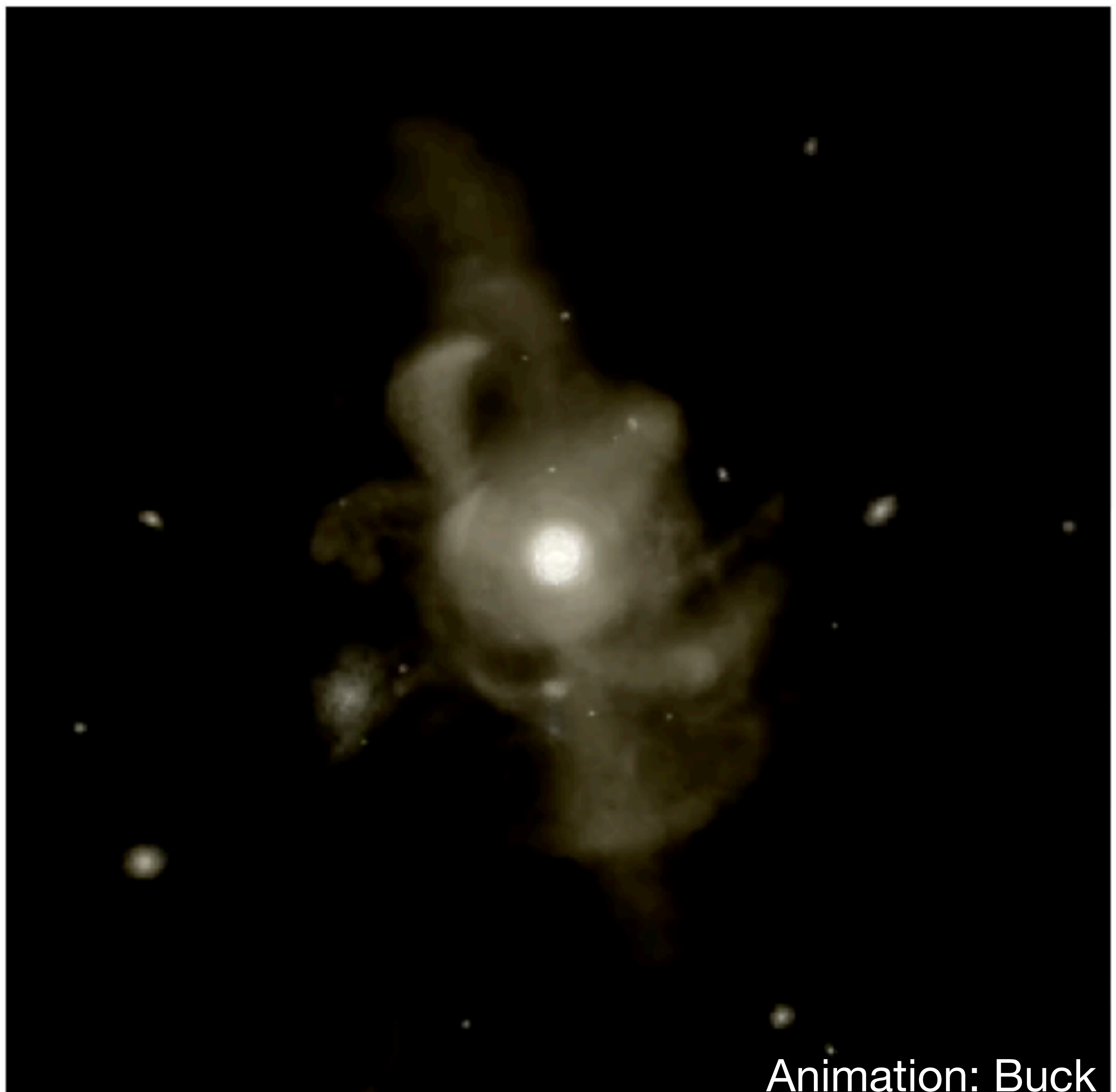
High-resolution cosmological simulations: The impact of the host galaxy on Galactic dwarf galaxies

14.06.2018 CLUES meeting Tenerife

Tobias Buck

buck@mpia.de



Animation: Buck

Andrea Macciò,
Aura Obreja,
Aaron Dutton,
Jonas Frings,
Hans-Walter Rix

Max-Planck-Institut für Astronomie Heidelberg
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SFB 881

