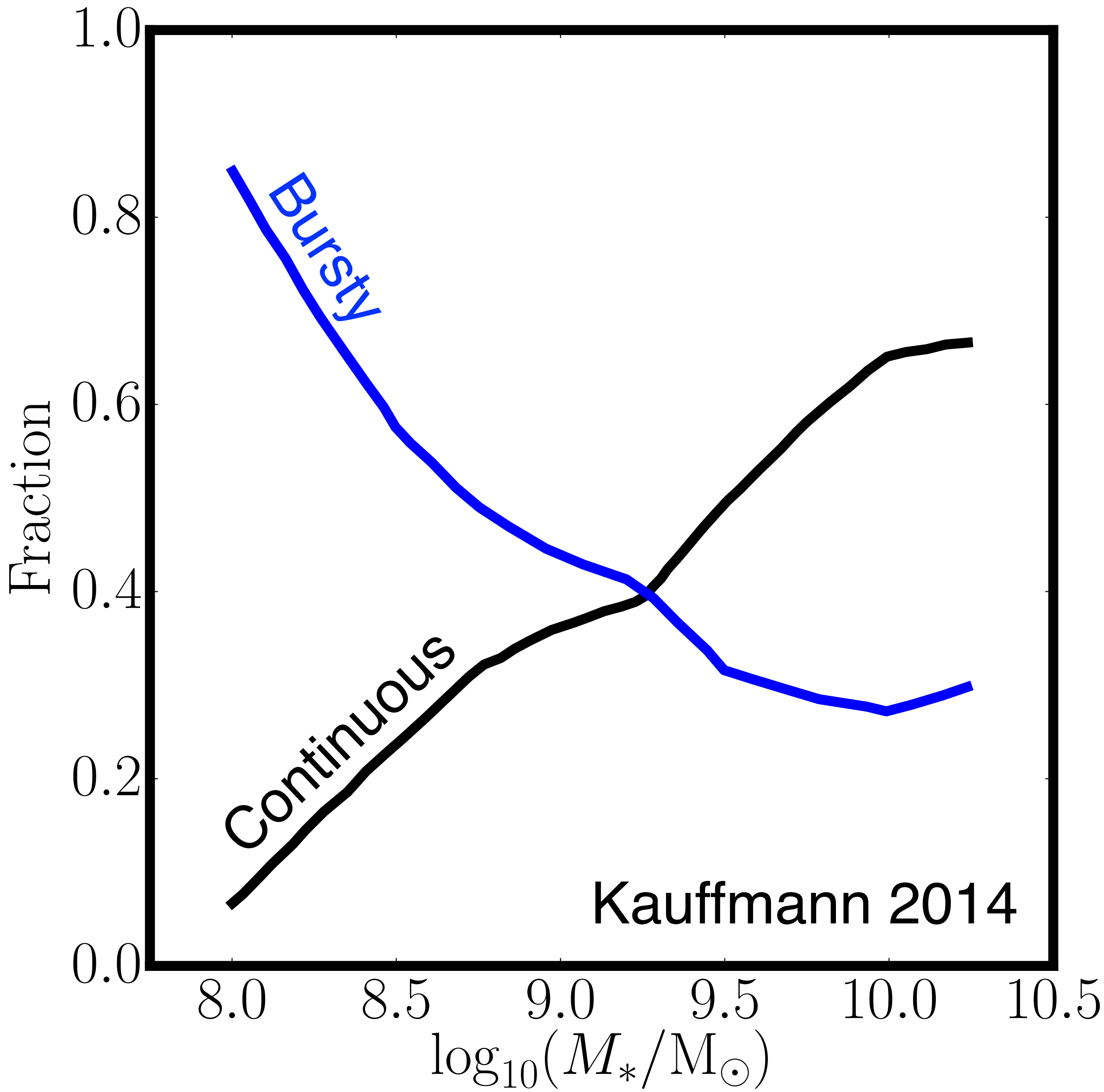
Predictions | Bursty star formation



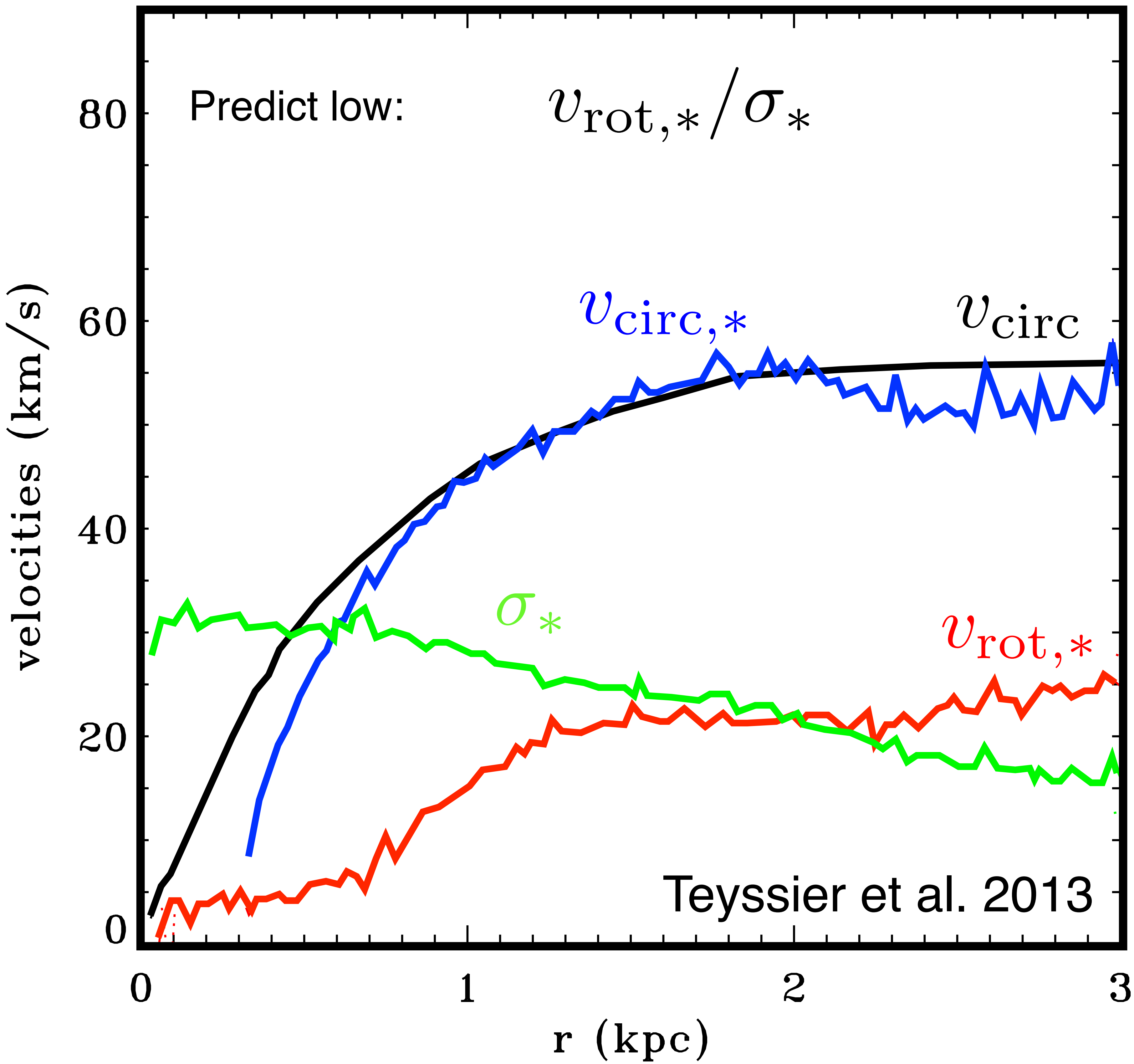
Read et al. 2016; Teyssier et al. 2013; Pontzen & Governato 2011/2014; Kauffmann 2014

