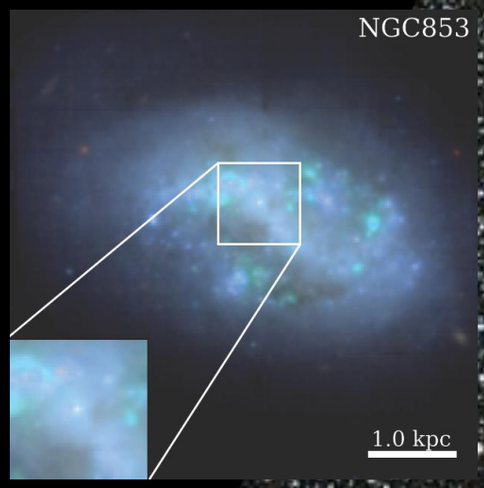
Towards Predictive Simulations of the Smallest Stellar Systems



Prof. Justin I. Read

Oscar Agertz, Michelle Collins, Izzy Gray,
Matthew Orkney, Andrew Pontzen, Martin Rey,
Stacy Kim, Ethan Taylor, Alex Goater

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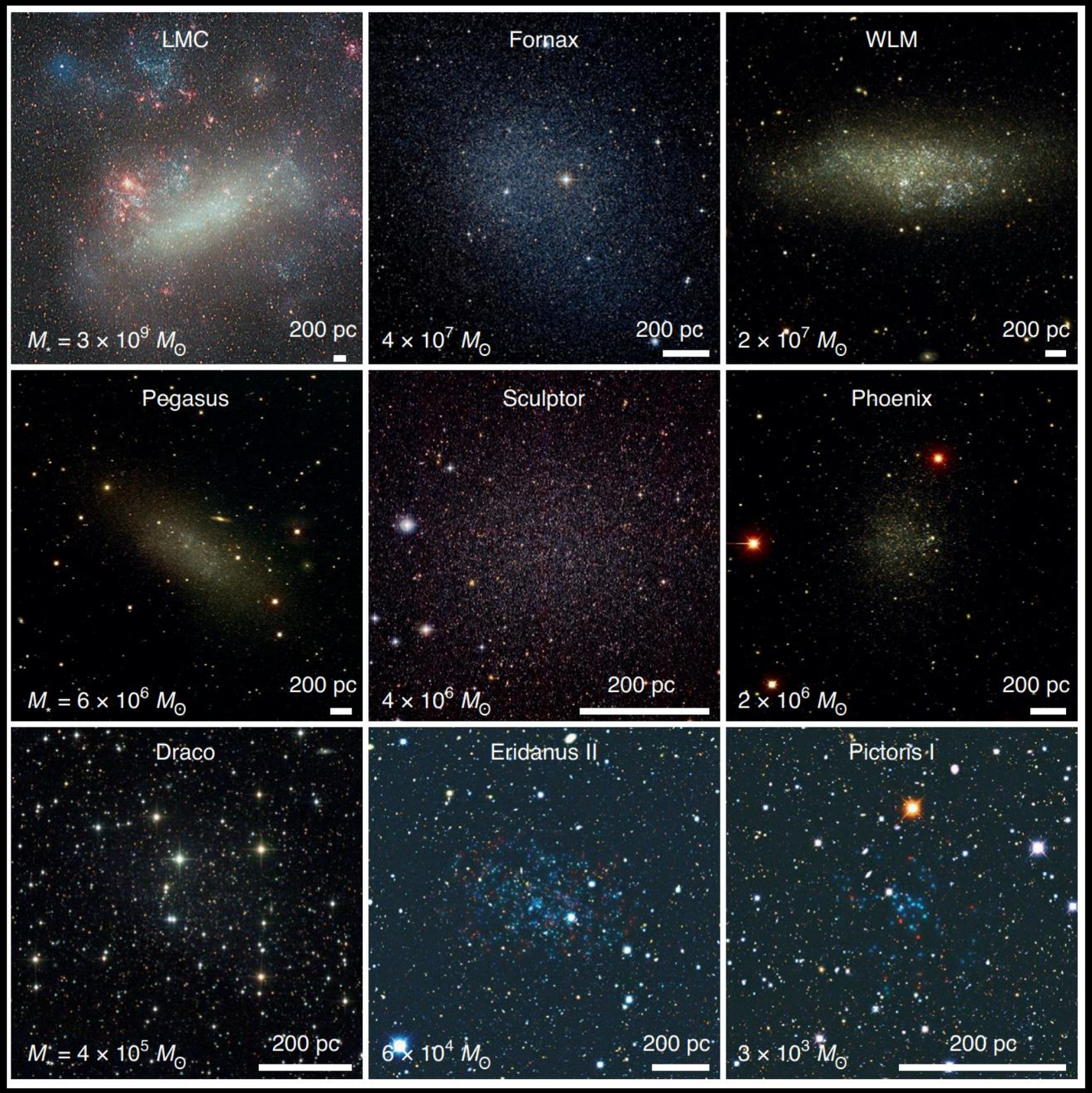
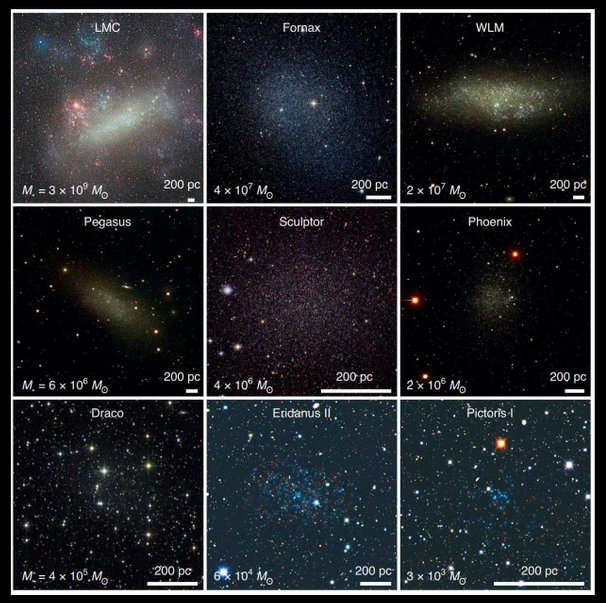
Dwarf galaxies



Crnojević & Mutlu-Pakdil 2021

Dwarf galaxies … rock!



- Numbers ➔ *test DM models*
- Internal dark matter distribution ➔ *test DM models*
- Winds/gas content ➔ *test galaxy form. models*
- Metallicity/abundance ➔ *test galaxy form. models*

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Simulating dwarf galaxies

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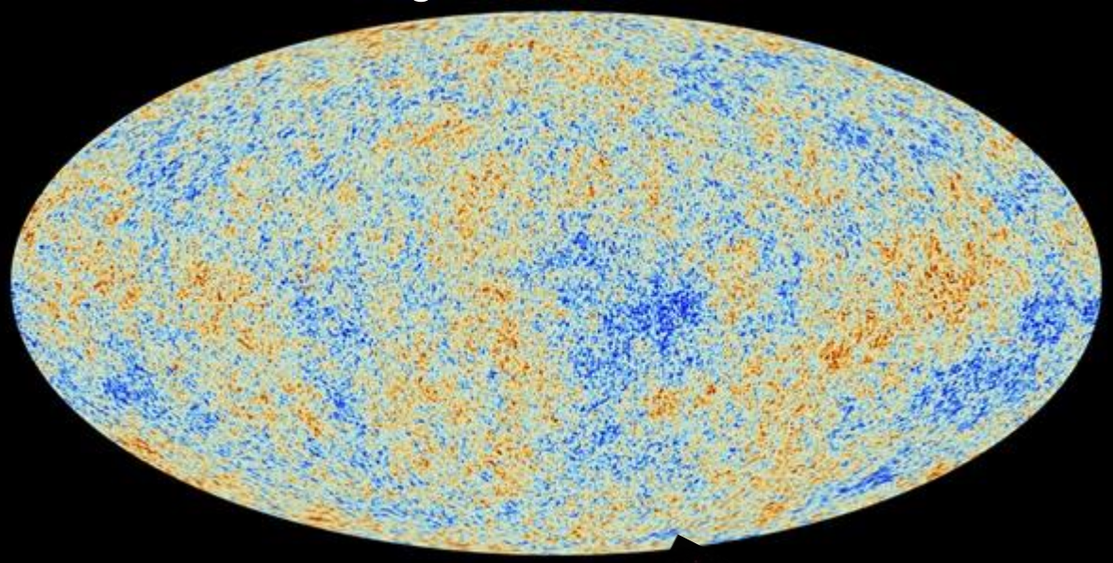
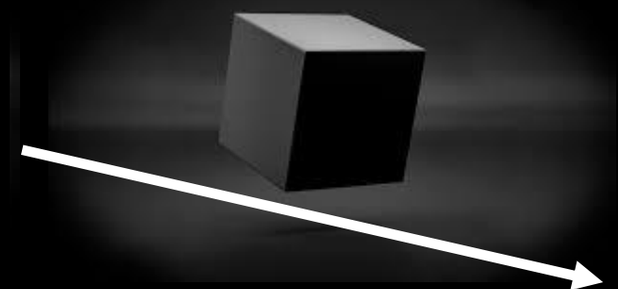
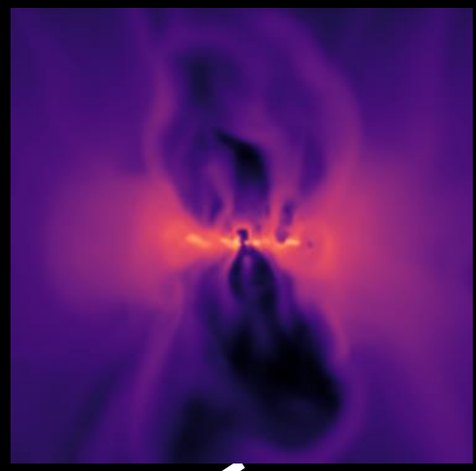
Cosmic Microwave Background
+ Large Scale Structure



Simulation methods

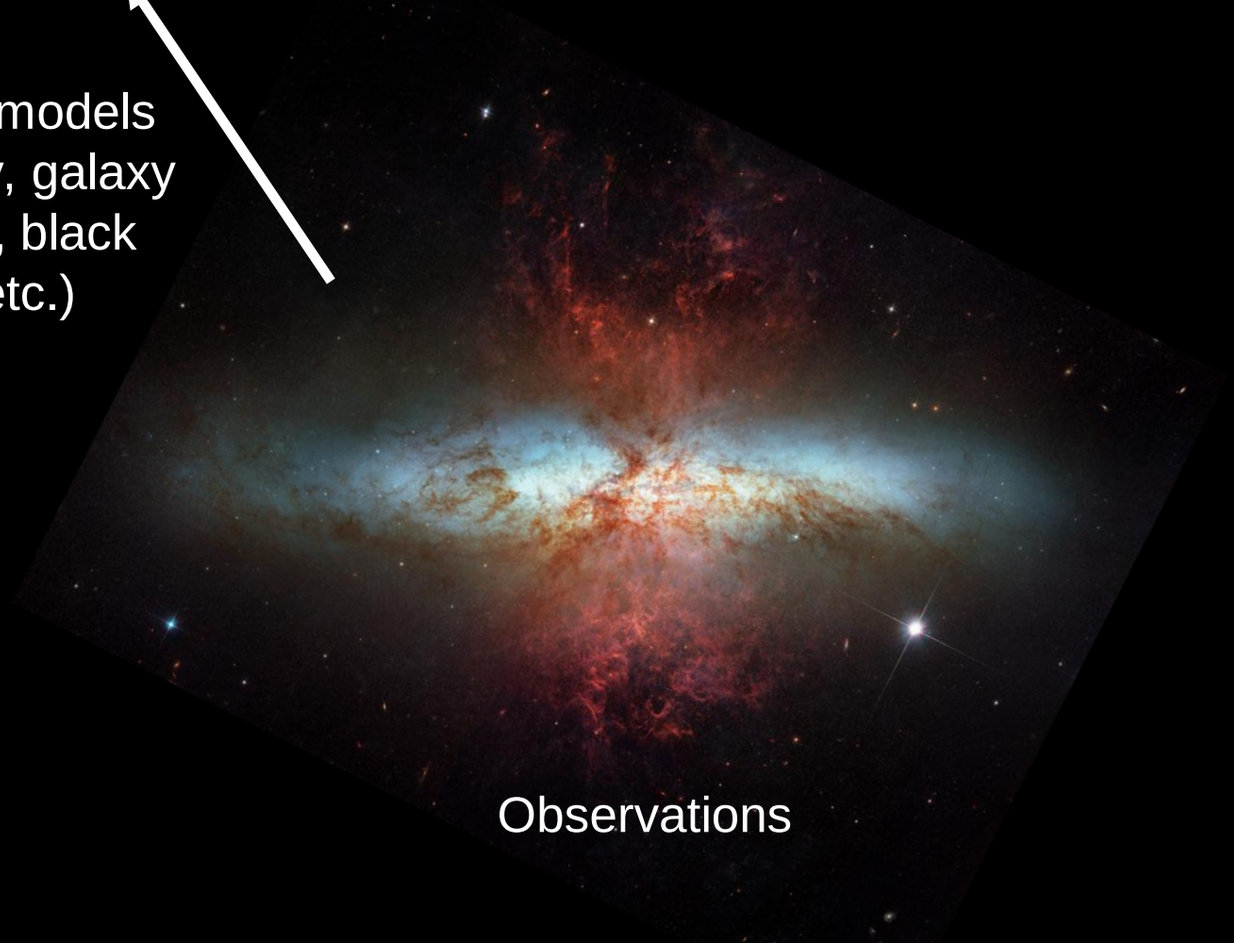


Simulations



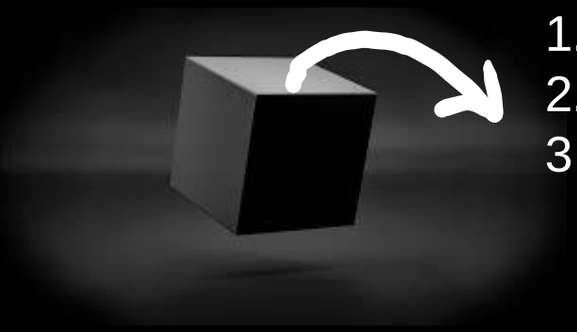
Project into observational data space

Constrain models (cosmology, galaxy formation, black holes etc.)