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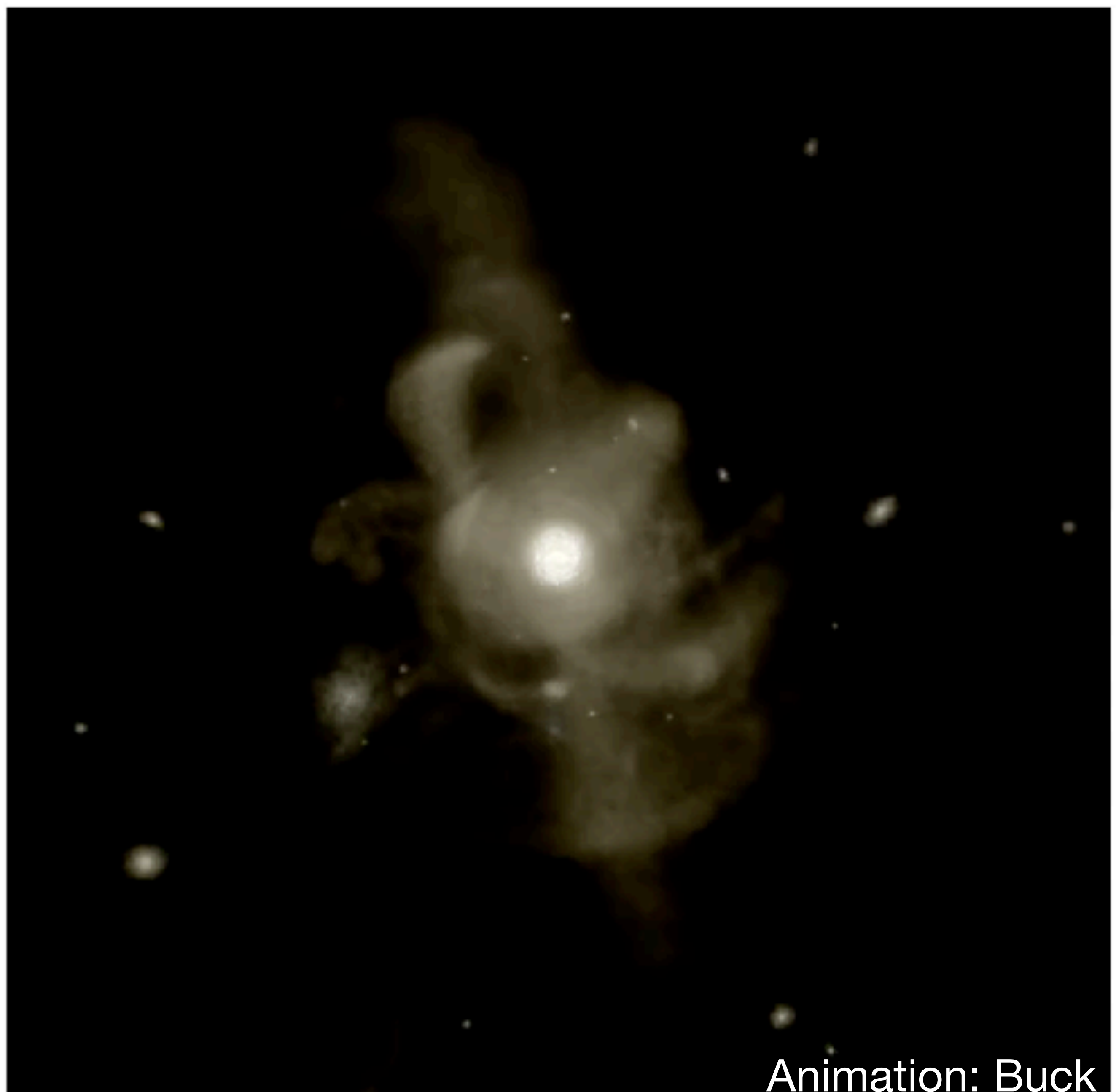