Predictions | Bursty star formation

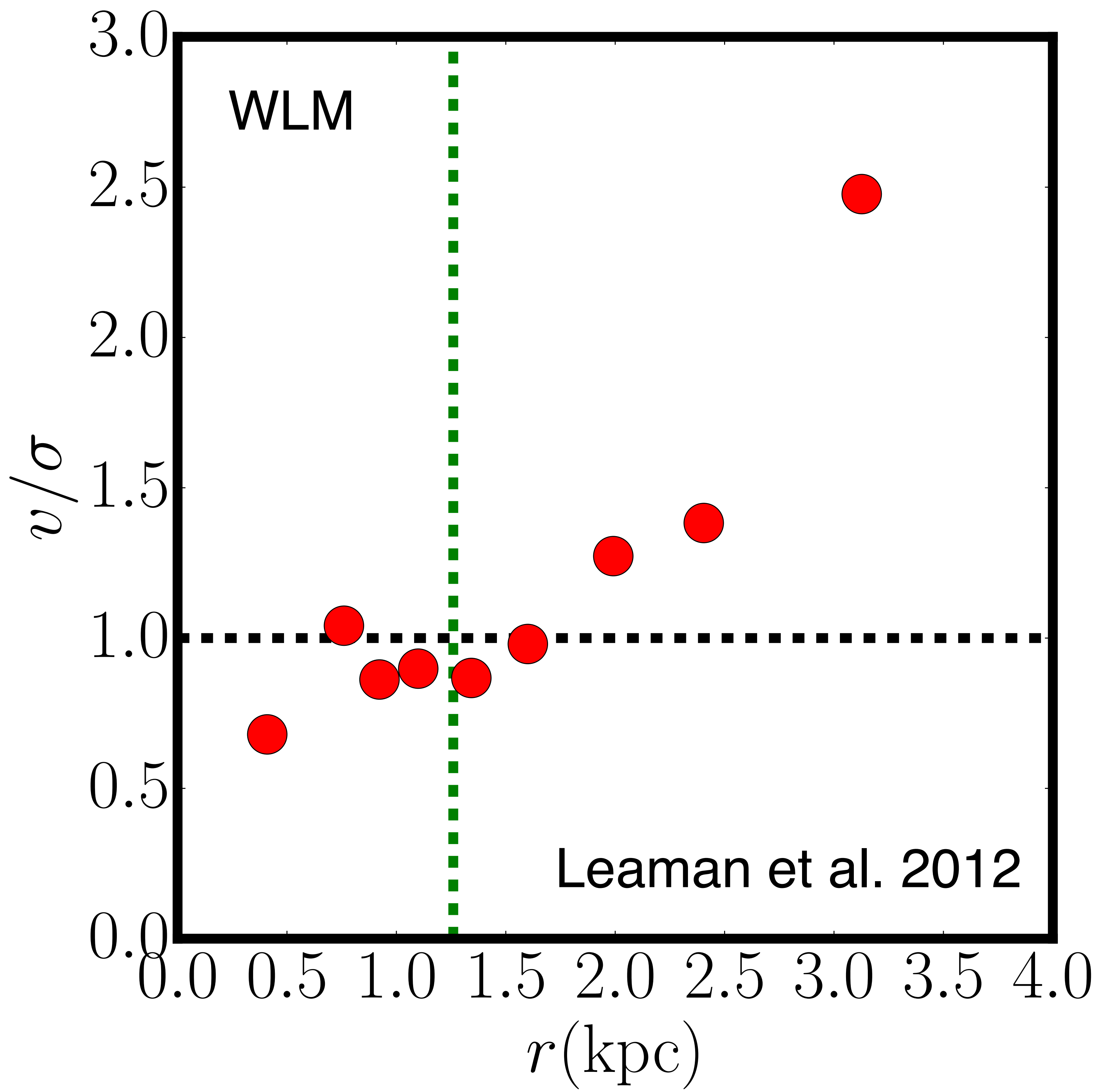


Read et al. 2016; Teyssier et al. 2013; Pontzen & Governato 2011/2014; Kauffmann 2014

Predictions | Kinematically “hot” stars



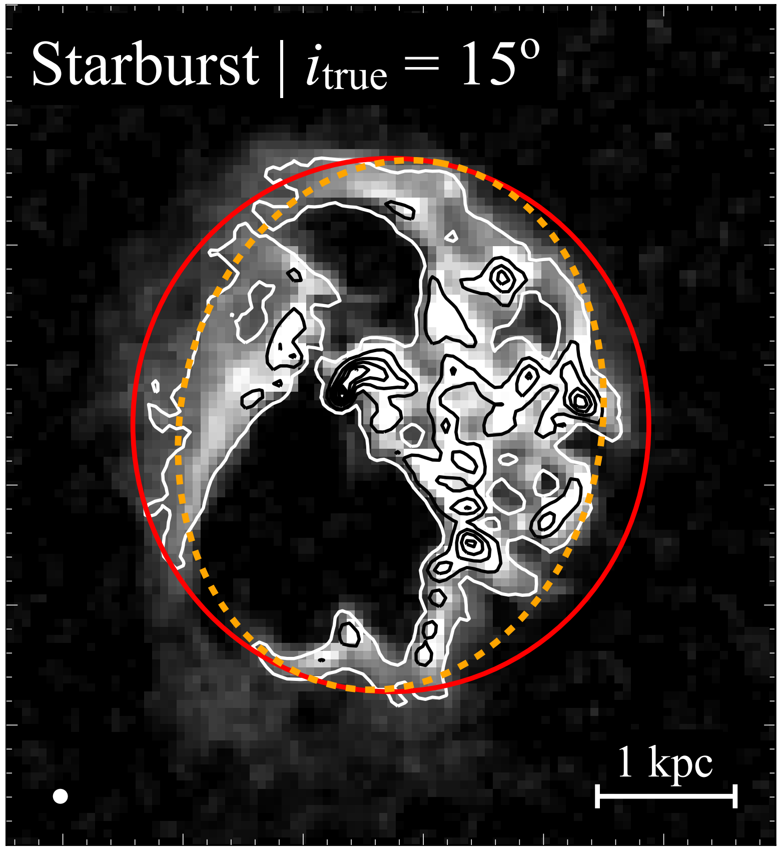
Predictions | Kinematically “hot” stars

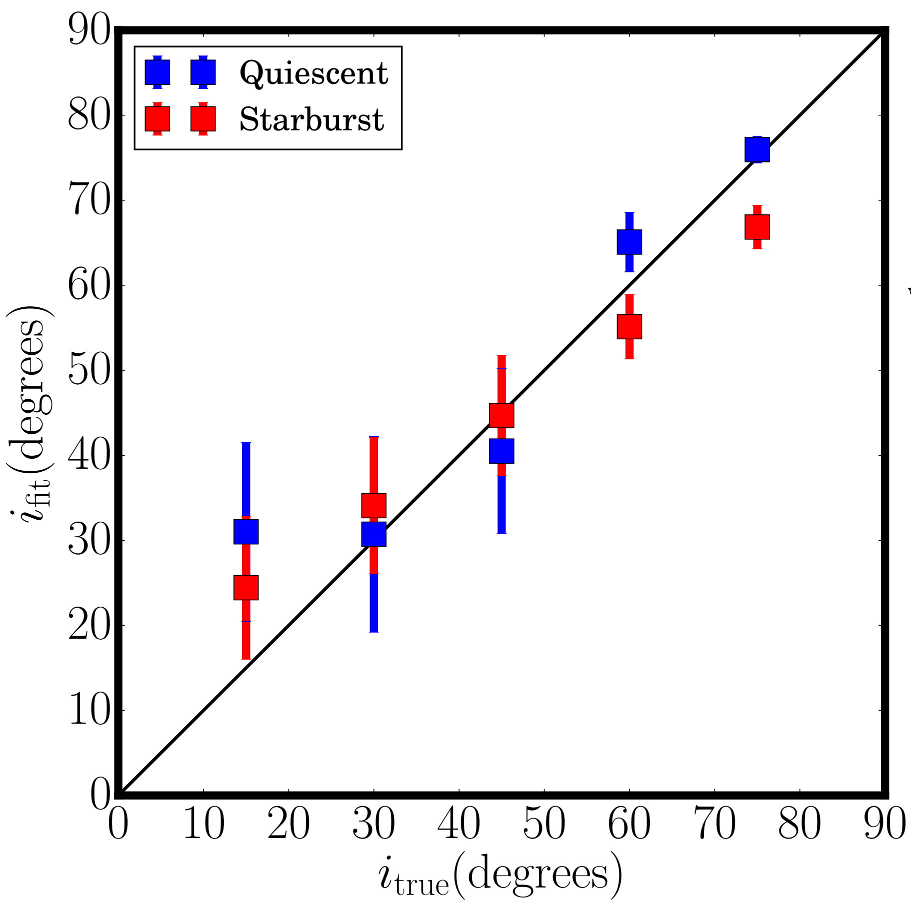


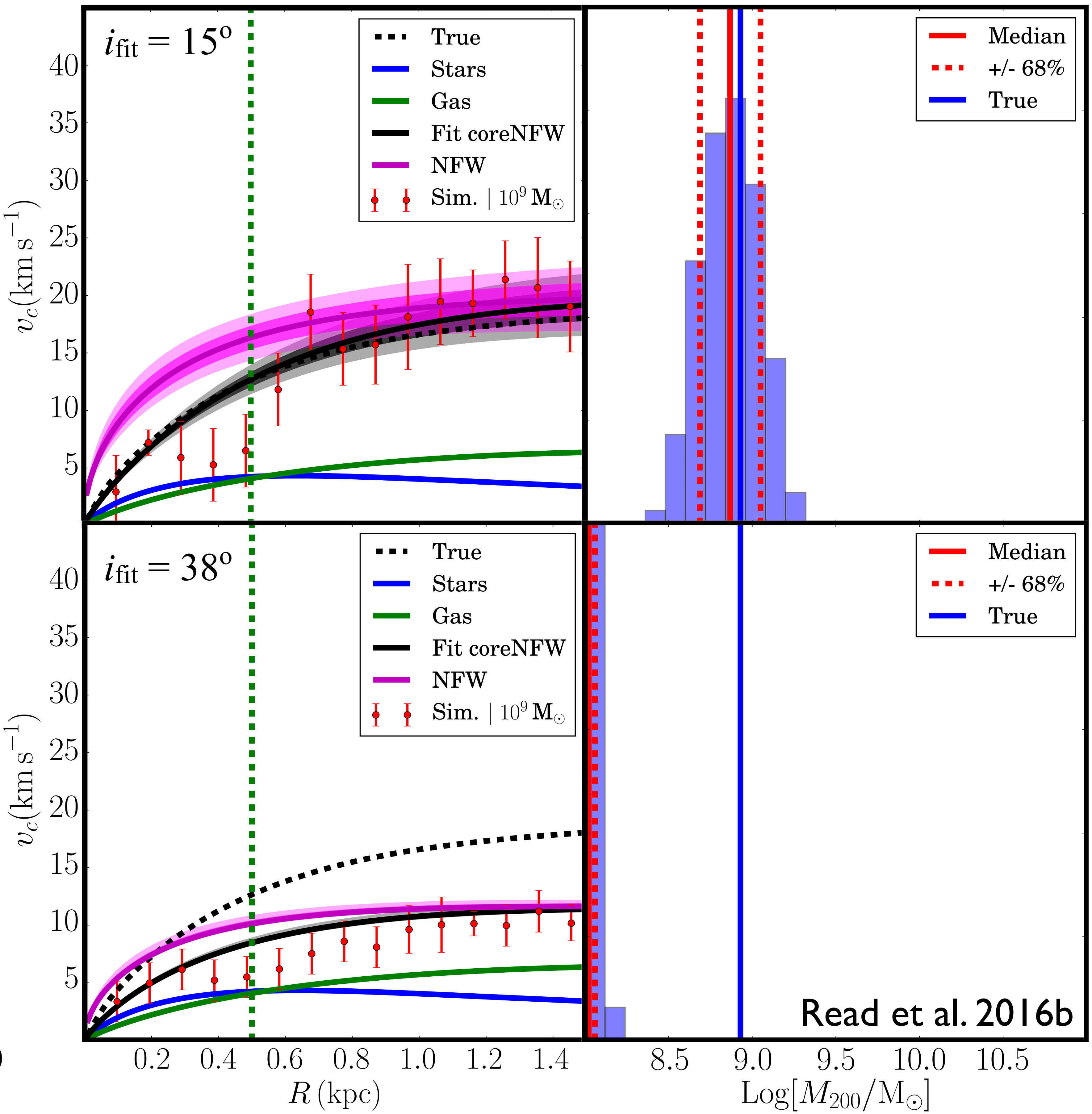
Read & Gilmore 2005; Teyssier et al. 2013