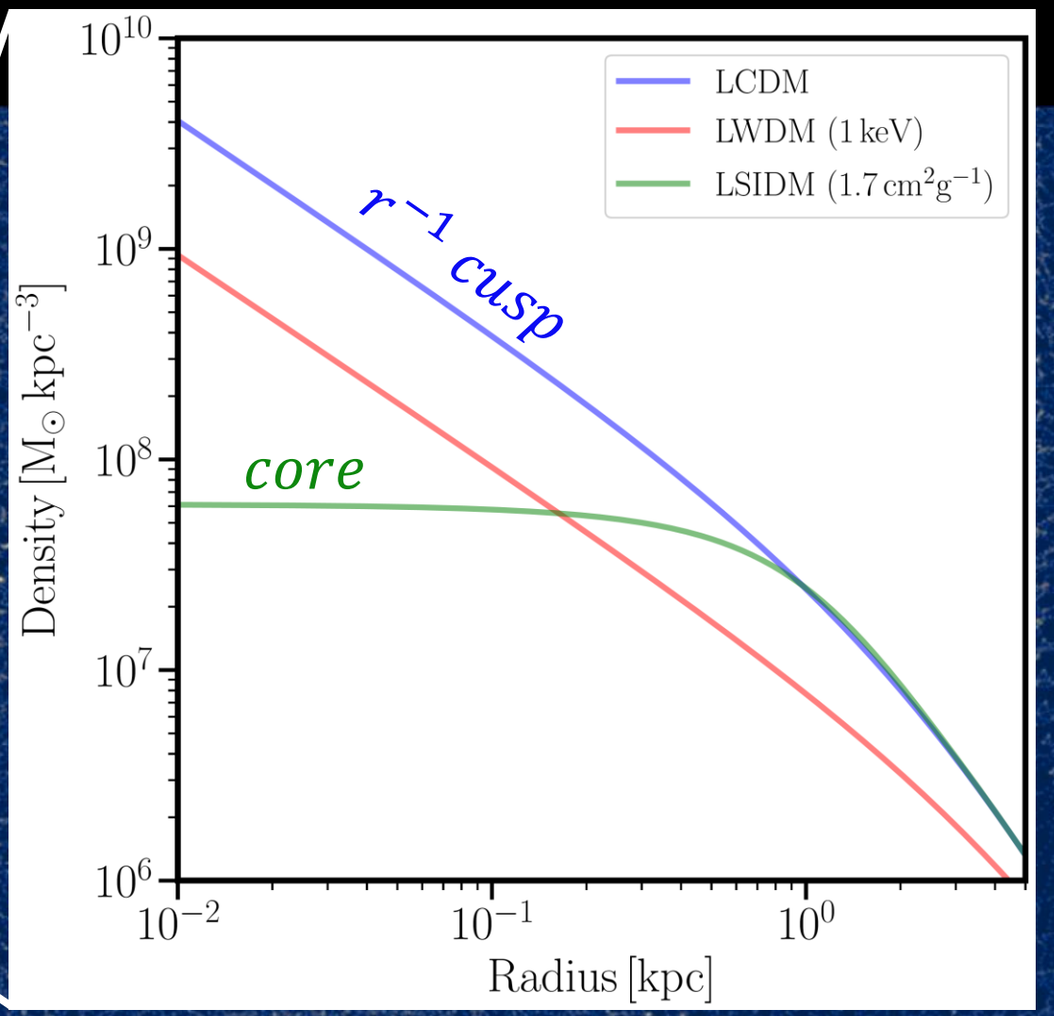
Observations

Simulating dwarf galaxies



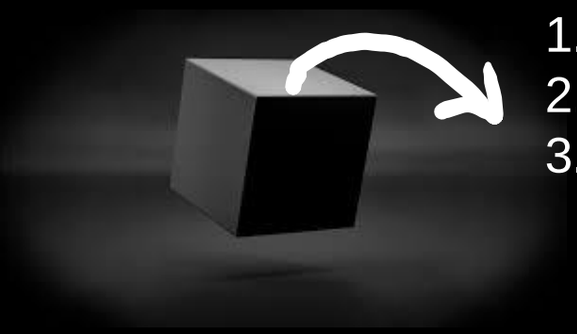
1. Initial conditions from CMB + LSS
2. Newtonian gravity on expanding FLRW metric
3. (Cold) Dark Matter

$z = 23.57$



Movie: Ethan Taylor

Simulating dwarf galaxies



1. Initial conditions from CMB + LSS
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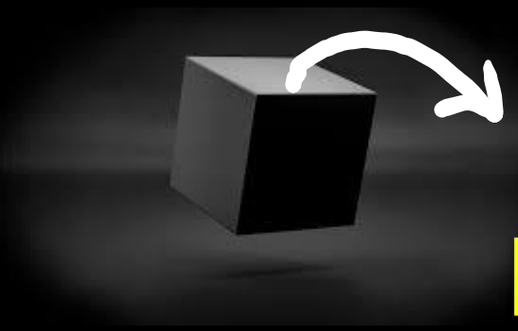
Simulating dwarf galaxies



1. Initial conditions from CMB + LSS
2. Newtonian gravity on expanding FLRW metric
3. (Cold) Dark Matter
4. Gas hydrodynamic forces (Euler equations)
5. Gas cooling, star formation & “feedback” (e.g. winds, SN, radiation, BHs...)

“Subgrid” physics

$z = 23.57$

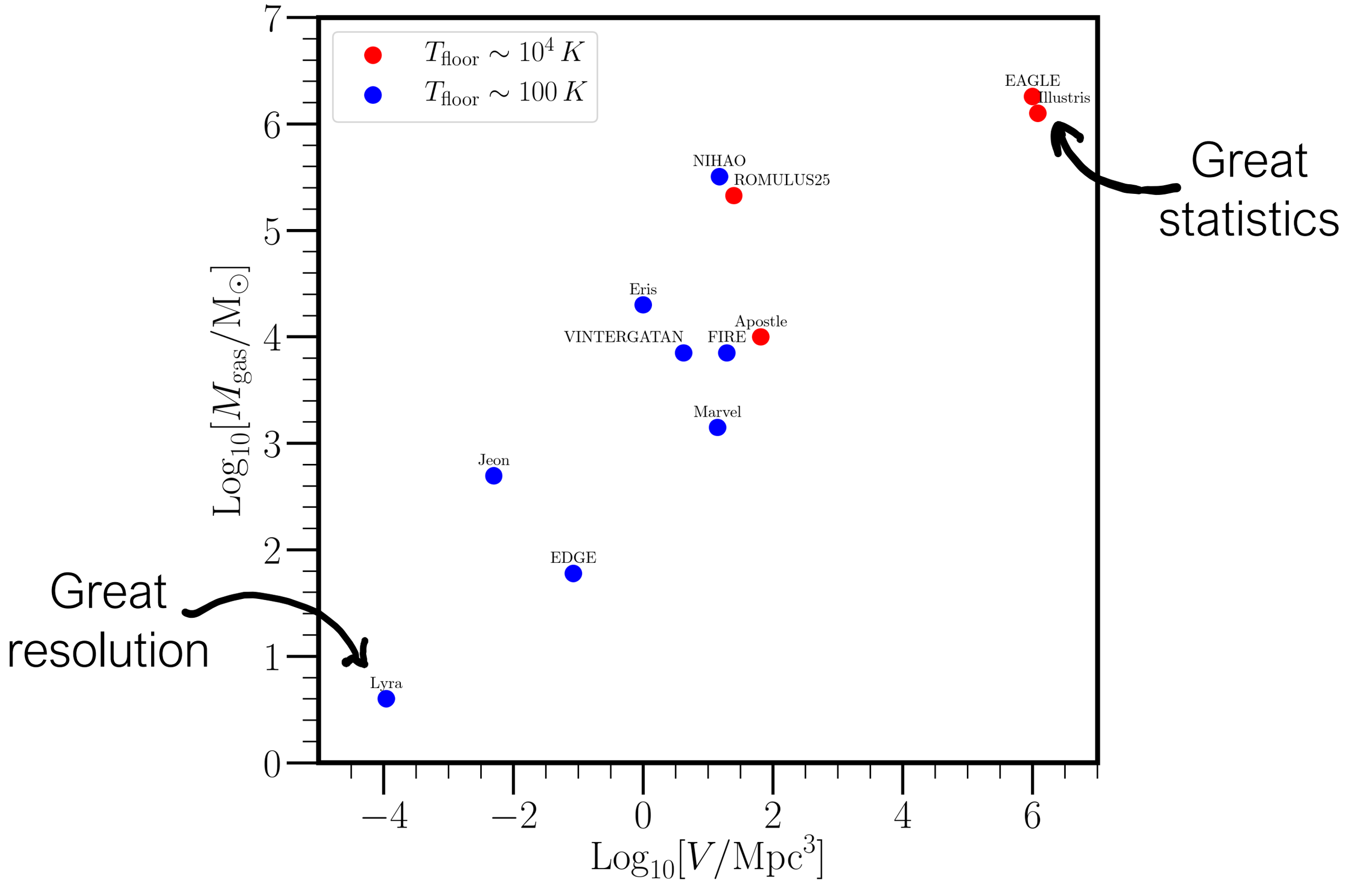
Gas density

- $M_{200} = 1.3 \times 10^9 M_\odot$
- $M_* = 1.4 \times 10^5 M_\odot$
- Reionisation quenched