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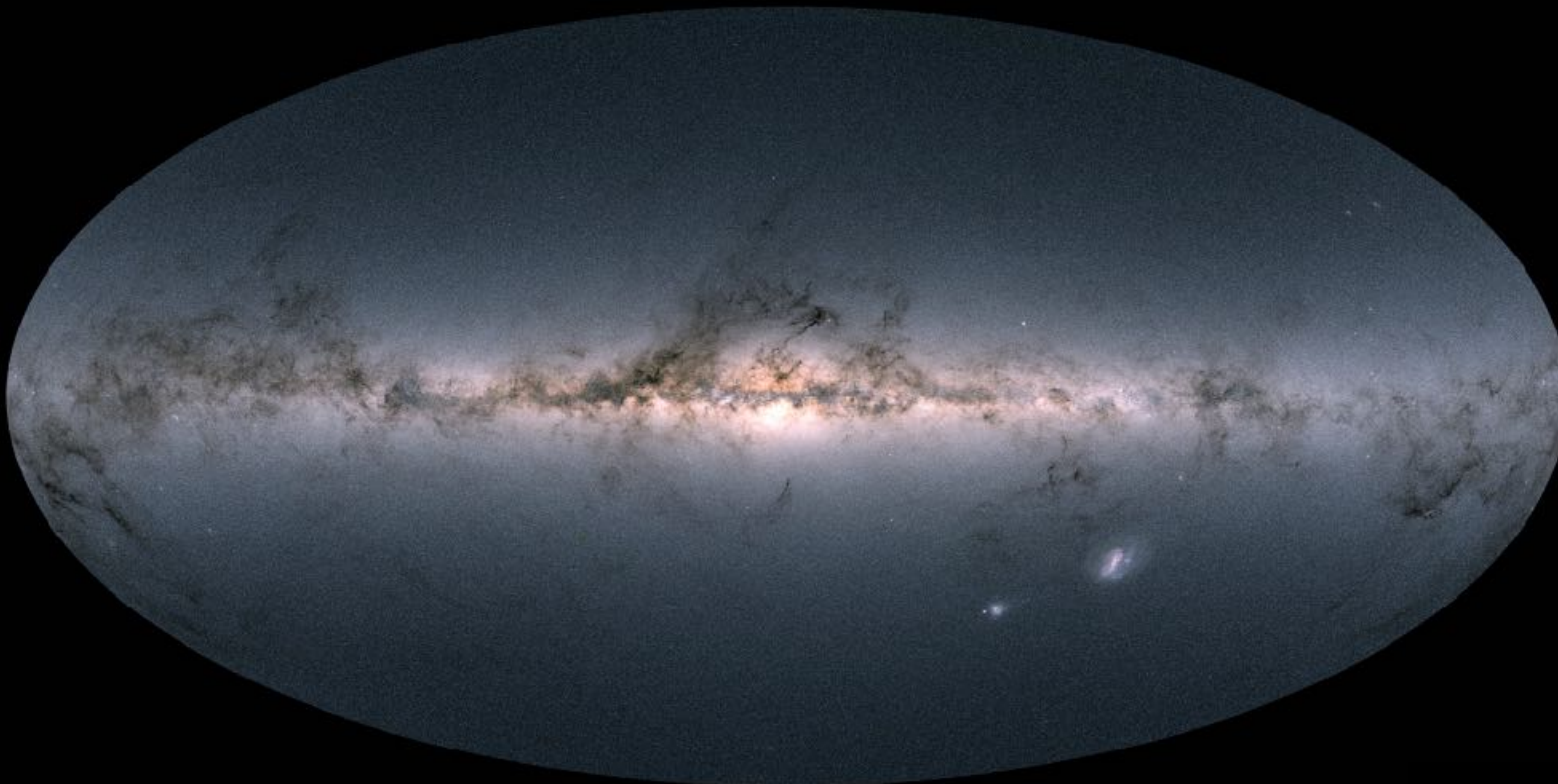
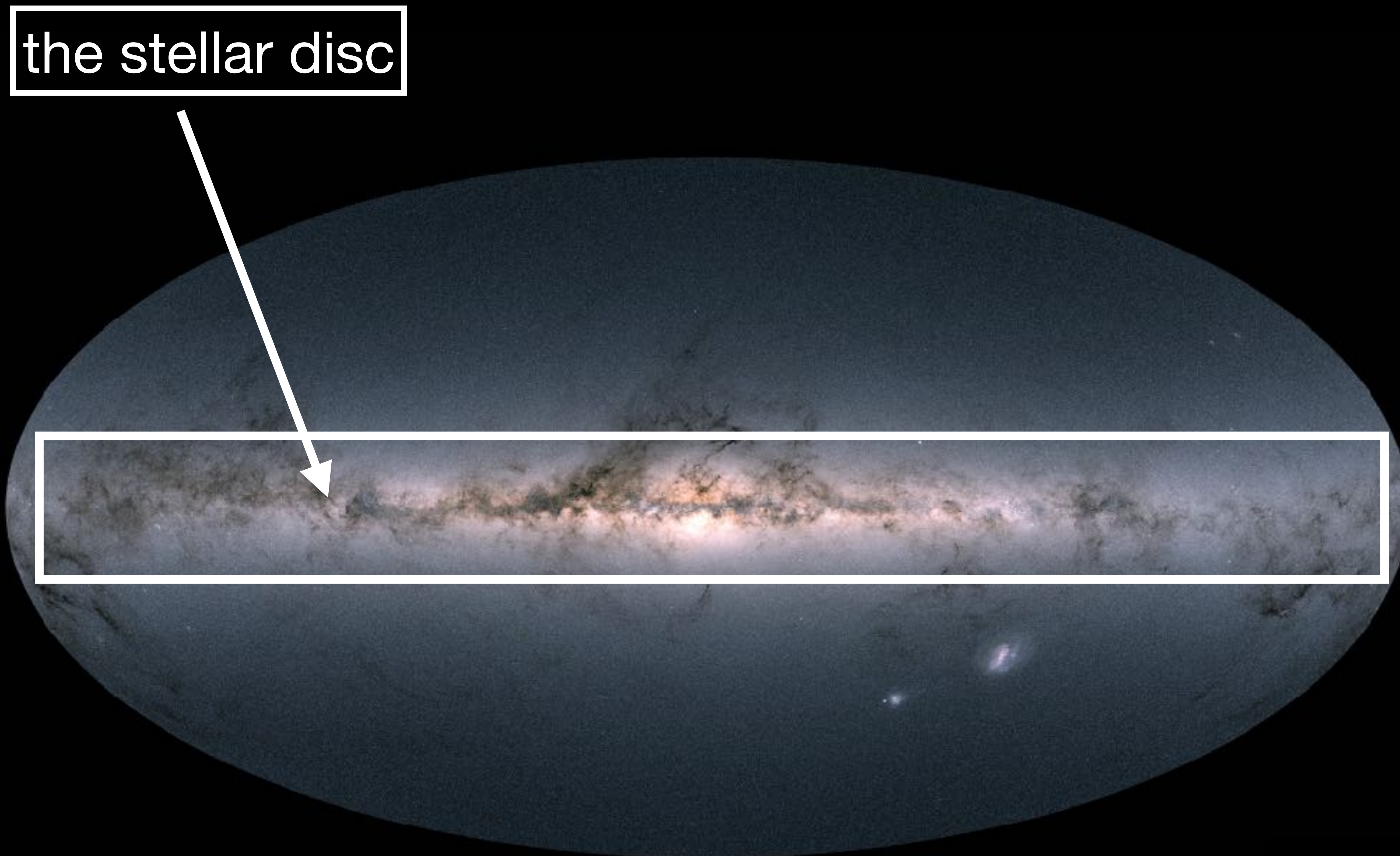