Tests with mock data

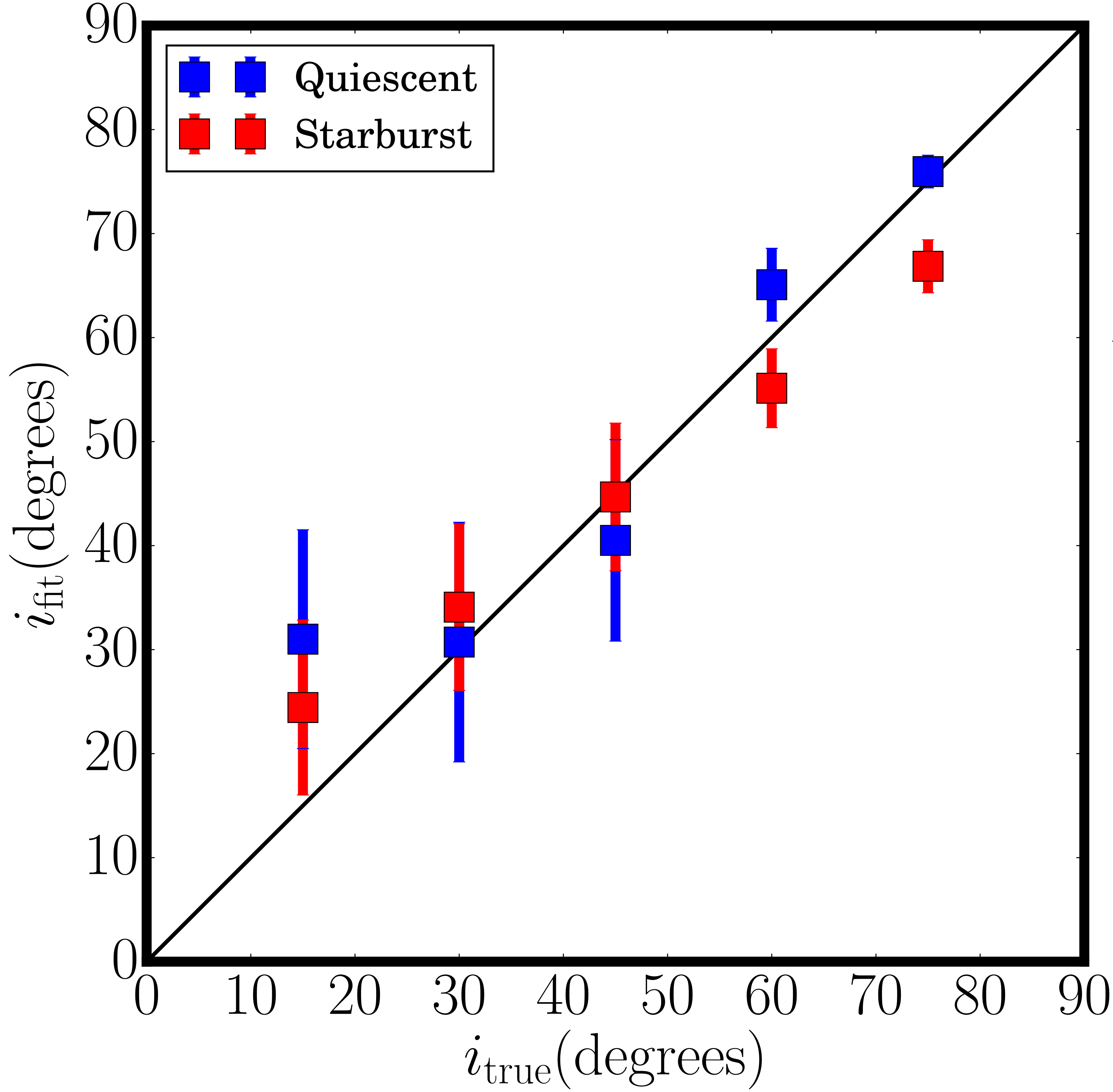
Rotation curve fitting | Tests with mock data