Movie: Ethan Taylor


SUBGRID PHYSICS

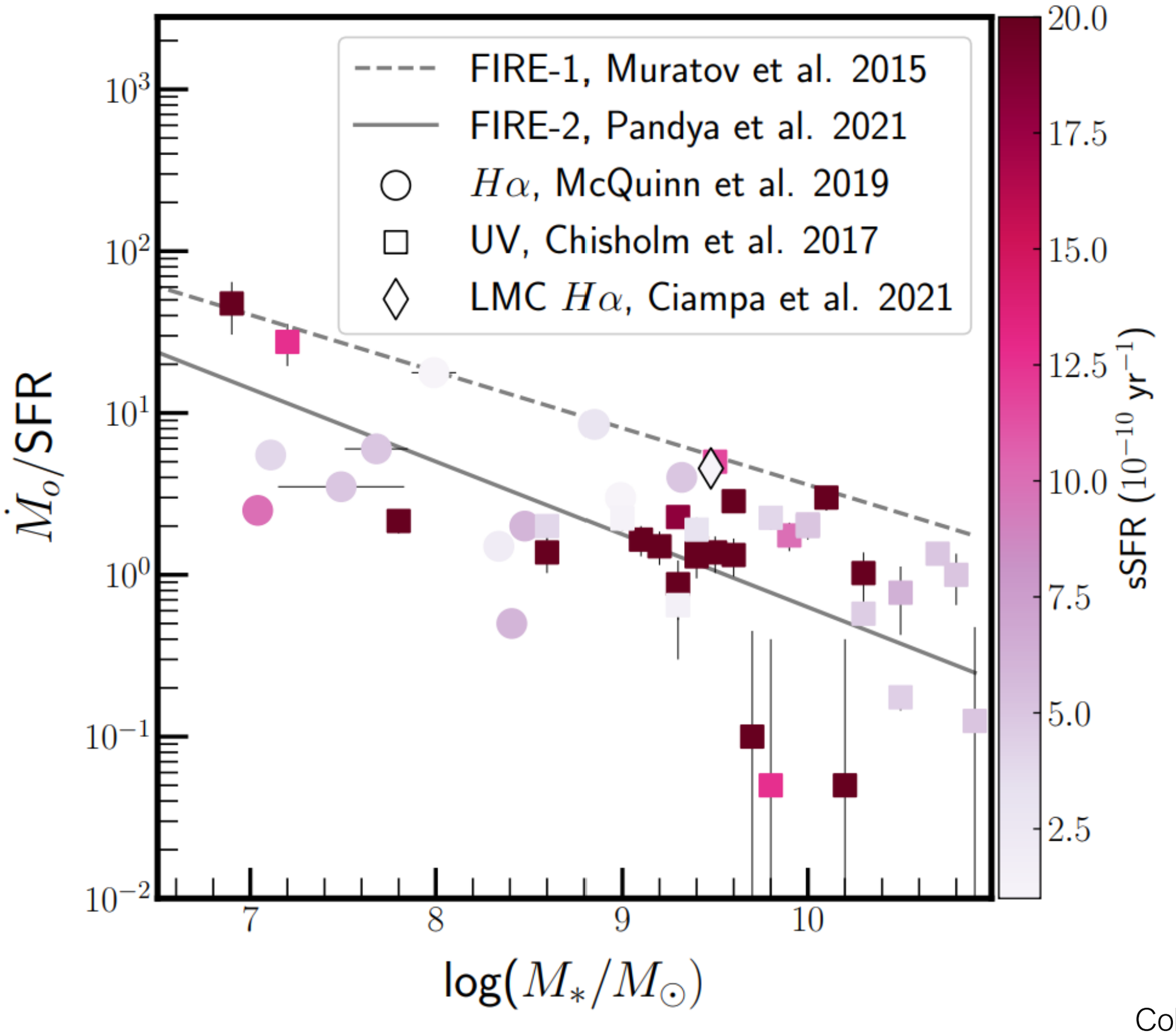
Subgrid | Volume versus resolution



Subgrid | Stellar feedback is observed

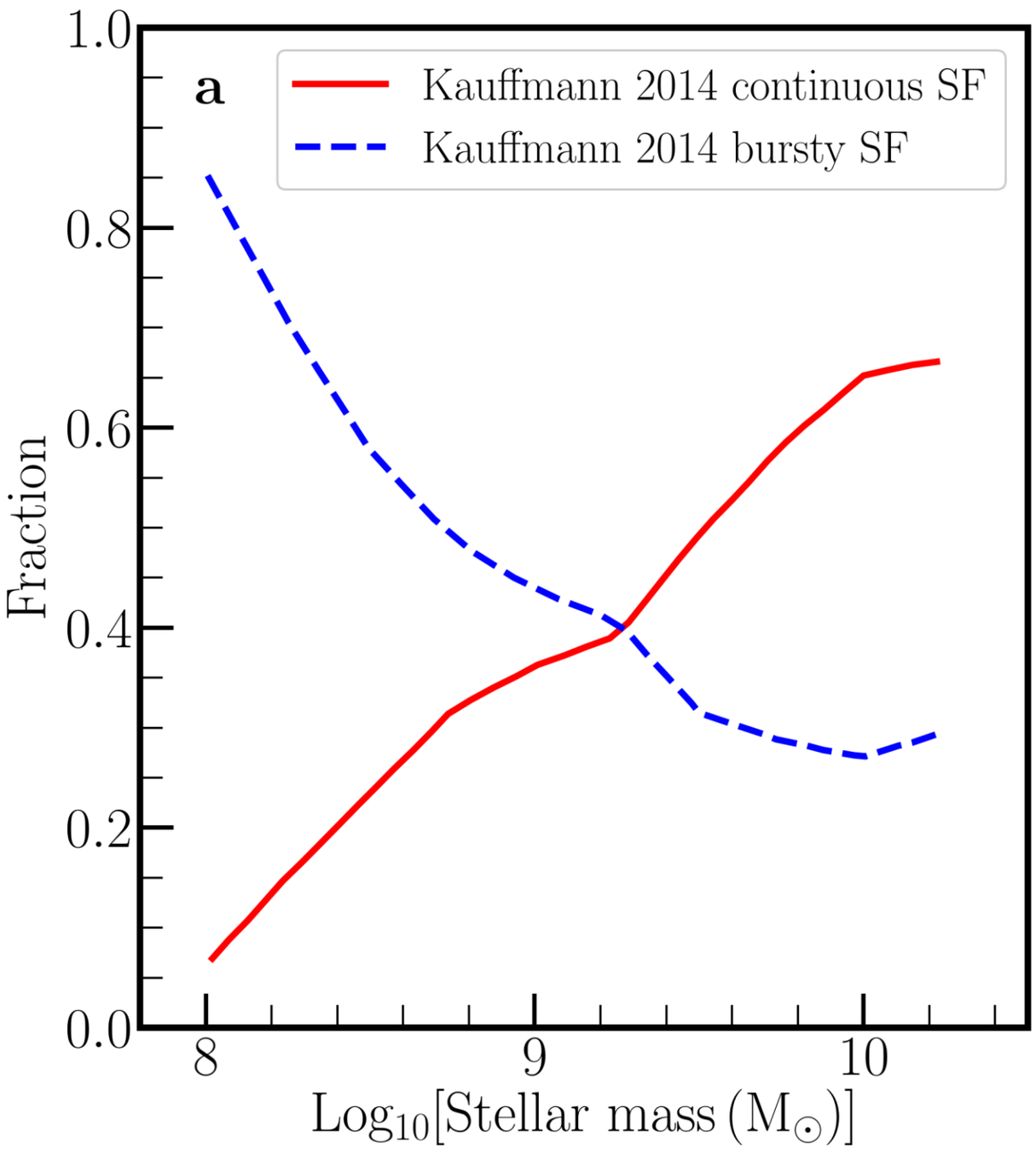
Westmoquette et al. 2009; and see Strickland & Heckman 2009; McQuinn et al. 2018