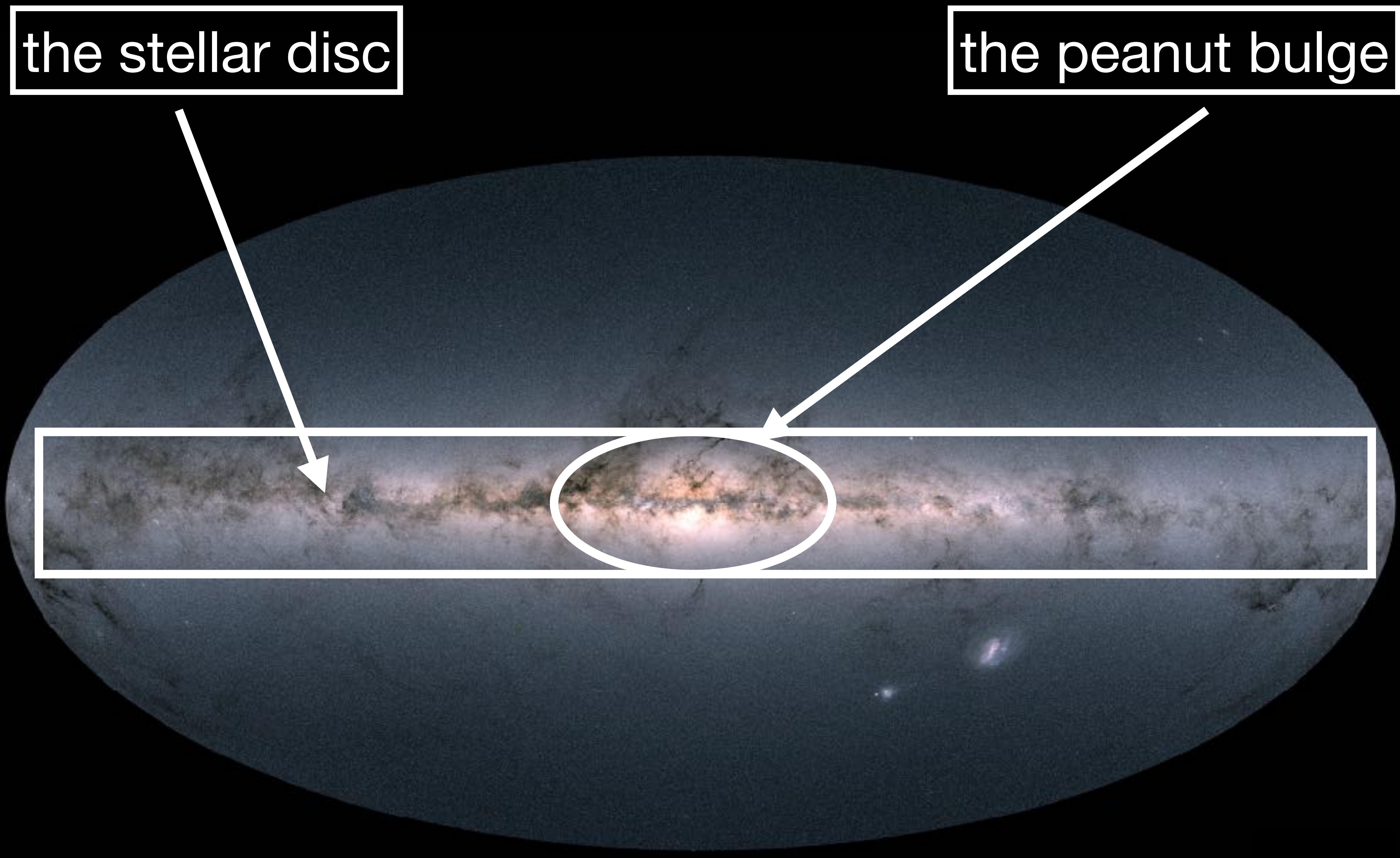