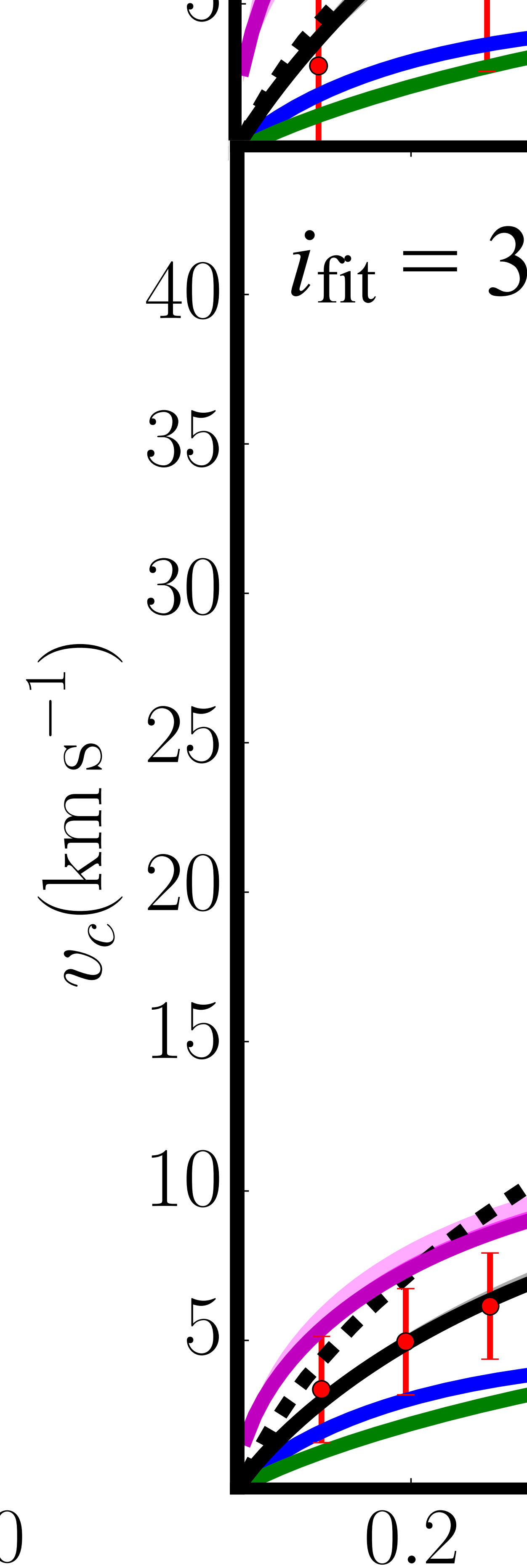




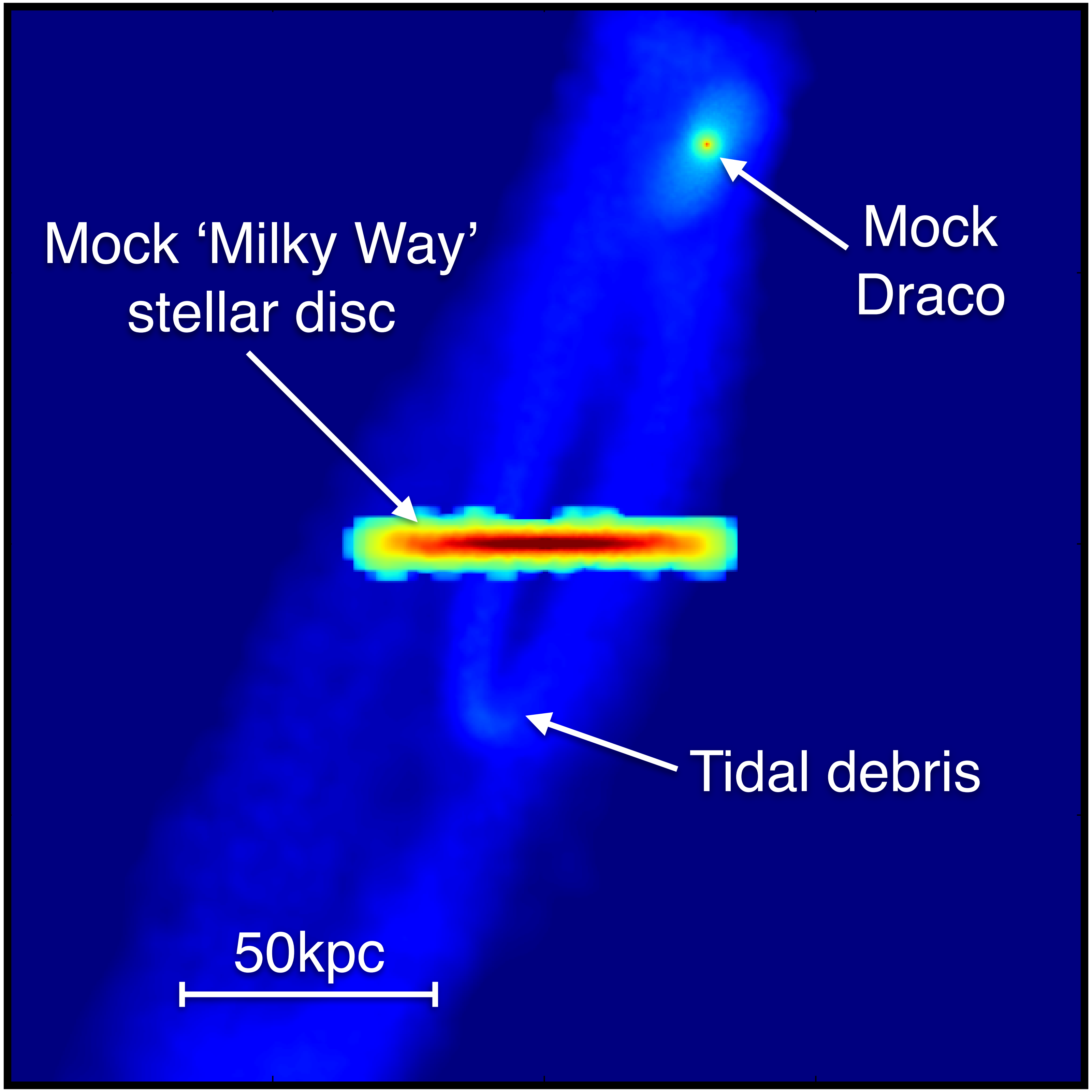


Rotation curve fitting | Tests with mock data

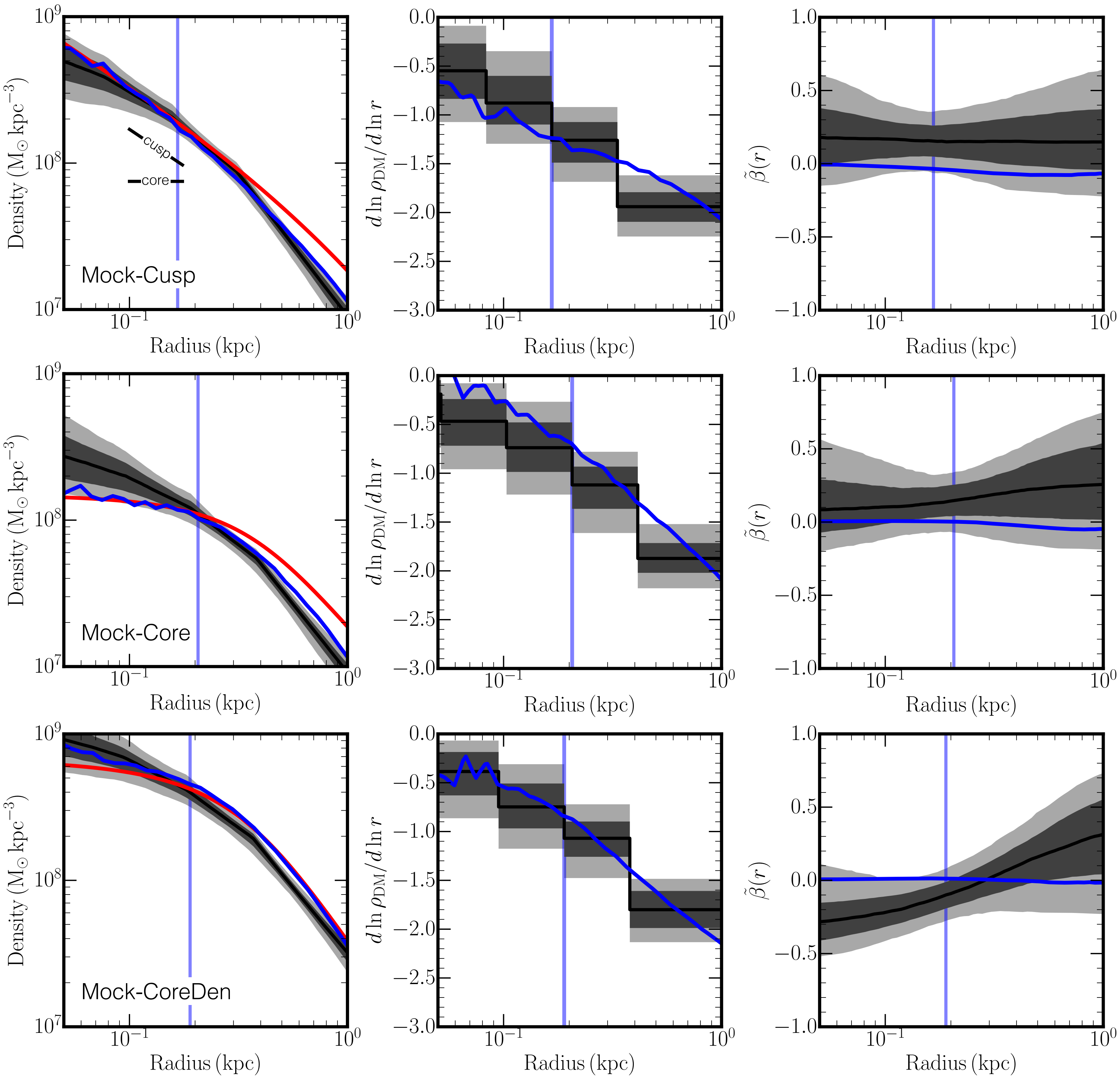




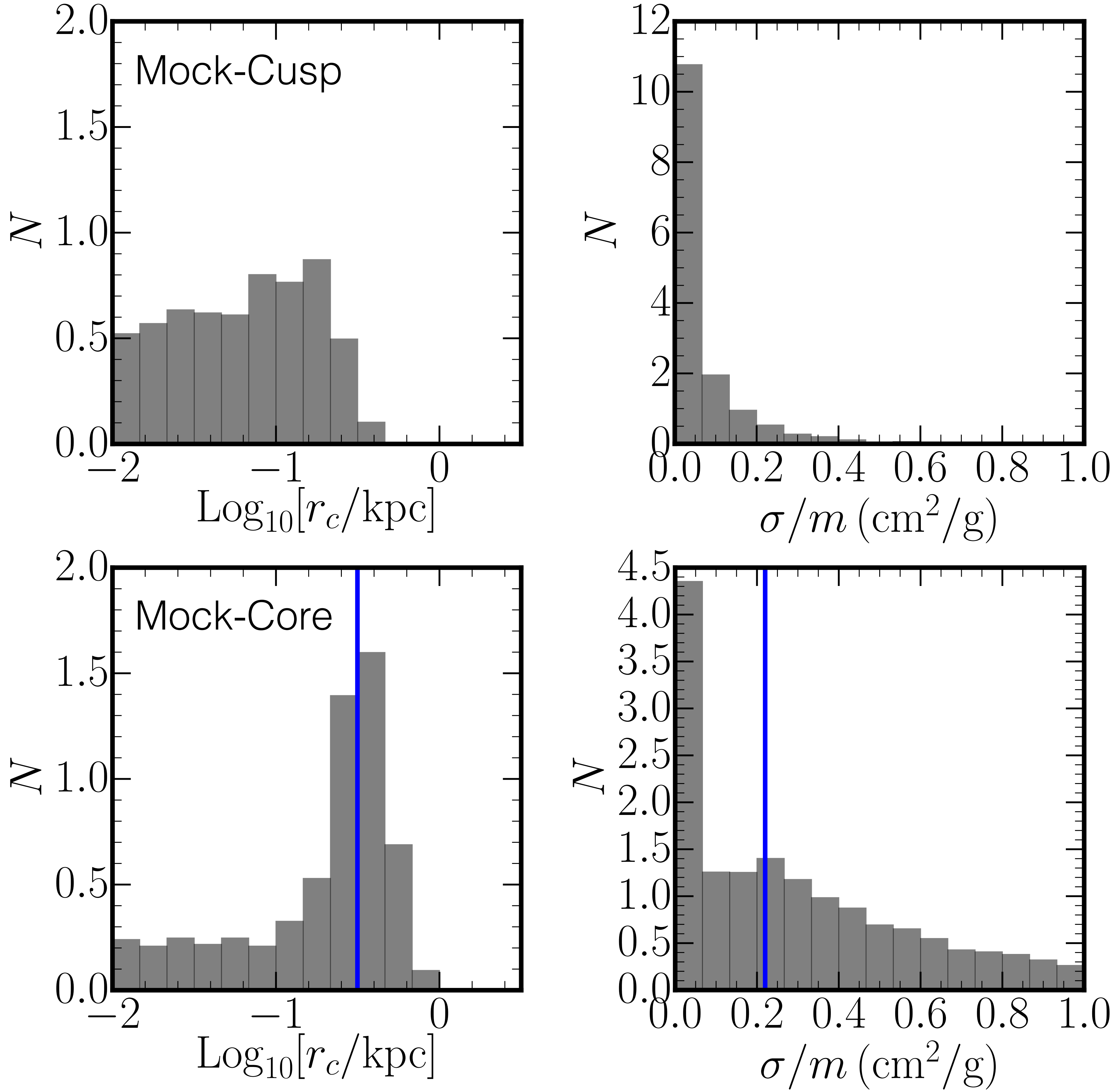
GravSphere | Tests with mock data



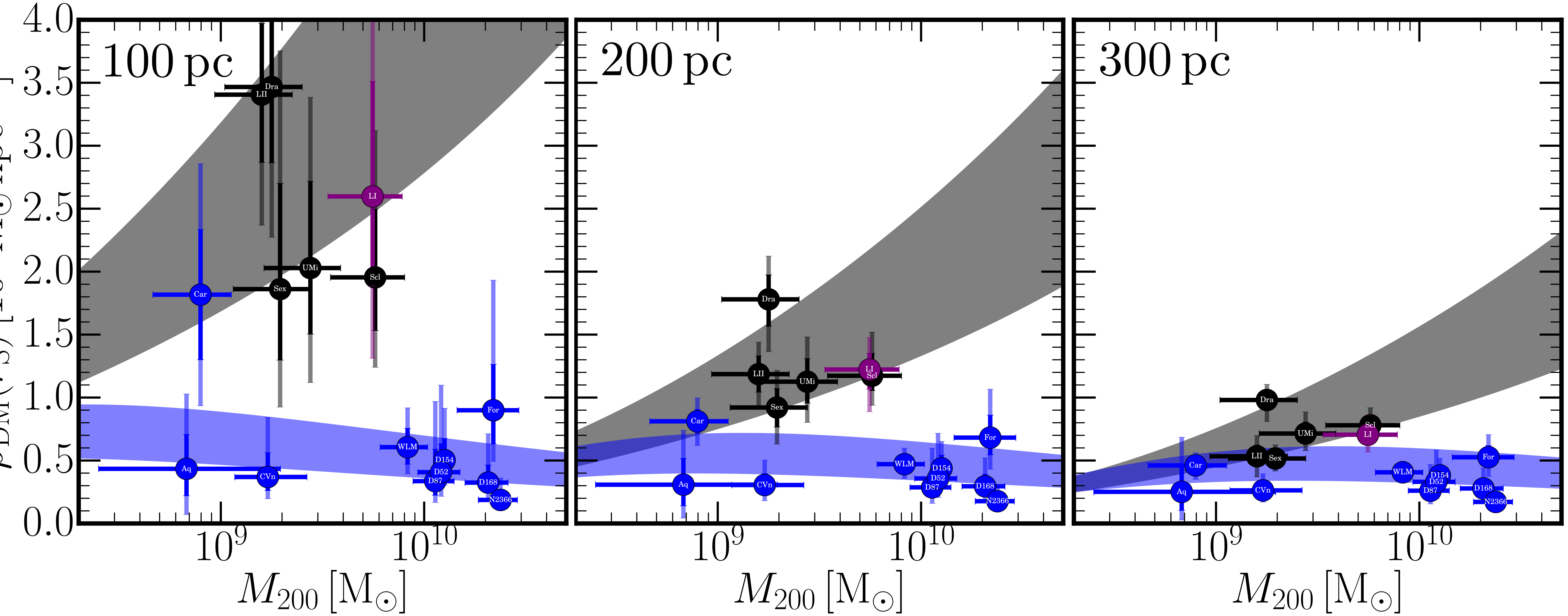