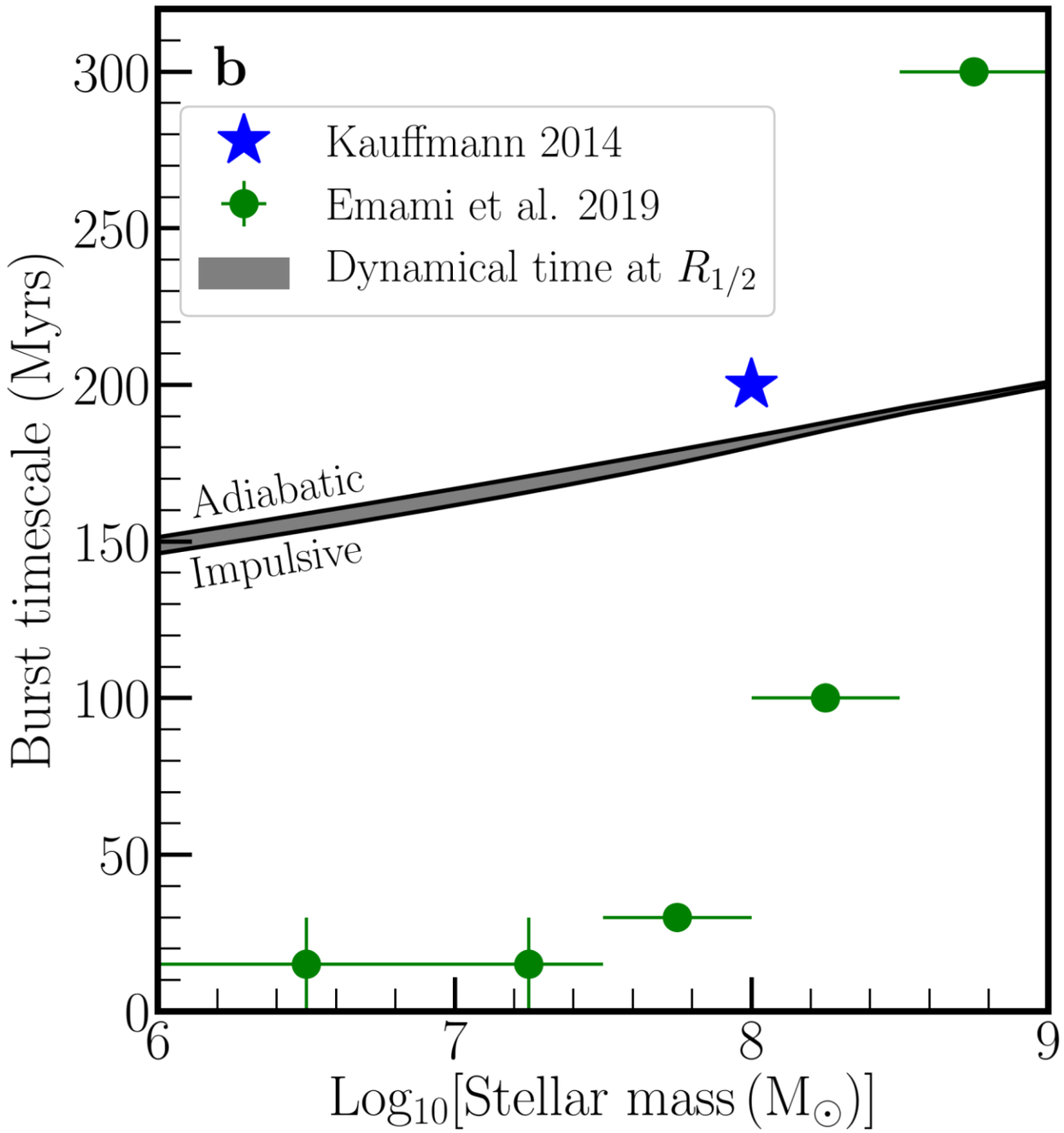
Subgrid | Stellar feedback is observed



Collins & Read 2022

Subgrid | Stellar feedback is observed





Collins & Read 2022

Subgrid | Resolution requirements

2 kpc

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

Subgrid | Resolution requirements

$\Delta x < 50\text{pc}$

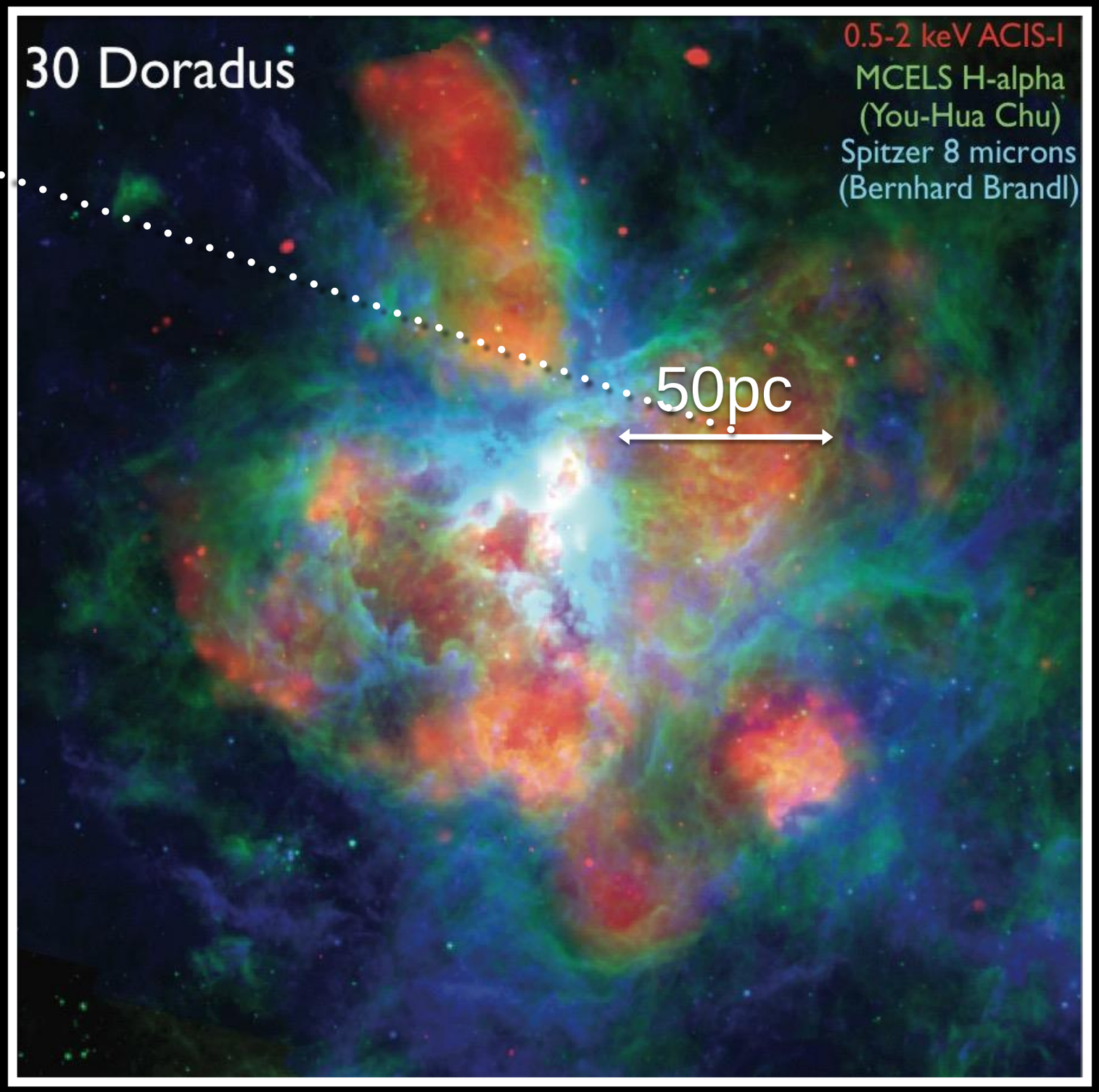


Image composite credit: Leisa Townsley et al. 2006

Subgrid | Resolution requirements

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

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

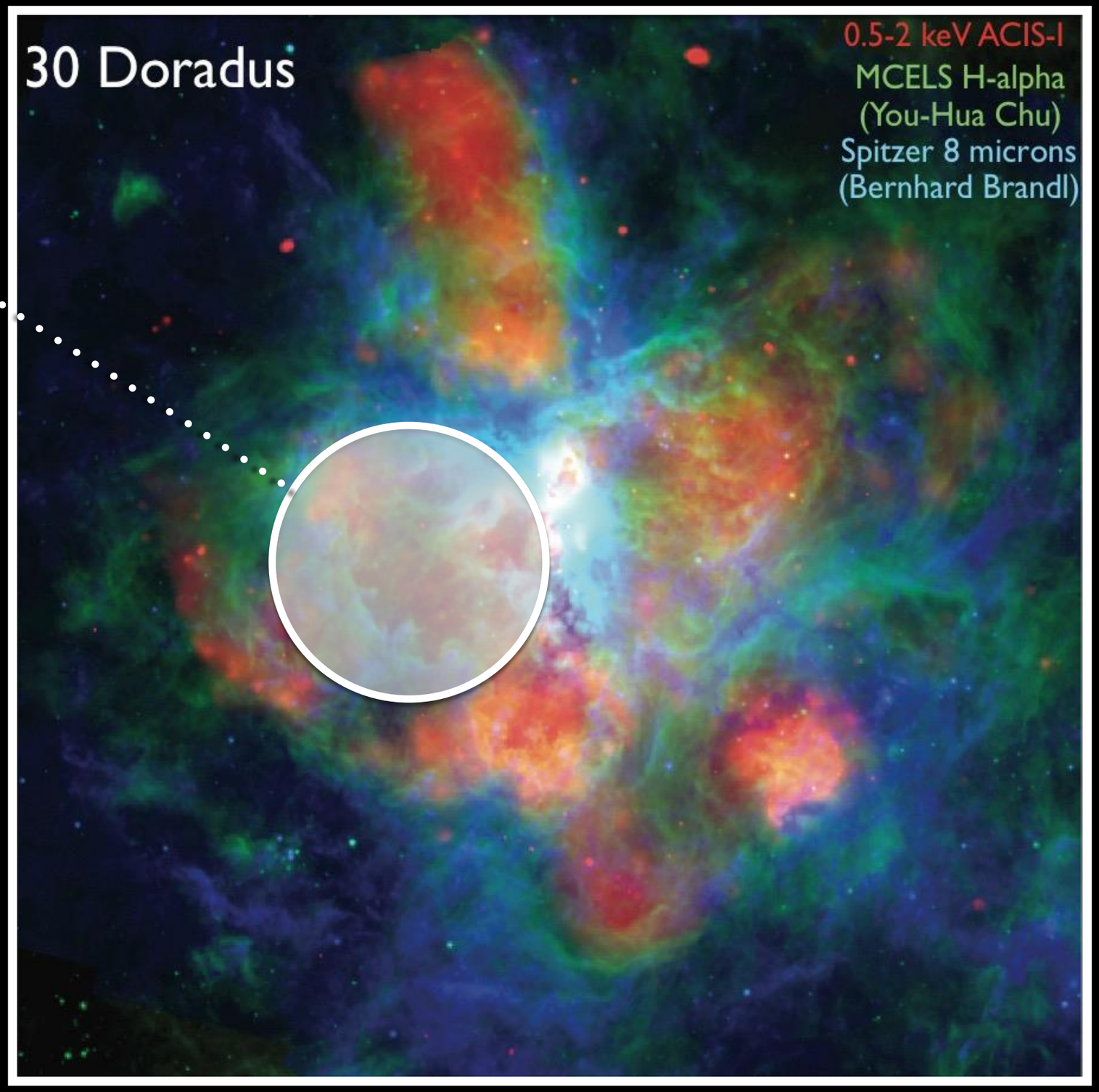


Image composite credit: Leisa Townsley et al. 2006

Subgrid | Resolution requirements

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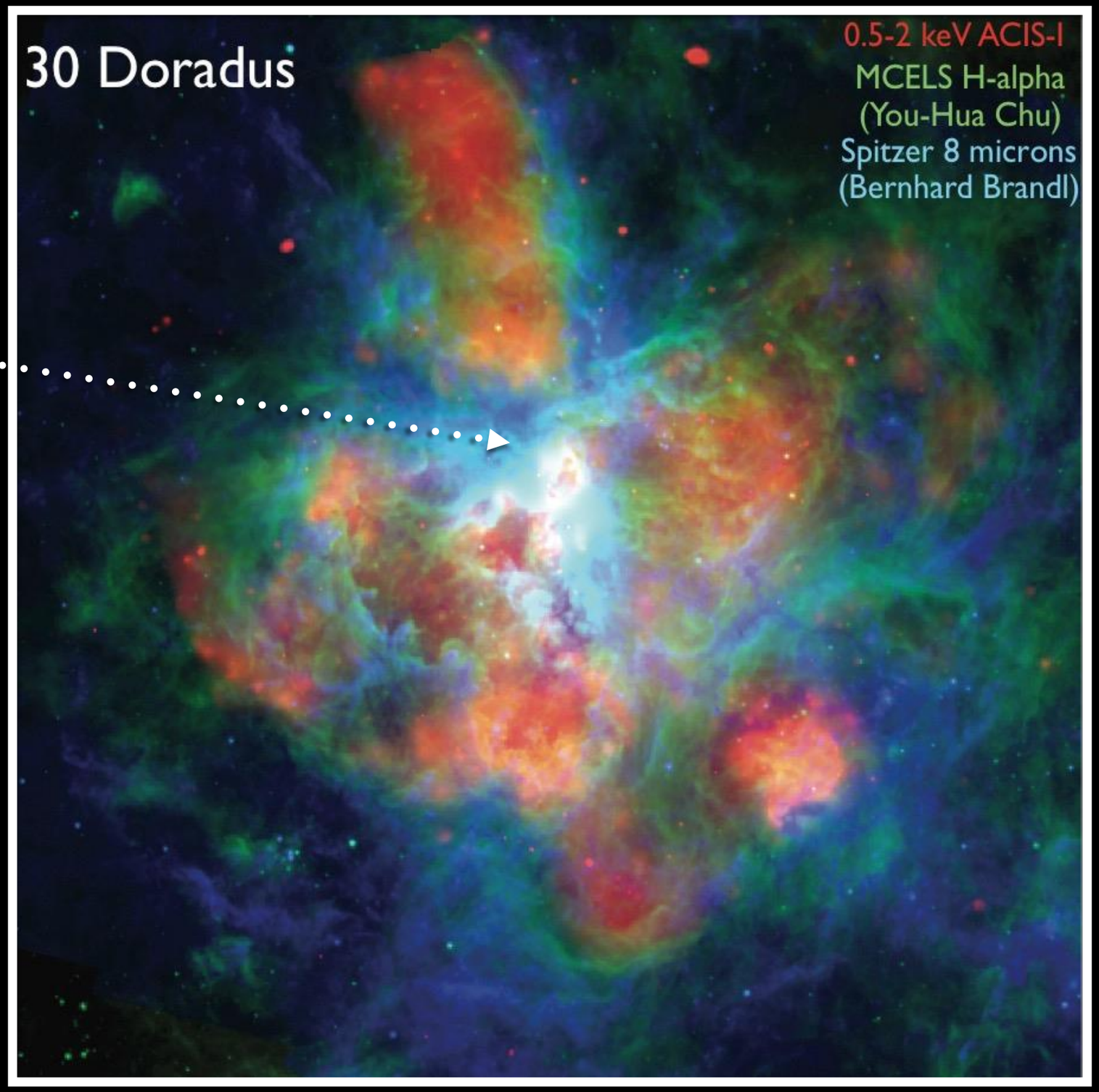
$\Delta x < 50\mathrm{pc}$

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

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

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



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Subgrid | Resolution requirements