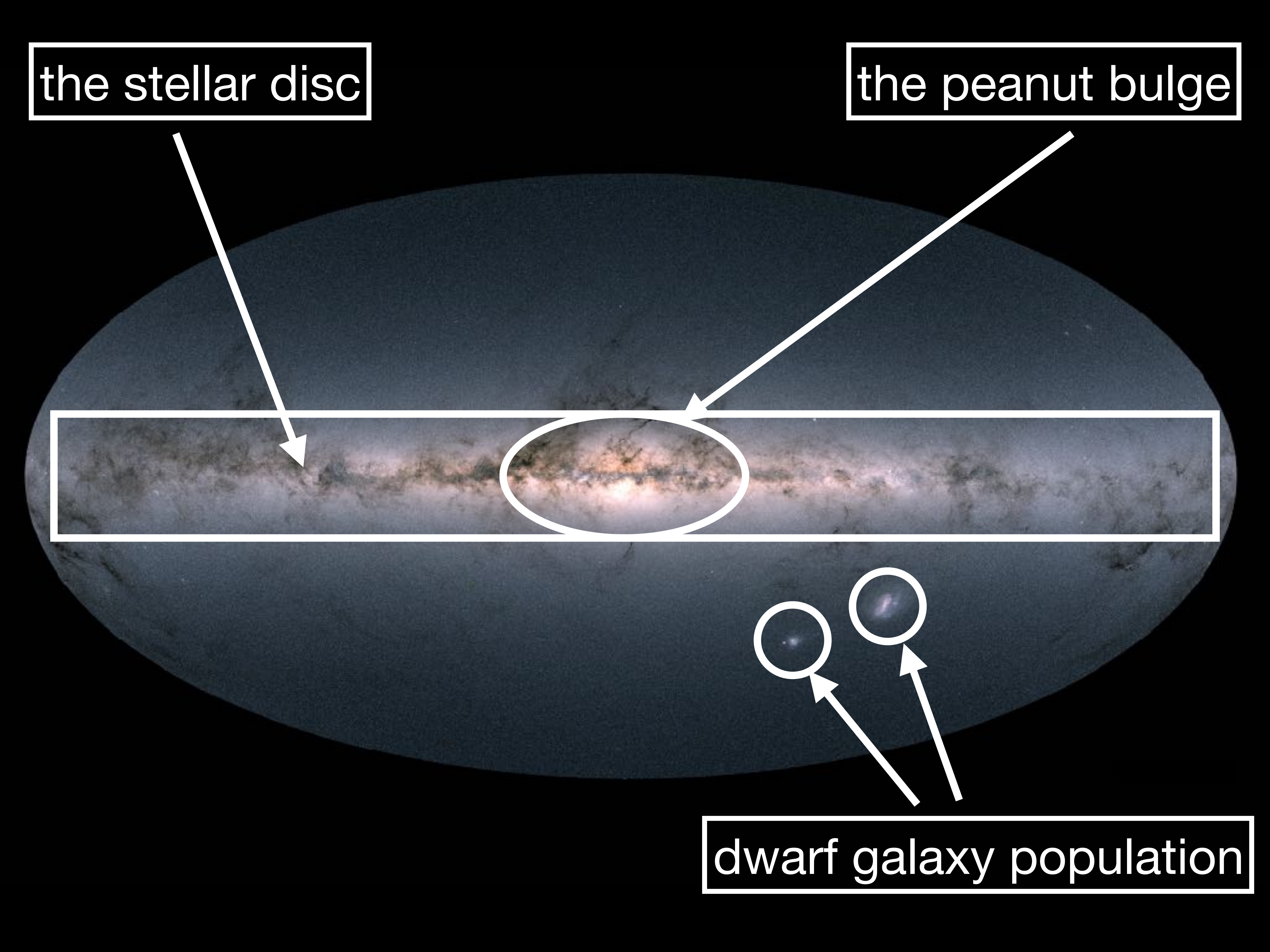
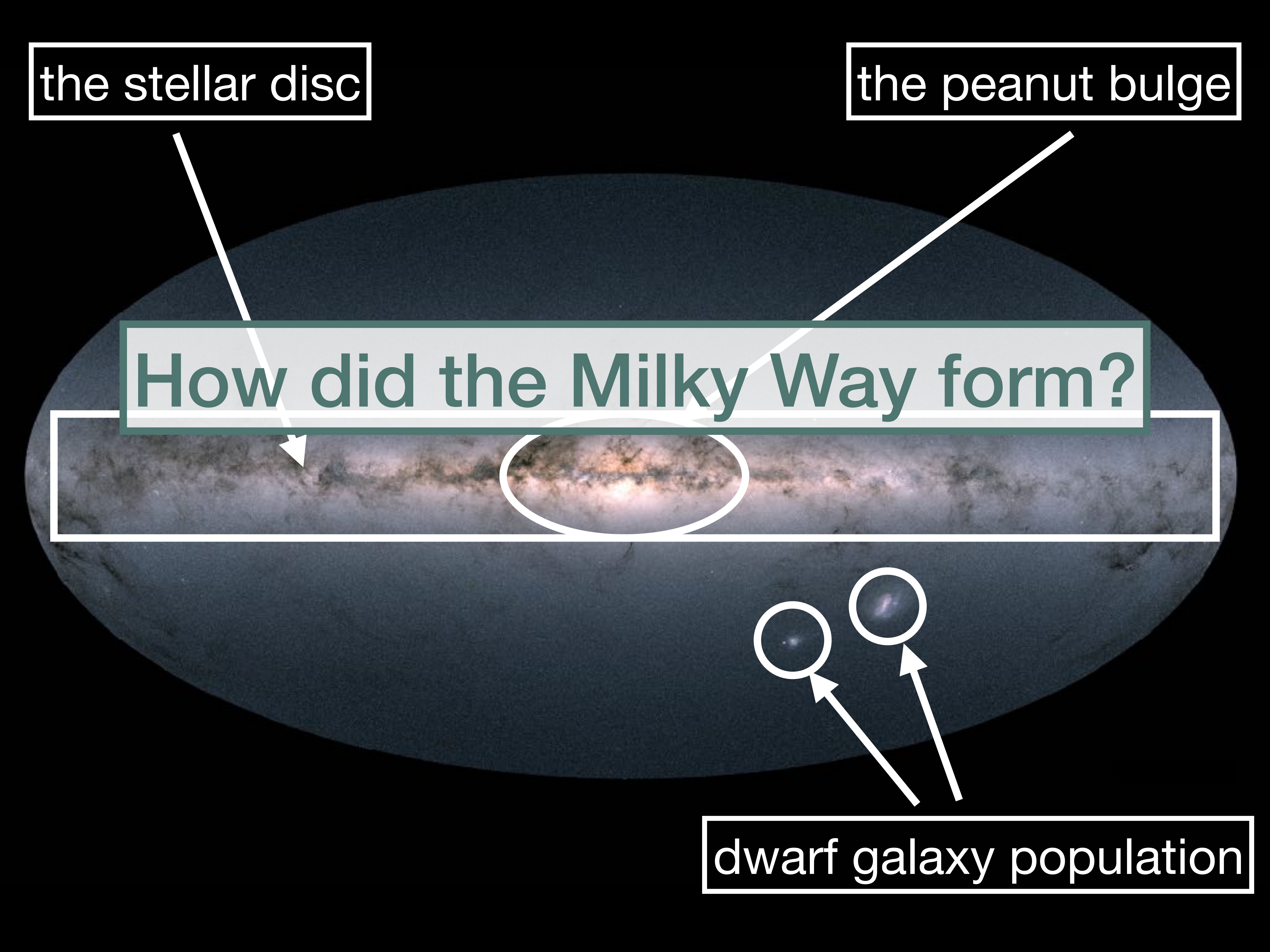