GravSphere | Tests with mock data



GravSphere | Tests with mock data

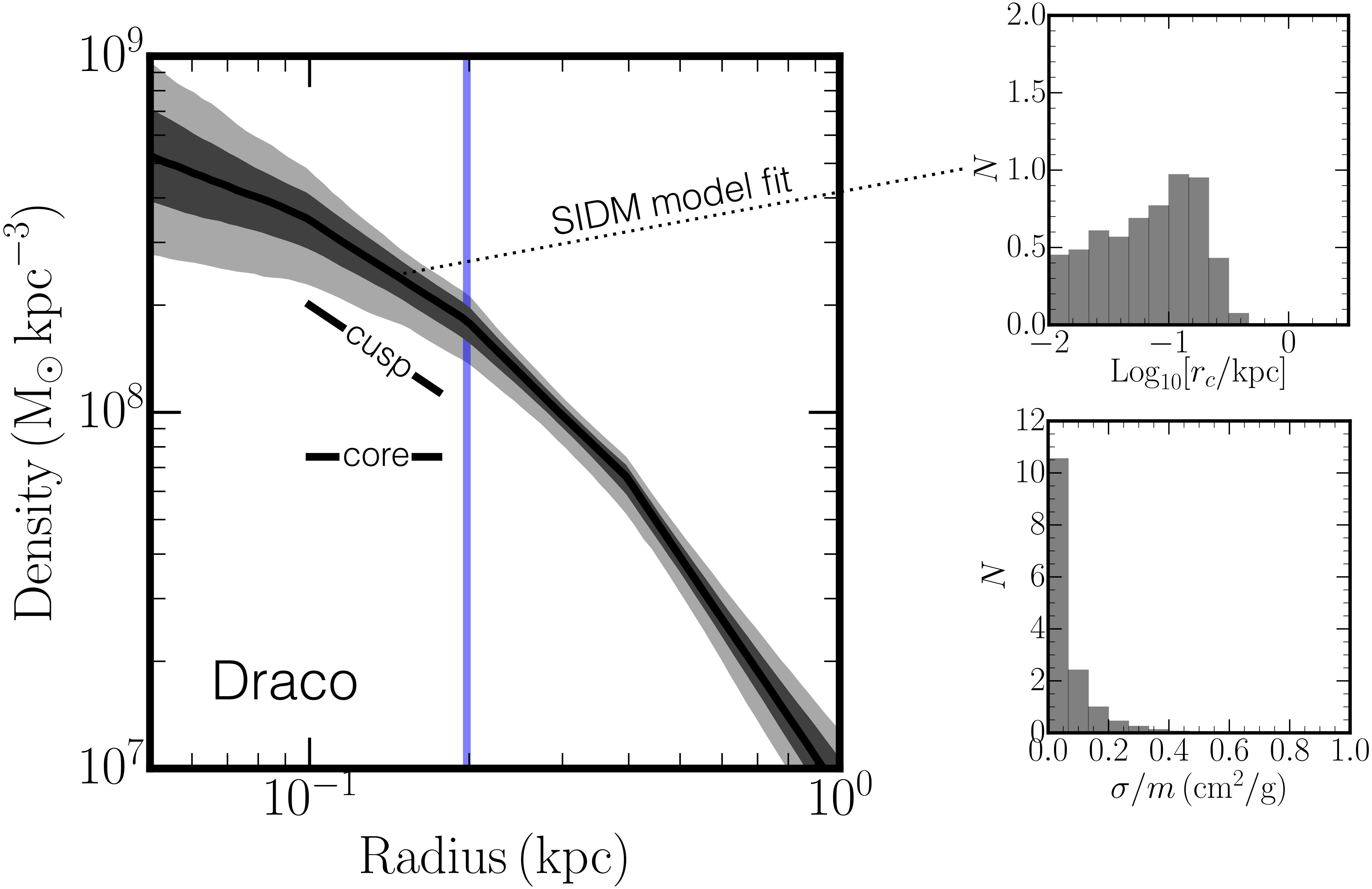


Robustness



100 pc
200 pc
300 pc
$\rho_{\rm DM}(r_{\rm S})\,[10^8\,{\rm M_\odot\,kpc^{-3}}]$
$M_{200}\,[{\rm M_\odot}]$
Dra
LII
LI
UMi
Sex
Scl
Car
Aq
CVn
WLM
D154
D52
D87
For
D168
N2366