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

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

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

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

Subgrid | Overcooling

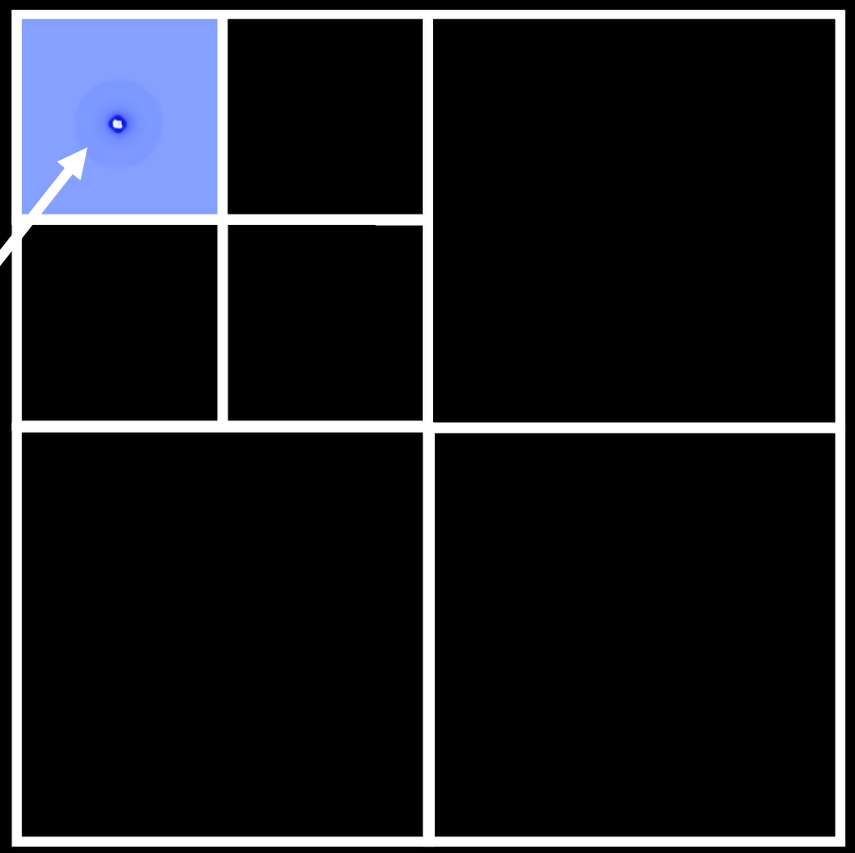
$\Delta x < 50\mathrm{pc}$

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

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

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

$\Delta x = 100\mathrm{pc} | \rho_{\mathrm{th}} = 10\mathrm{atoms/cc}$

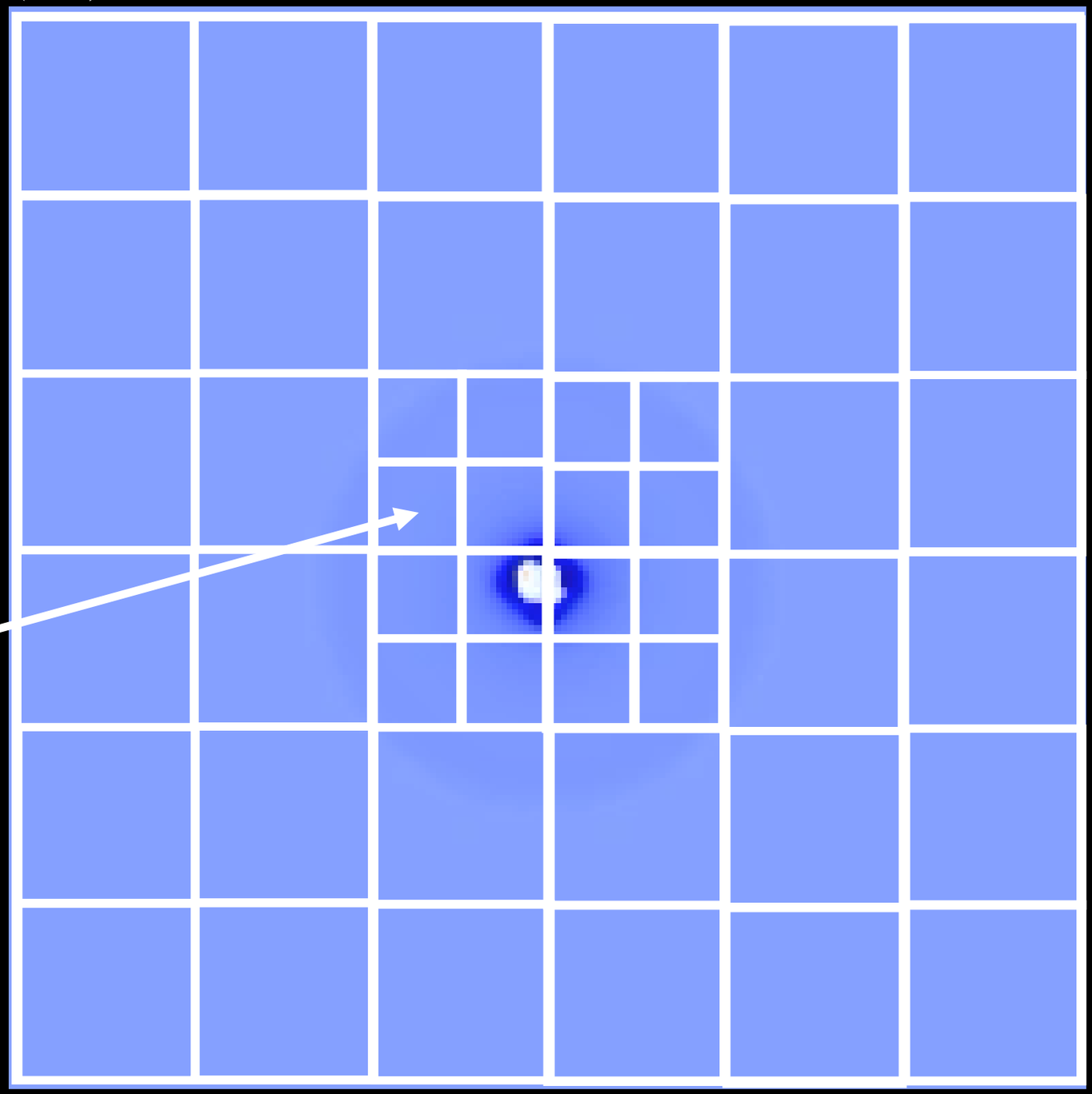


$T_{\mathrm{cell}} \sim 2 \times 10^{4}\mathrm{K}$

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

Subgrid | Overcooling

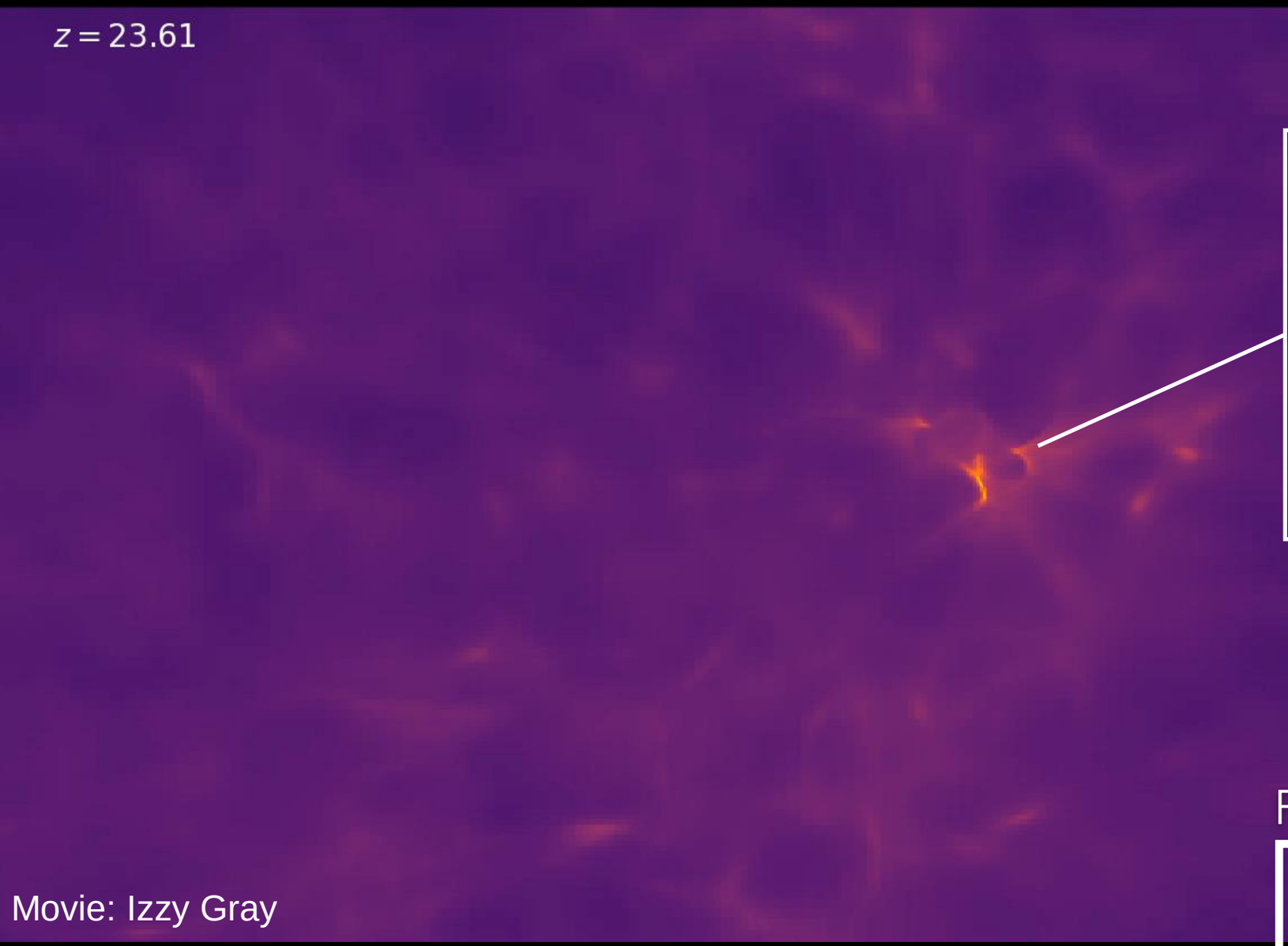
$\Delta x = 10\mathrm{pc} | \rho_{\mathrm{th}} = 100\mathrm{atoms/cc}$



$T_{\mathrm{cell}} > 10^6\mathrm{K}$

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

Subgrid | Meeting the requirements



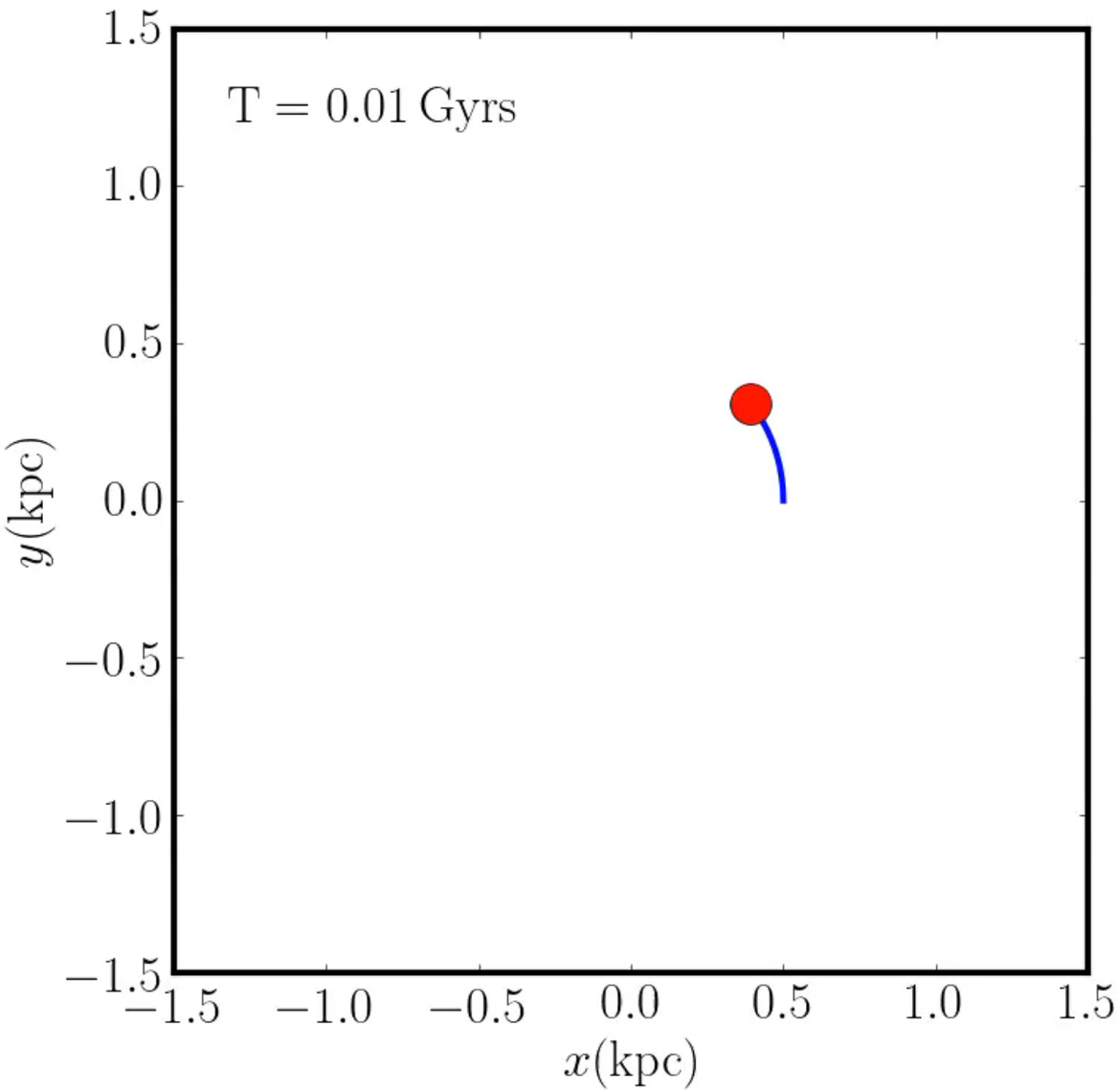
- $M_{200} = 5 \times 10^9 M_\odot$
- $M_* = 8.7 \times 10^6 M_\odot$
- Survives reionisation

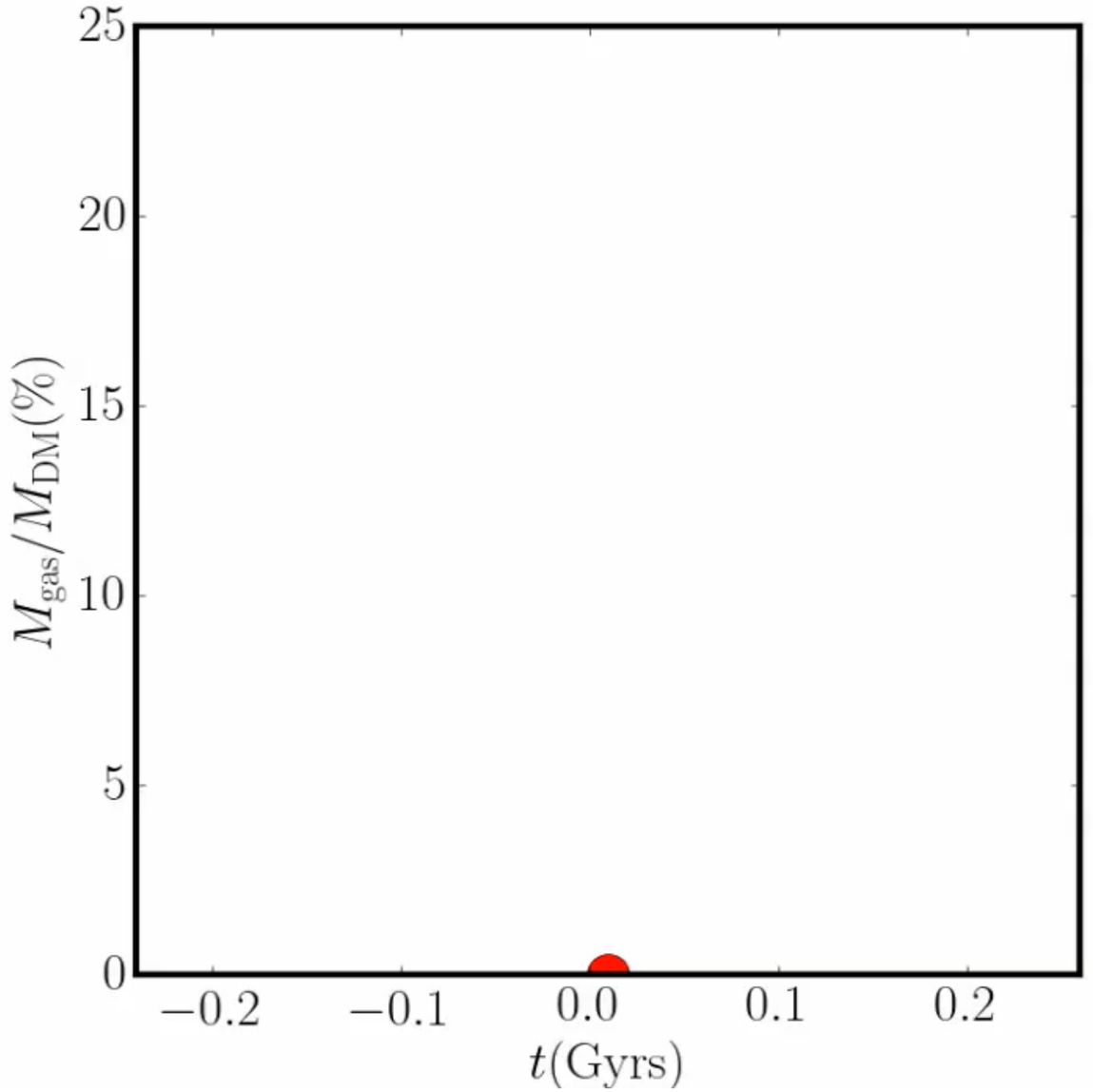
Fiducial	High resolution
$\Delta x = 3\mathrm{pc}$	$\Delta x = 3\mathrm{pc}$
$M_{\mathrm{bar}} = 161\mathrm{M}_\odot$	$M_{\mathrm{bar}} = 20\mathrm{M}_\odot$
$M_{\mathrm{dm}} = 945\mathrm{M}_\odot$	$M_{\mathrm{dm}} = 118\mathrm{M}_\odot$