the stellar disc


the stellar disc
the peanut bulge


the stellar disc
the peanut bulge
dwarf galaxy population


the stellar disc
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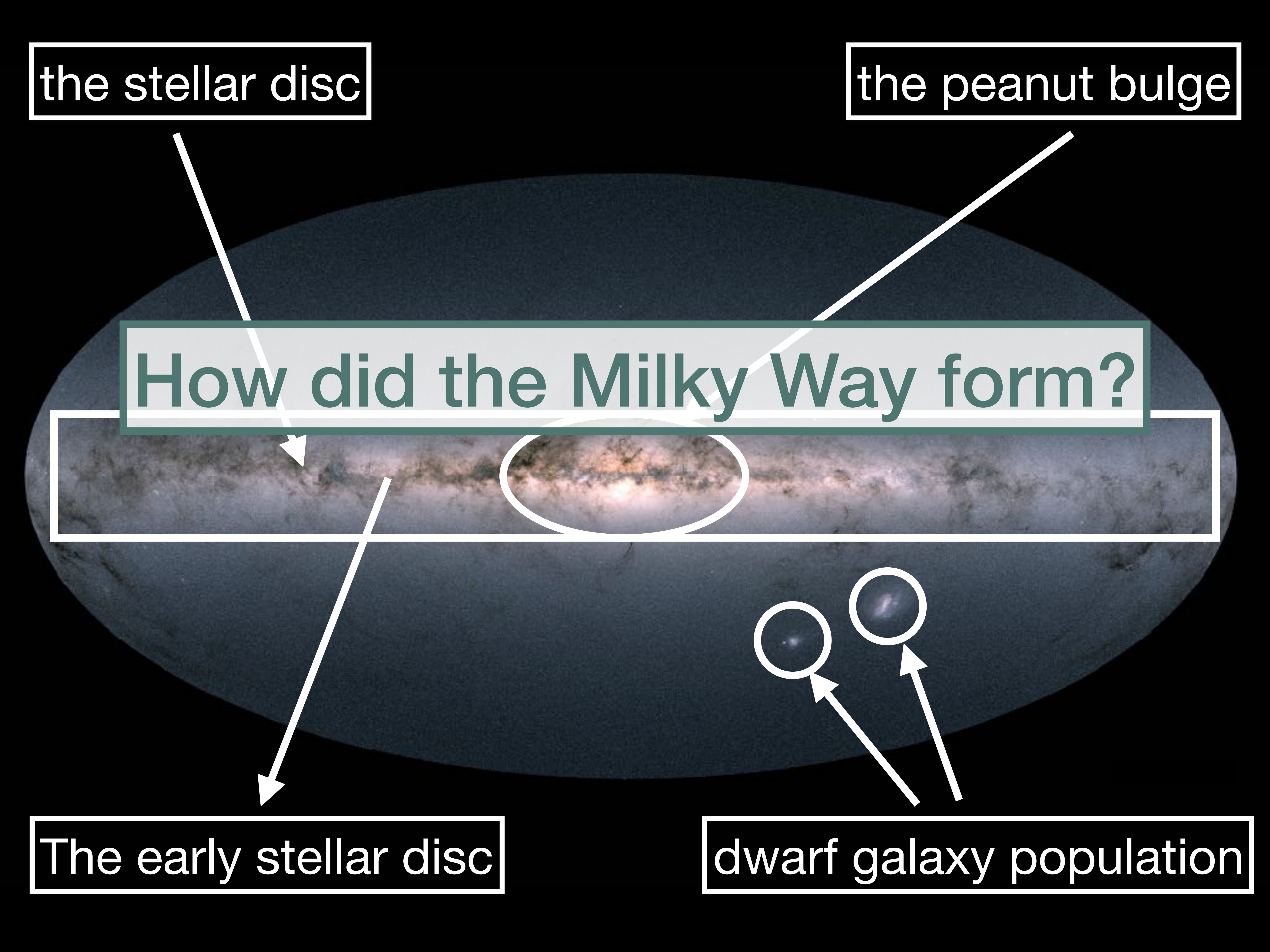
How did the Milky Way form?
dwarf galaxy population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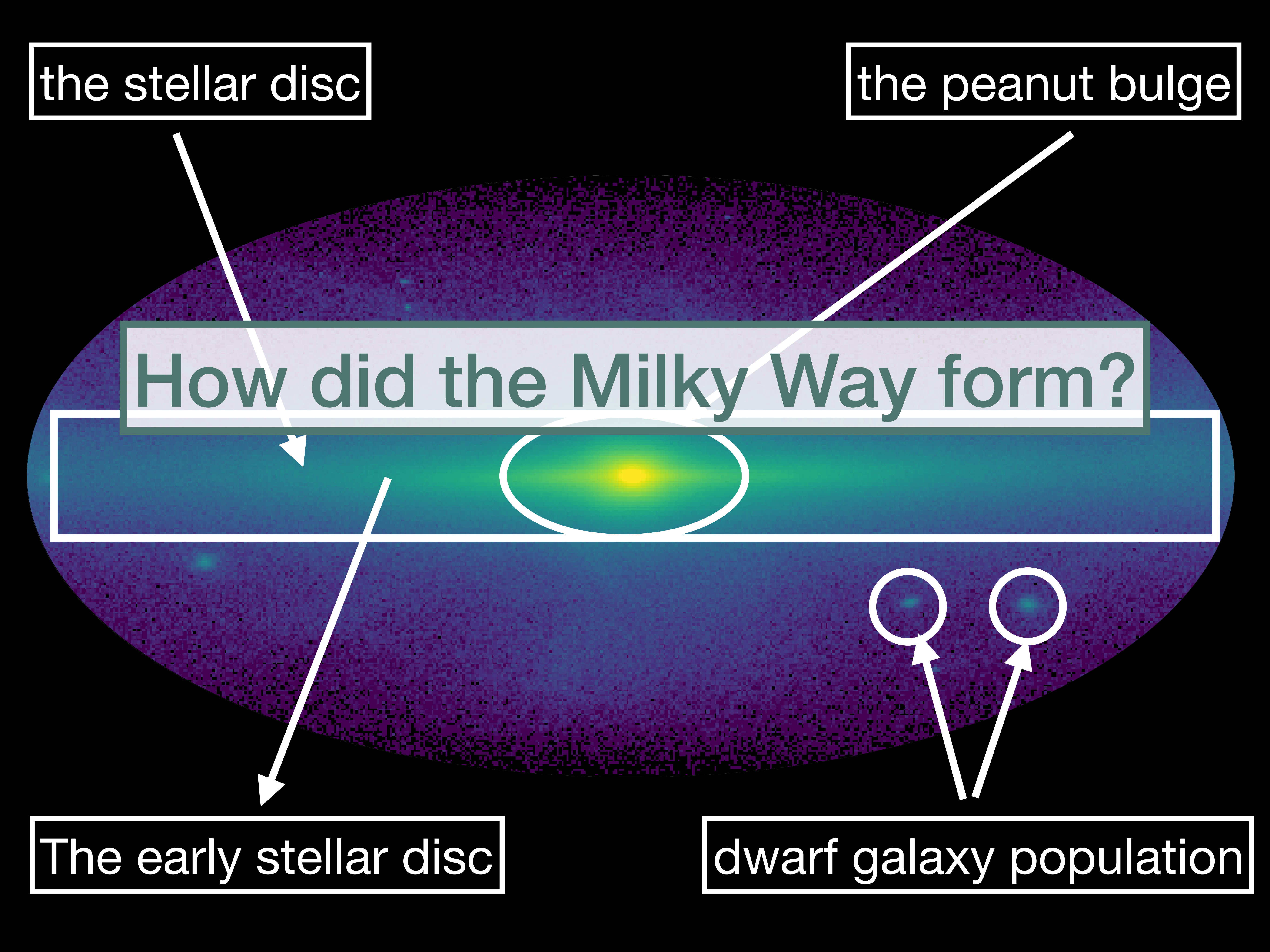
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How did the Milky Way form?