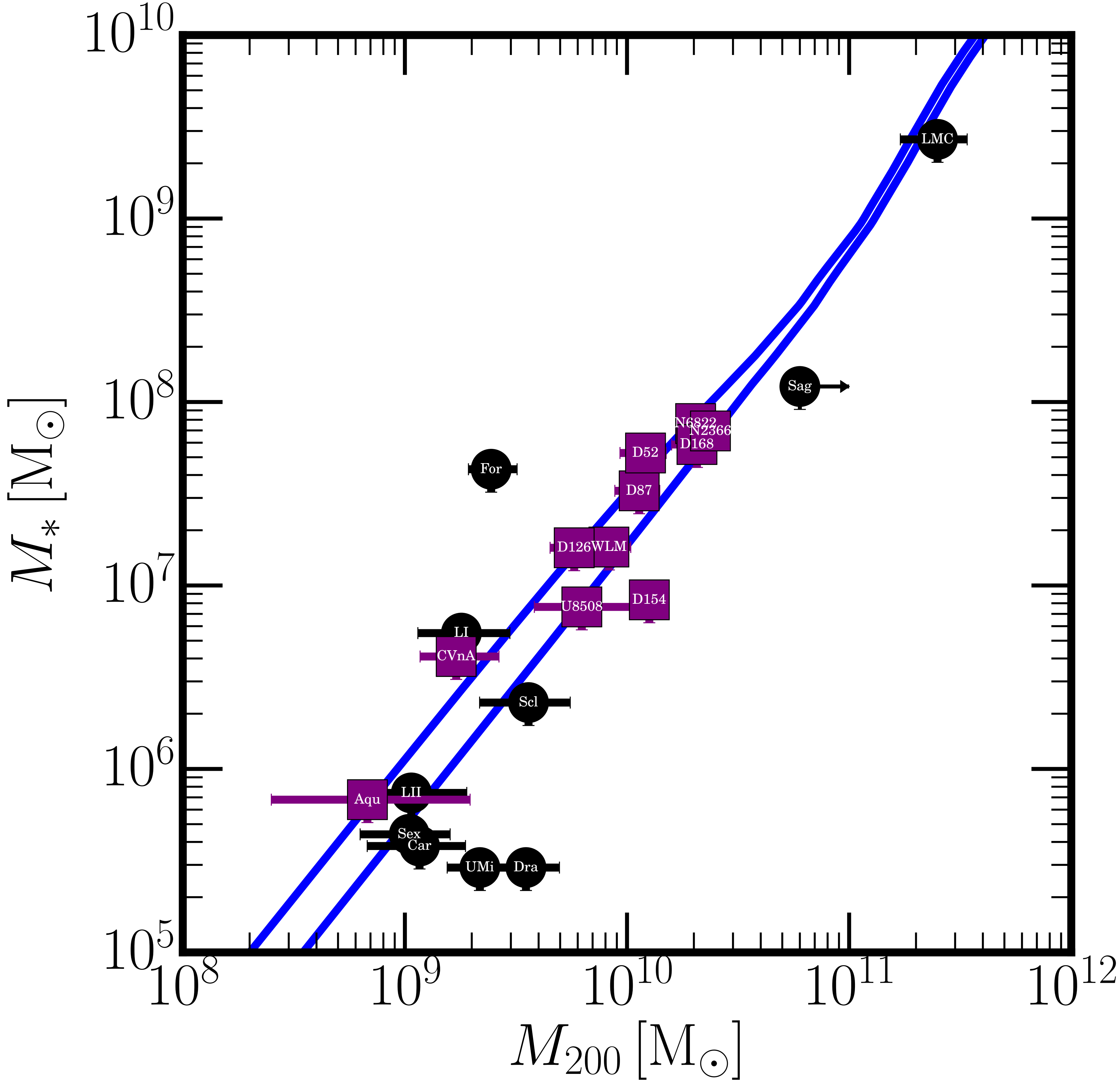
SIDM results



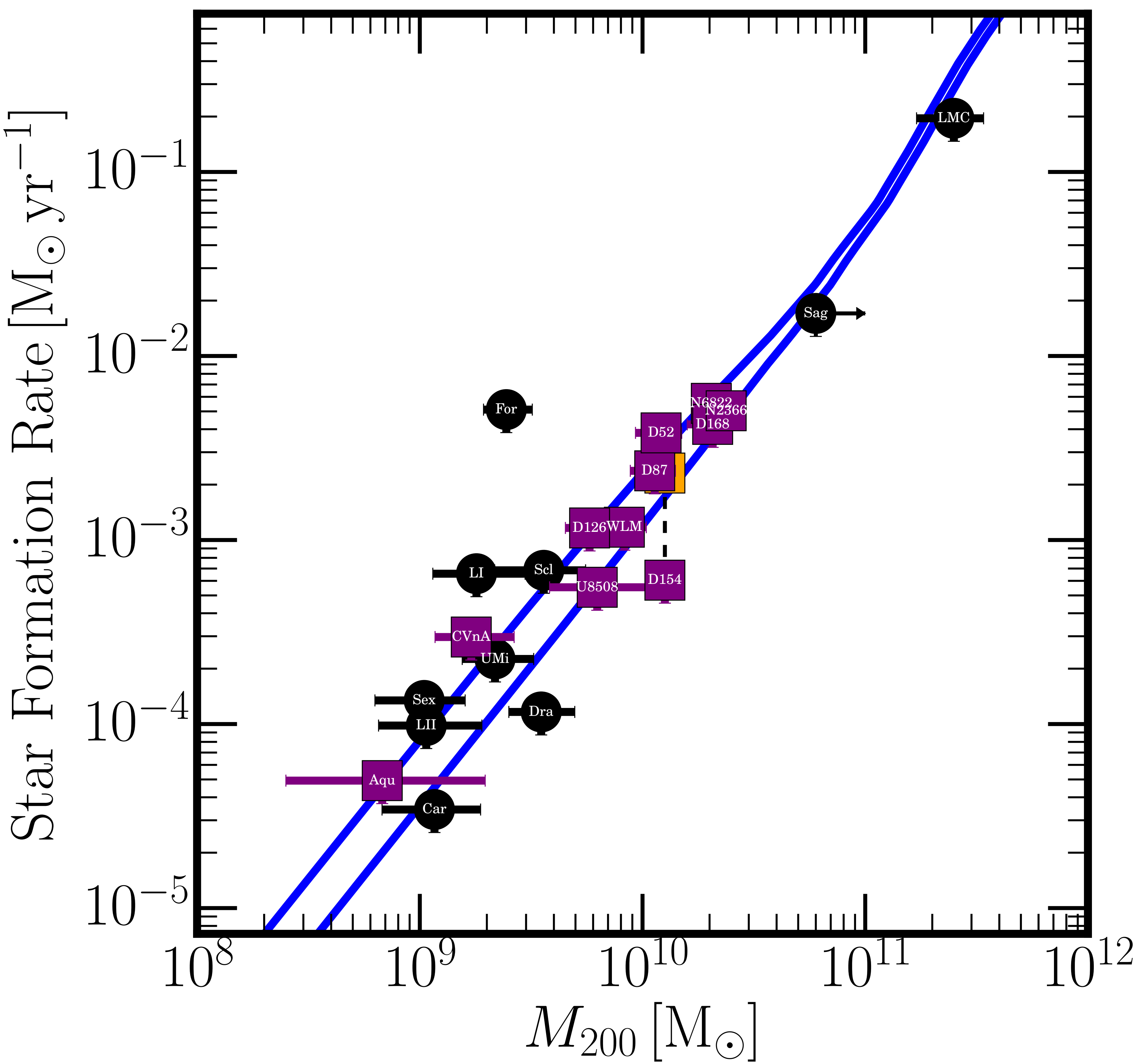
$$\sigma/m \;<\; 0.57\,\mathrm{cm^2\,g^{-1}} \;\text{ at }\; 99\% \;\text{ confidence.}$$

Read et al. 2018 (arXiv:1805.06934)

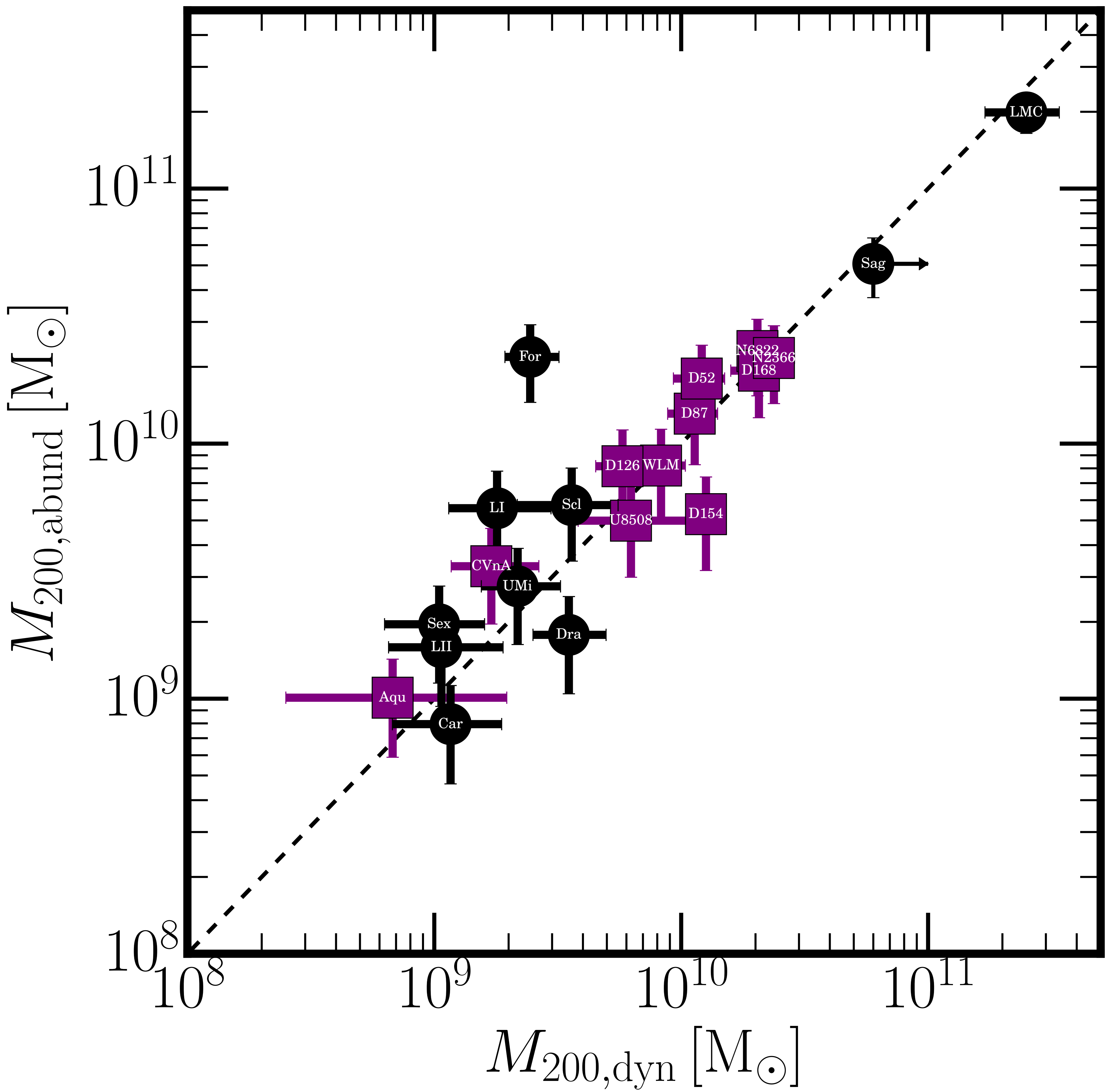
Pre-infall halo masses



M_* [M$_\odot$]
M_{200} [M$_\odot$]
10^{5}
10^{6}
10^{7}
10^{8}
10^{9}
10^{10}
10^{8}
10^{9}
10^{10}
10^{11}
10^{12}
LMC
Sag
N6822
N2366
D168
D52
For
D87
D126
WLM
D154
U8508
LI
CVnA
Scl
Aqu
LII
Sex
Car
UMi
Dra