Predictions

#1. Dark matter heating

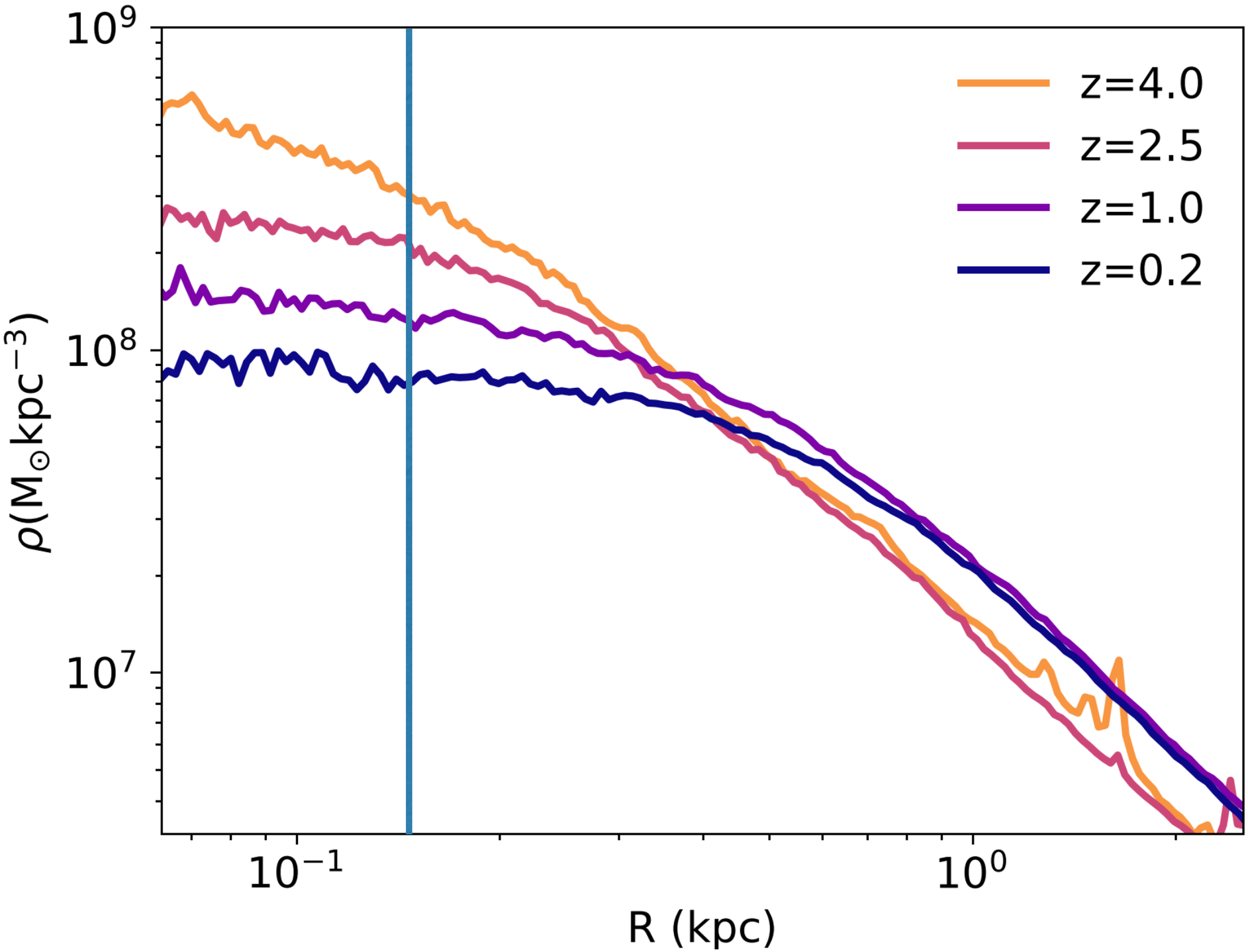
Predictions | Dark matter heating





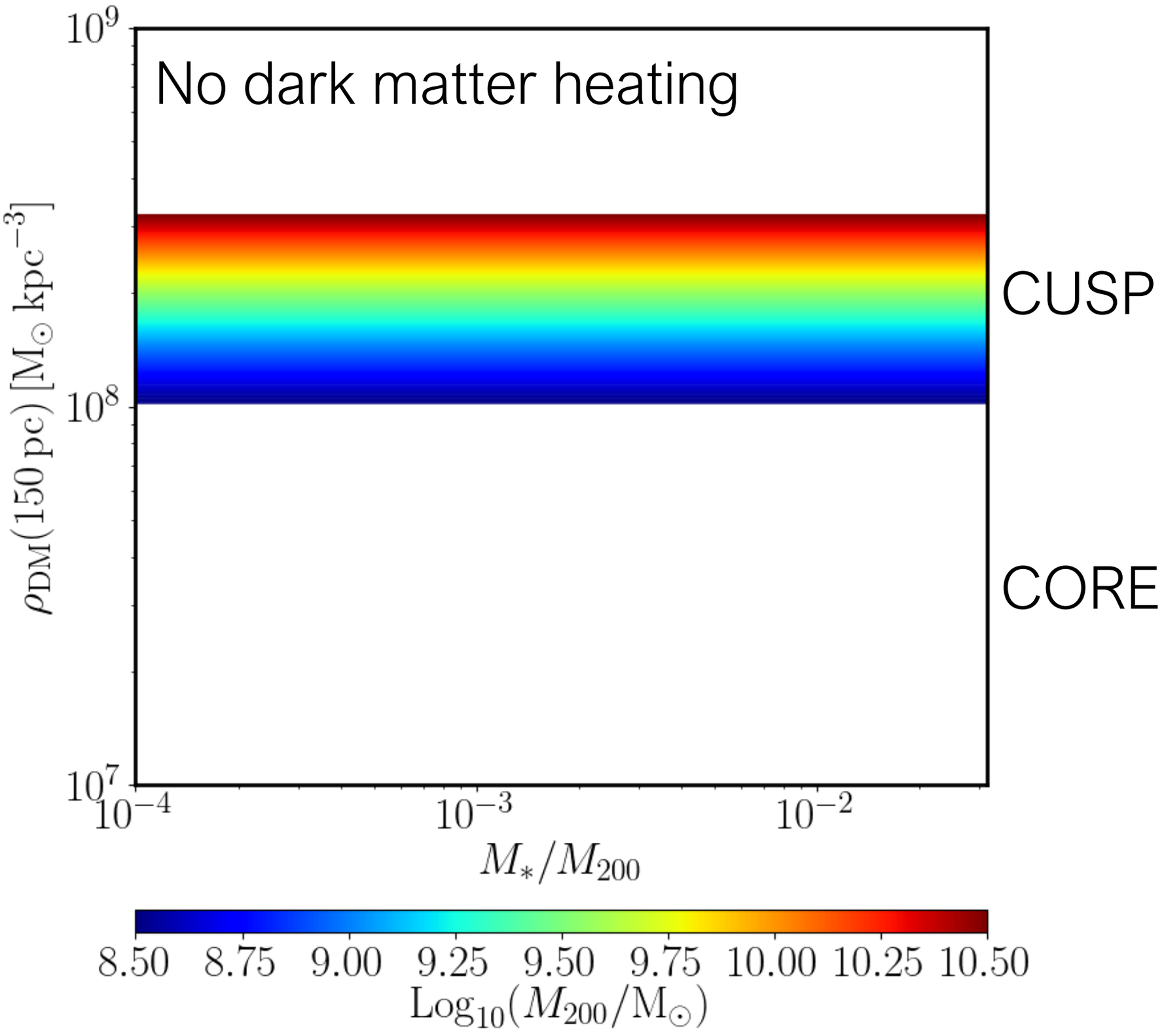
e.g. Navarro et al. 1996; Read & Gilmore 2005; Pontzen & Governato 2012; Read et al. 2016

Predictions | Dark matter heating

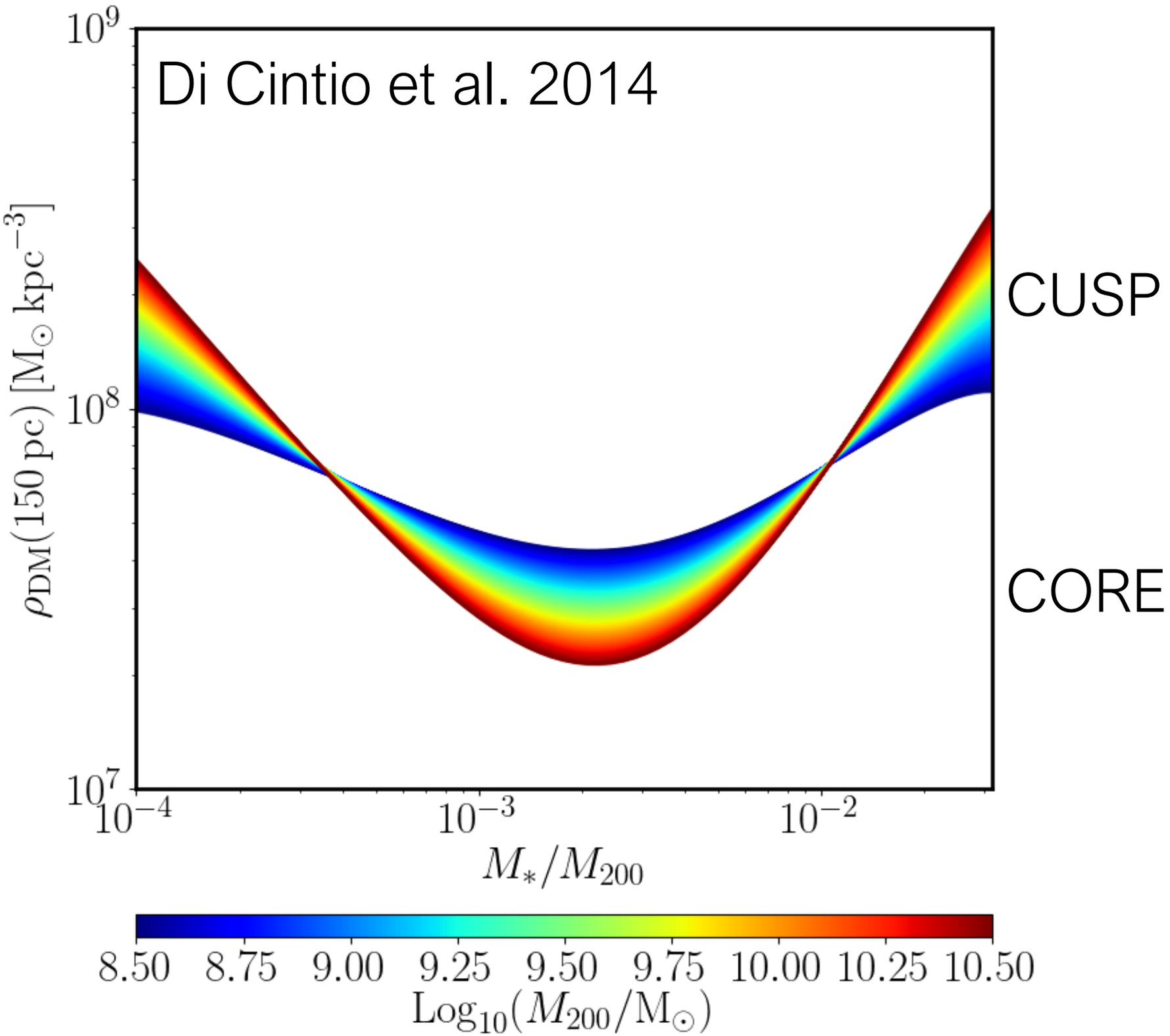


Credit: Izzy Gray

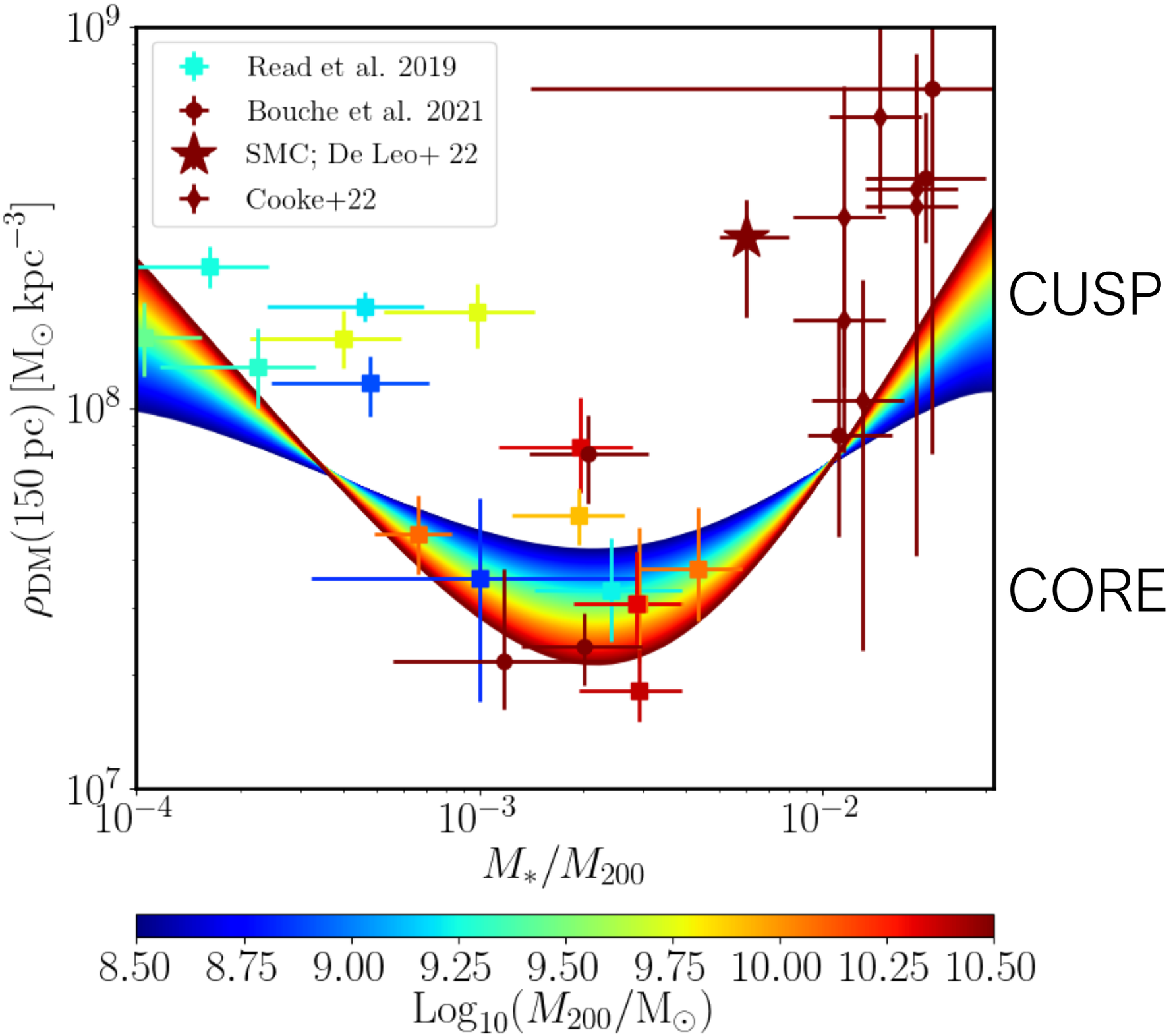
Predictions | Dark matter heating



Predictions | Dark matter heating



Predictions | Dark matter heating



CUSP

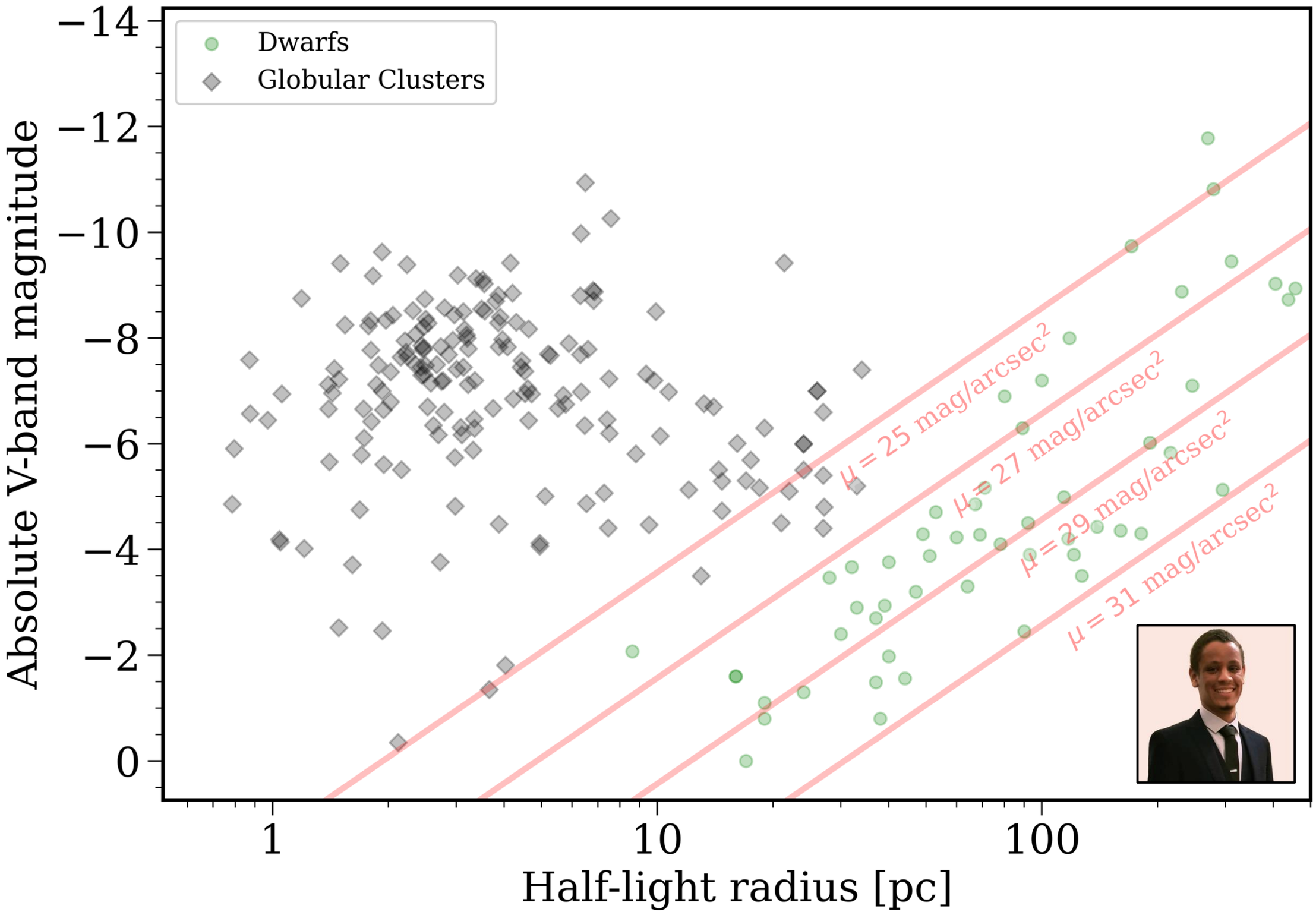
CORE

Read et al. 2019, De Leo et al. 2023

Predictions

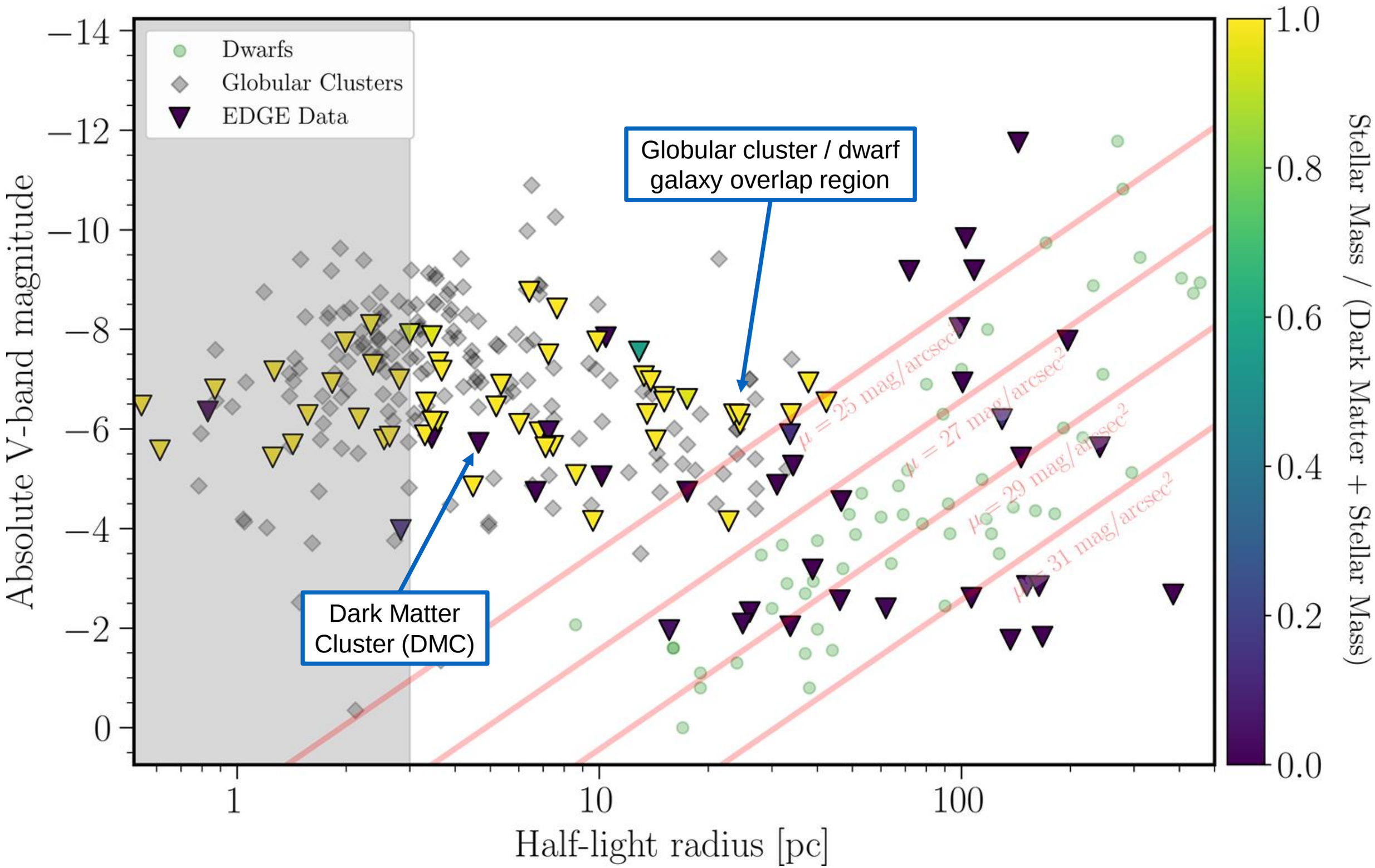
#2. Emergence of dwarfs & star clusters

Predictions | Dwarfs & Star Clusters



Taylor et al. 2023 in prep.

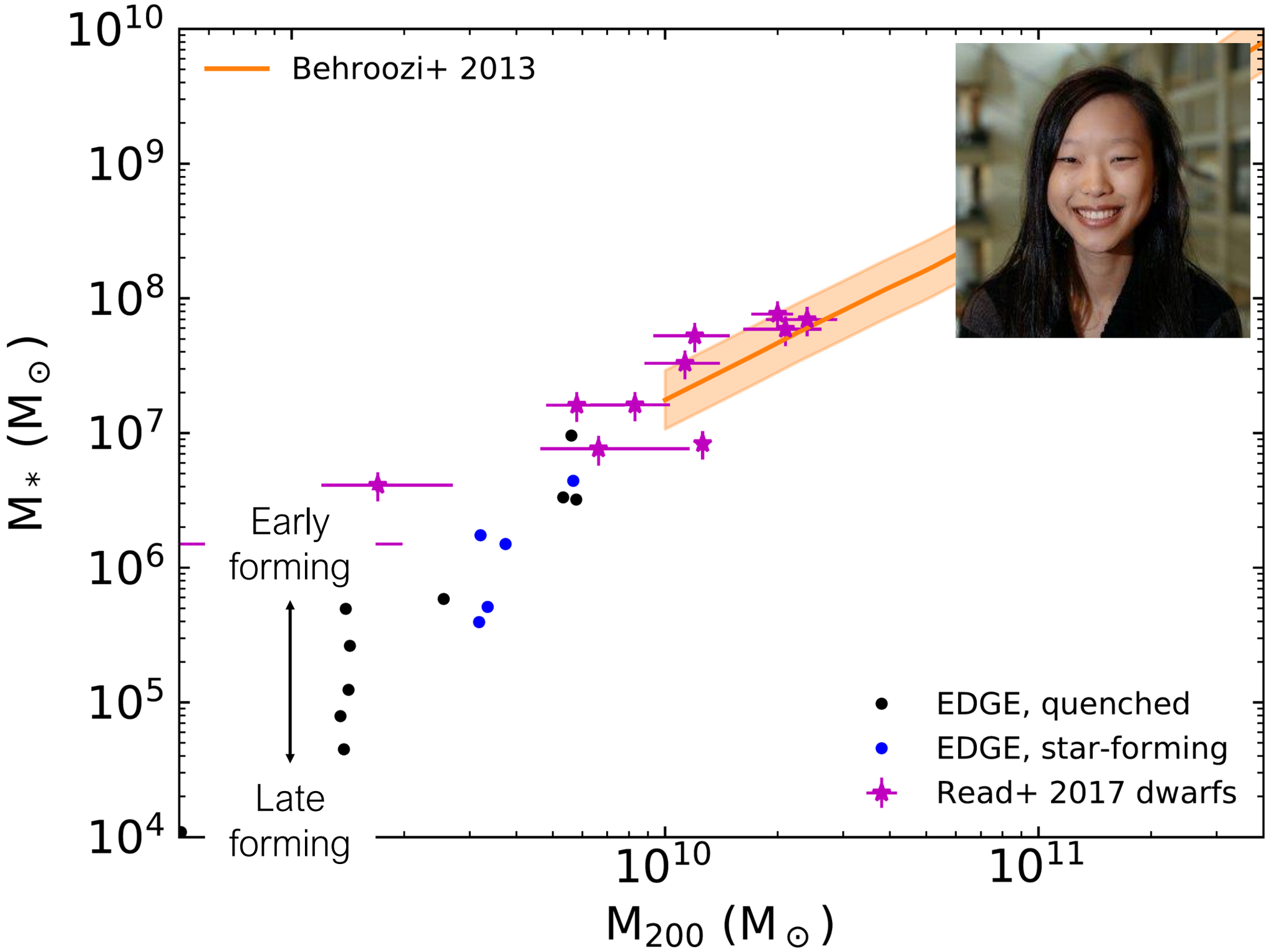
Predictions | Dwarfs & Star Clusters



Taylor et al. 2023 in prep.

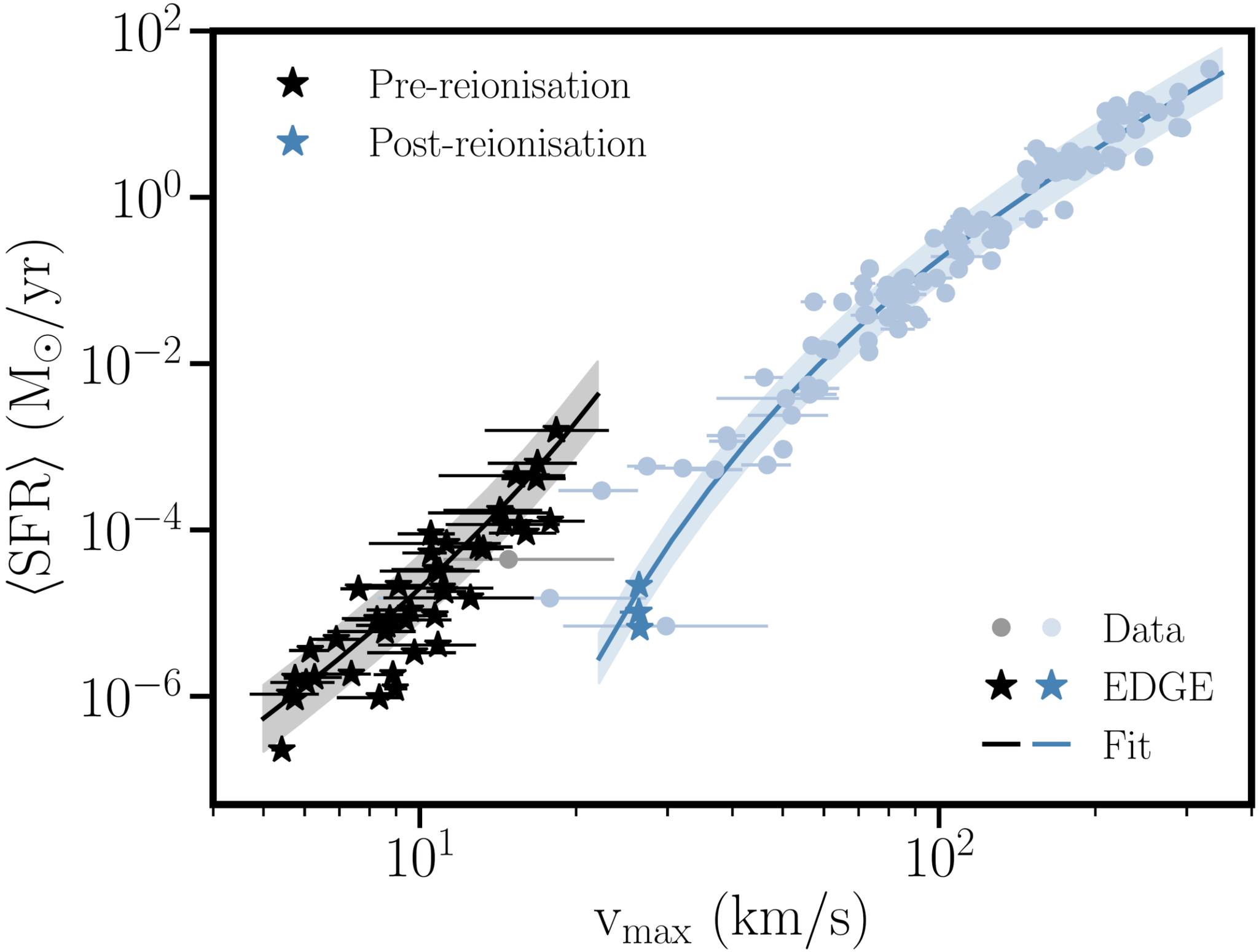
Towards Volume and Resolution

Volume & resolution: DarkLight



Kim et al. 2023, in prep.