Star Formation Rate $[\mathrm{M_\odot\,yr^{-1}}]$
$M_{200}\,[\mathrm{M_\odot}]$
10^{8}
10^{9}
10^{10}
10^{11}
10^{12}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
LMC
Sag
For
N6822
N2366
D168
D52
D87
D126
WLM
LI
Scl
U8508
D154
CVnA
UMi
Sex
LII
Dra
Aqu
Car

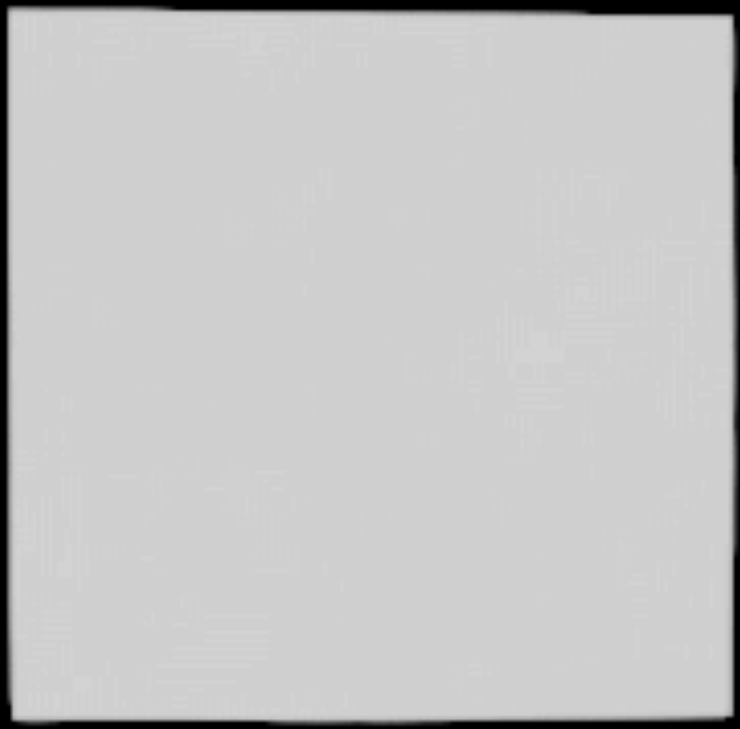


$M_{200,\rm abund}\,[\rm M_\odot]$
$M_{200,\rm dyn}\,[\rm M_\odot]$
10^8
10^9
10^{10}
10^{11}
LMC
Sag
For
N6822
N2366
D168
D52
D87
D126
WLM
LI
Scl
U8508
D154
CVnA
UMi
Sex
LII
Dra
Aqu
Car

Cosmological simulations

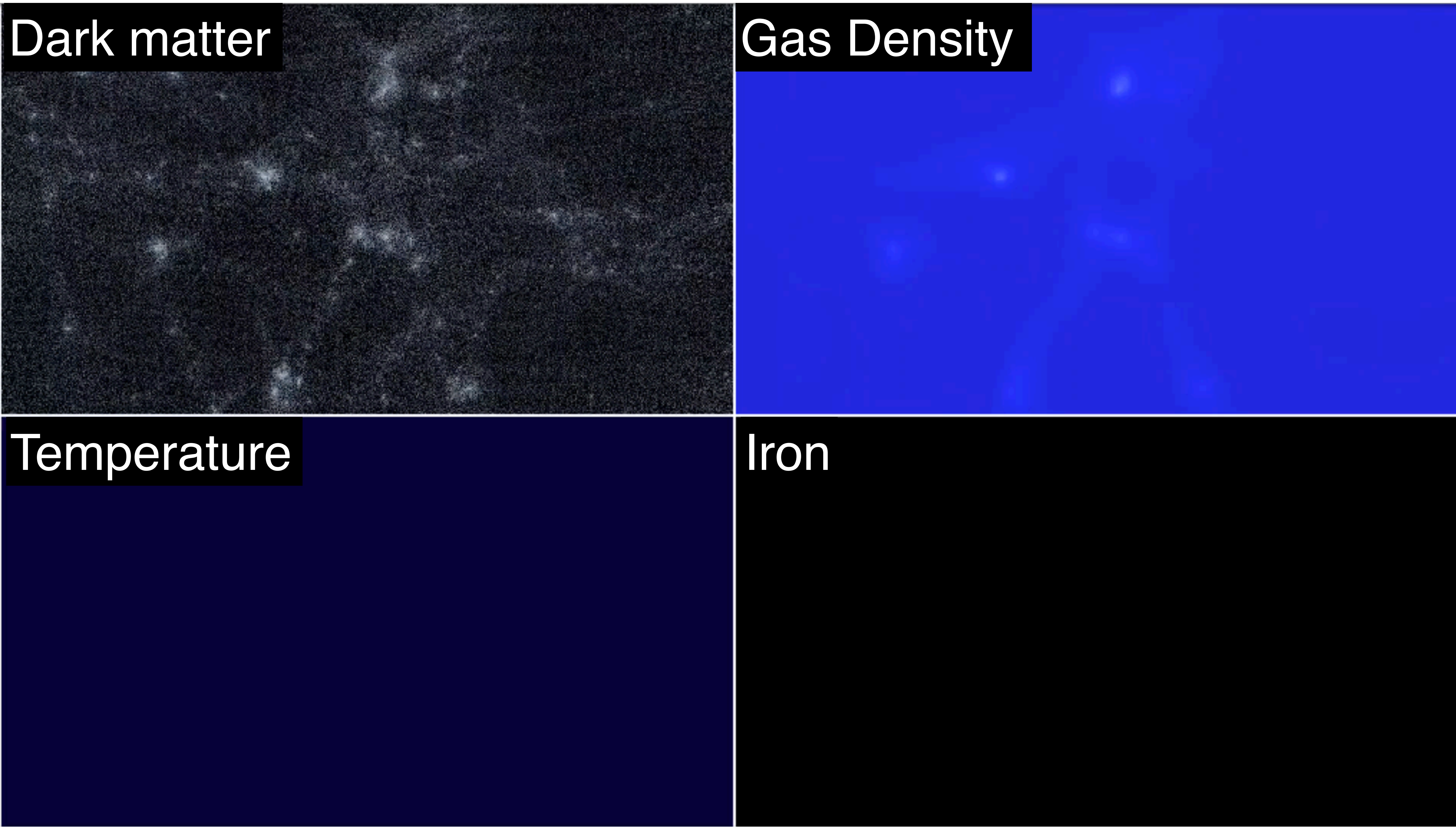
E.D.G.E.

Engineering **D**warfs at **G**alaxy formation's **E**dge



Oscar Agertz
Andrew Pontzen
Justin Read

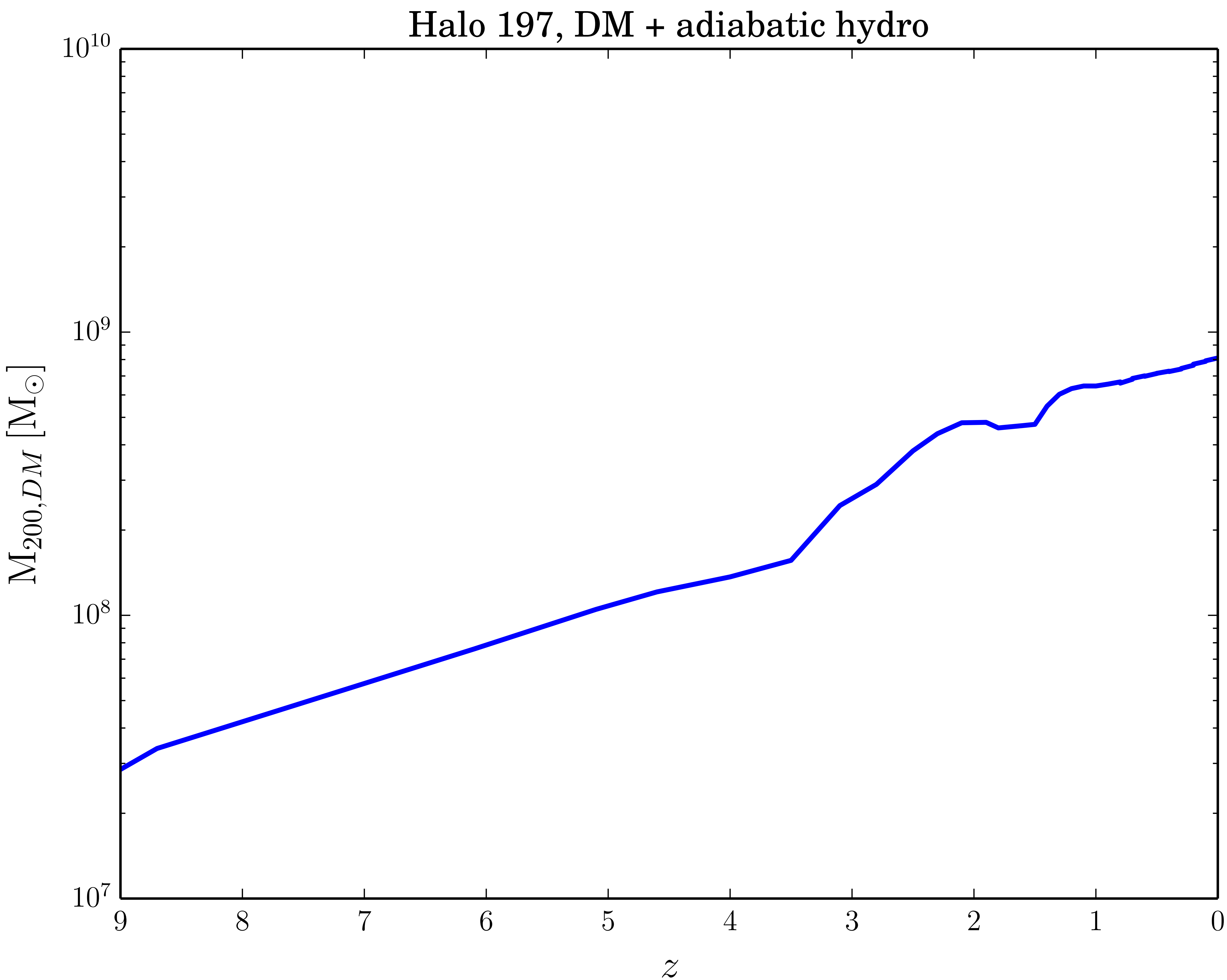
Cosmological simulations | E.D.G.E.