Volume & resolution: DarkLight



Kim et al. 2023, in prep.

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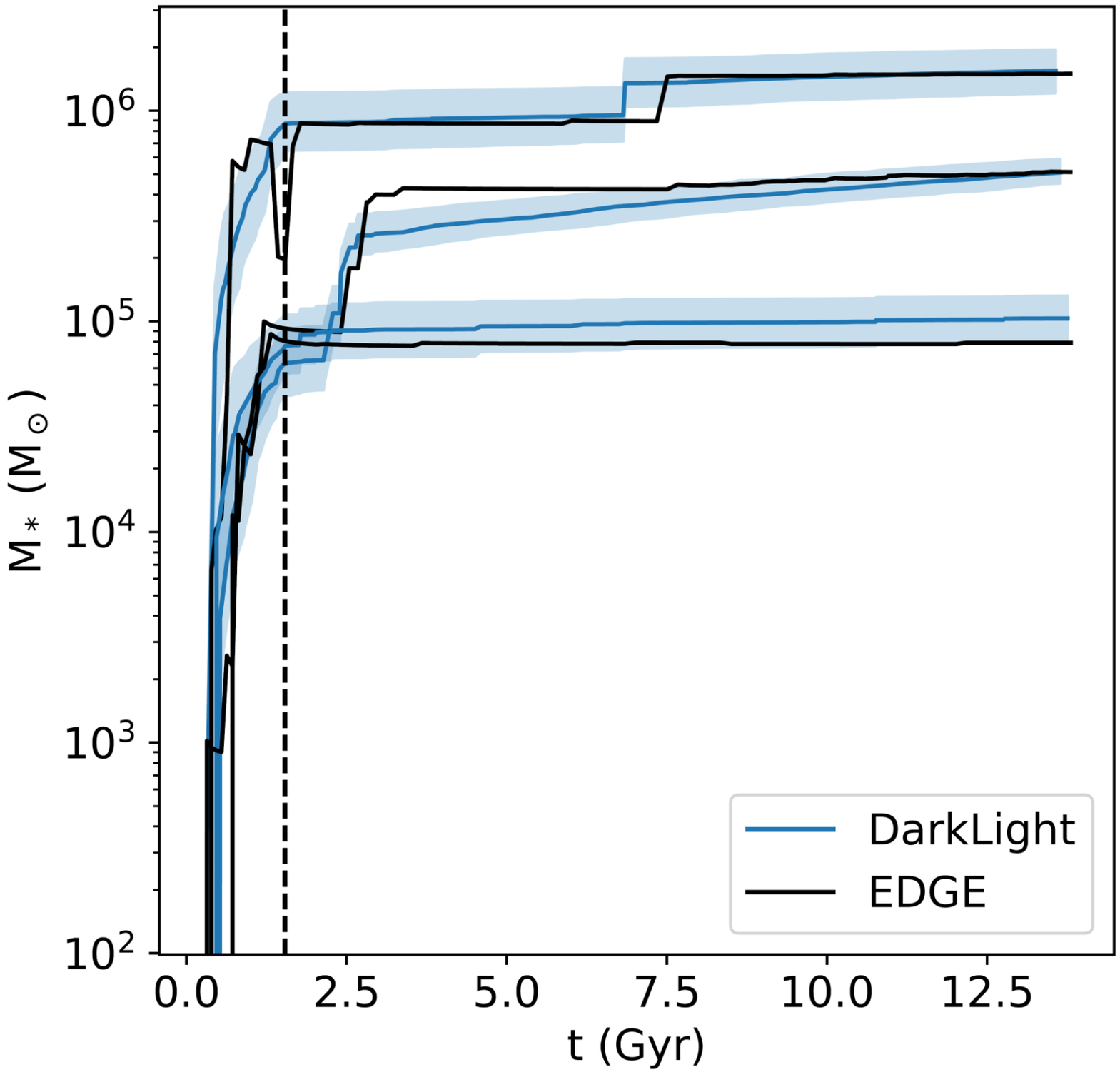

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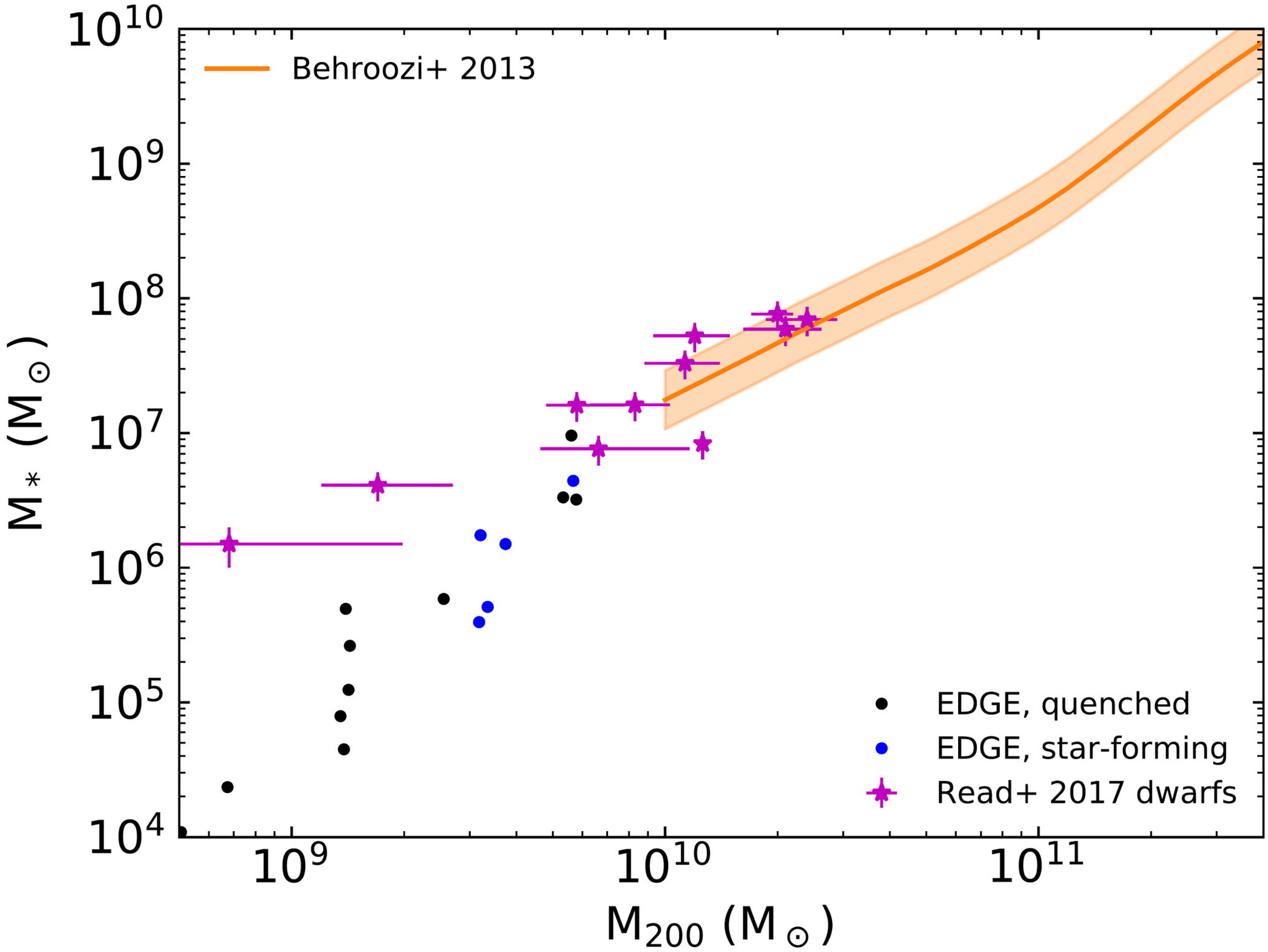

Kim et al. 2023, in prep.

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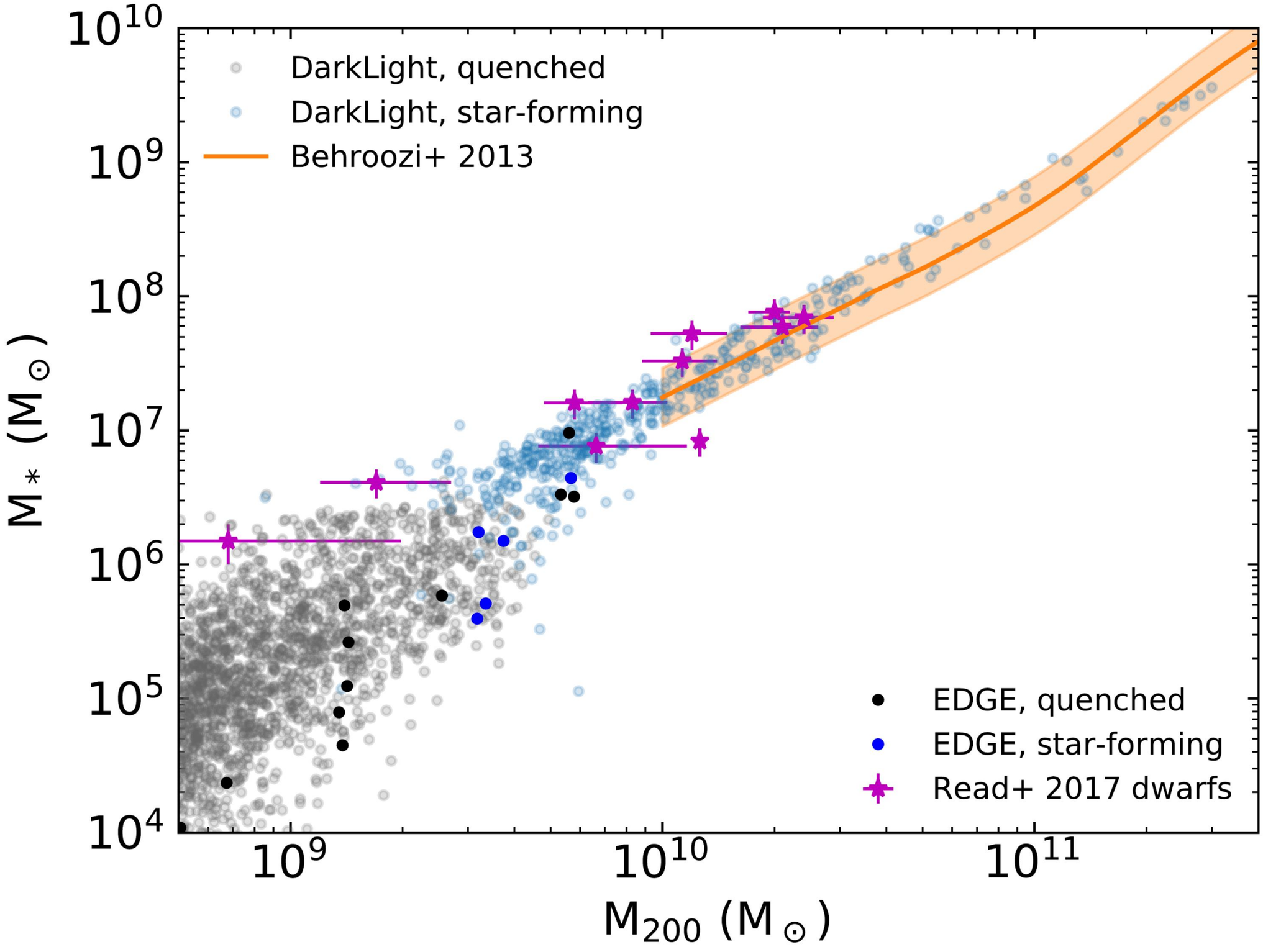

Kim et al. 2023, in prep.

Summary

Take home messages

1. The latest high-resolution simulations of dwarf galaxies (e.g. FIRE, EDGE, Marvel, Lyra) resolve the sites of star formation & feedback.
   [This is a key milestone. Such simulations can be tested and calibrated against star forming regions. It is not trivial that realistic galaxies emerge from such simulations.]

2. The latest simulations give a remarkable match to data for nearby dwarfs. And, they make a number of *testable predictions:*
   - *DM is "heated up" (most efficient for* $M_{200} \sim 10^{10} M_{\odot}, \frac{M_*}{M_{200}} \sim 10^{-3}$ *)*
   - *Star clusters (no DM) dwarfs (DM) overlap at* $M_V \sim [-5, -6]$ *and* $r_h \sim 5$-30*pc.*

3. Can have great resolution + great volume by combining detailed zoom simulations with semi-empirical models like DarkLight. This is key for making predictions for dwarf galaxy populations.

Justin I. Read