$$M_{\rm DM} = 960\,{\rm M}_\odot\ ({\rm fiducial}), 120\,{\rm M}_\odot\ ({\rm high})\ |\ M_{\rm bar} = 160\,{\rm M}_\odot$$

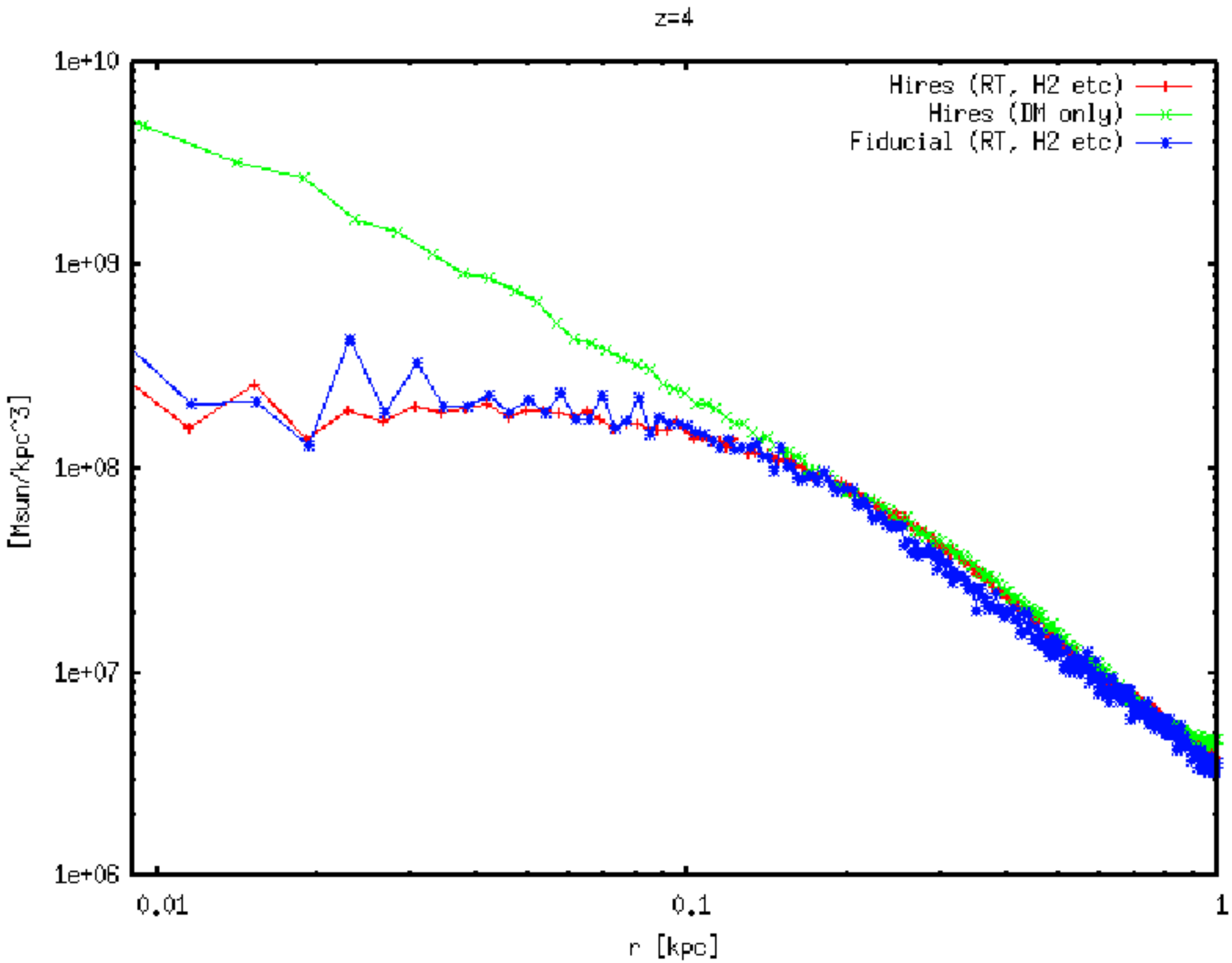
Agertz, Pontzen & Read in prep. 2018

Cosmological simulations | Cores & cusps in an ultra-faint



Agertz, Pontzen & Read in prep. 2018

Cosmological simulations | Cores & cusps in an ultra-faint



Agertz, Pontzen & Read in prep. 2018

Testing Predictions from DM Heating Models

Predictions

- Bursty star formation.
  [Dohm-Palmer et al. 1998, 2002; Teyssier et al. 2013; Kauffmann 2014; Sparre et al. 2017]
  ✔

- Stars kinematically “heated” along with the dark matter ⇒ $v/\sigma < 1$.
  [Read & Gilmore 2005; Teyssier et al. 2013; Leaman et al. 2012; Wheeler et al. 2017]
  ✔

- Radial migration of stars ⇒ age gradients.
  [El-Badry et al. 2016; Zhang et al. 2012]
  ✔

Predictions

Gravitational Potential fluctuations

$[t_{\rm fluc} \sim t_{\rm dyn} \mid \Delta M_{\rm gas}/M_{\rm DM} \sim 10\%]$

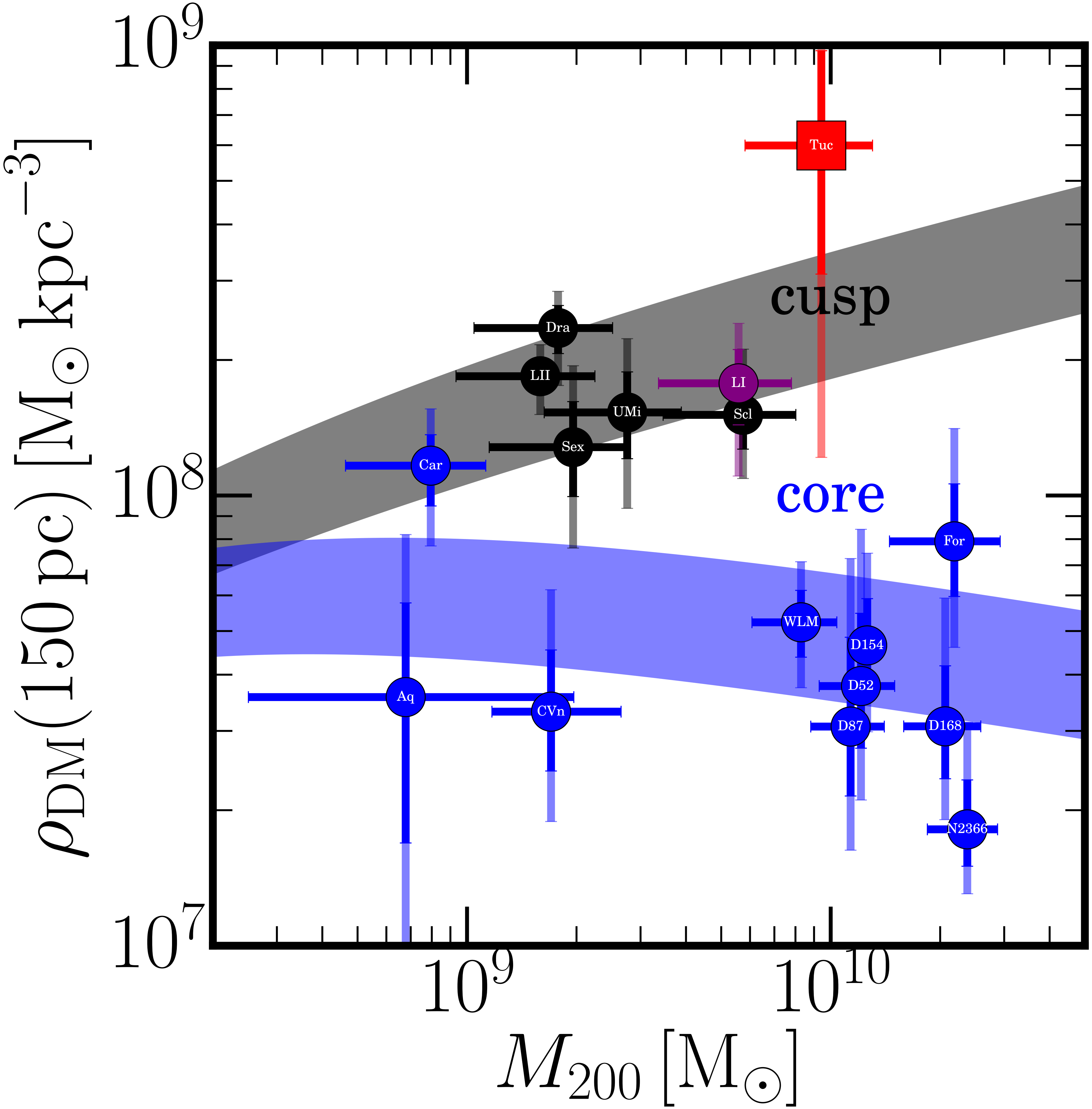
→ DM cusp-core transformations

→
- Bursty star formation
- “Hot” stellar kinematics
- Stellar age gradients

~~Bursty star formation ⇄ DM cusp-core transformations~~

Stinson et al. 2007; Bose et al. 2018

More data



Gregory et al. 2019, MNRAS submitted