NIHAO 你好

Galaxy Simulations

The early stellar disc

dwarf galaxy population

the stellar disc

the peanut bulge

How did the Milky Way form?

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How did the Milky Way form?

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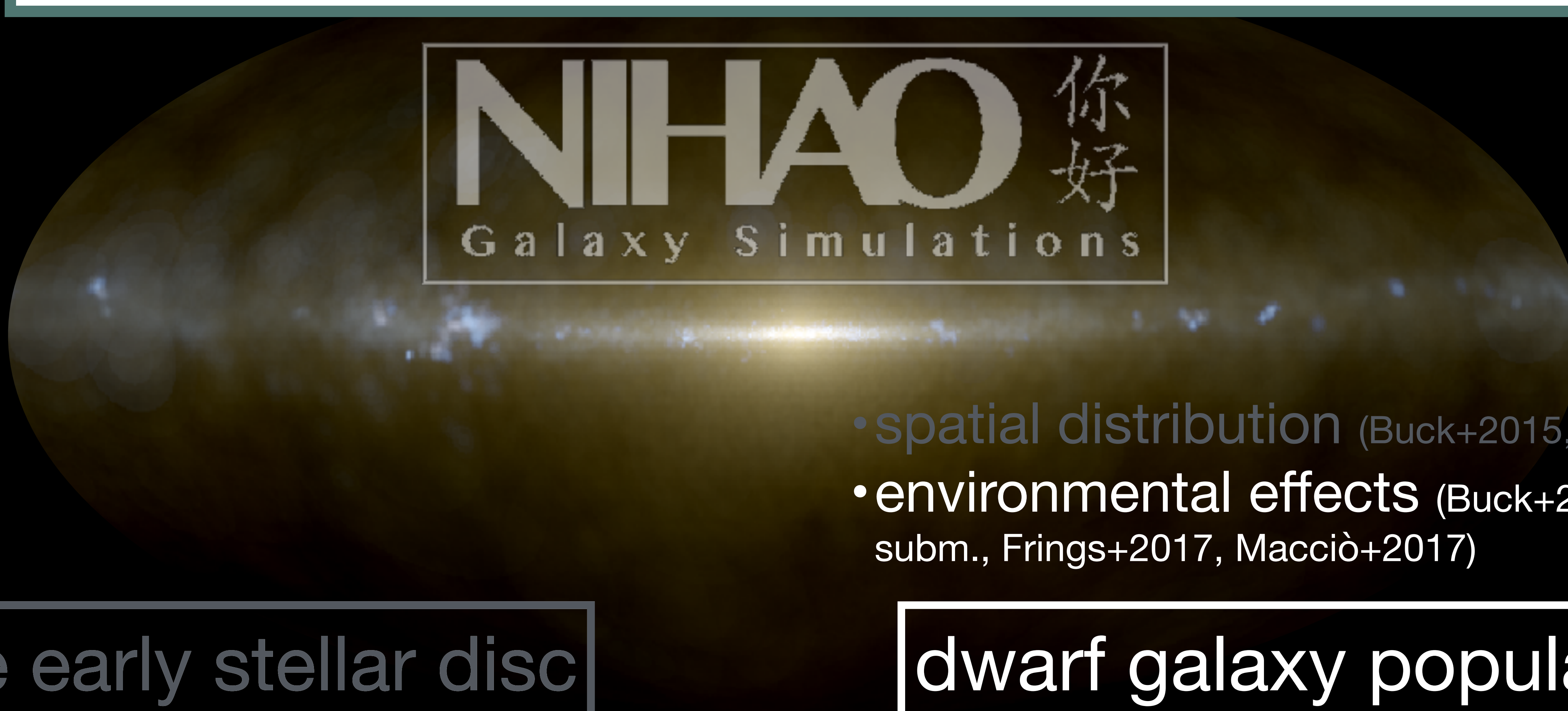
How did the Milky Way form?



- spatial distribution (Buck+2015,2016)
- environmental effects (Buck+2018b subm., Frings+2017, Macciò+2017)

The early stellar disc

dwarf galaxy population

the stellar disc

- structure in position and abundance space
- thin and thick disc

(Buck+ in prep.)

the peanut bulge

- morphology, kinematics
- formation

(Buck+2018a, Buck+2018c to be subm.)

How did the Milky Way form?

- spatial distribution (Buck+2015,2016)
- environmental effects (Buck+2018b subm., Frings+2017, Macciò+2017)

The early stellar disc

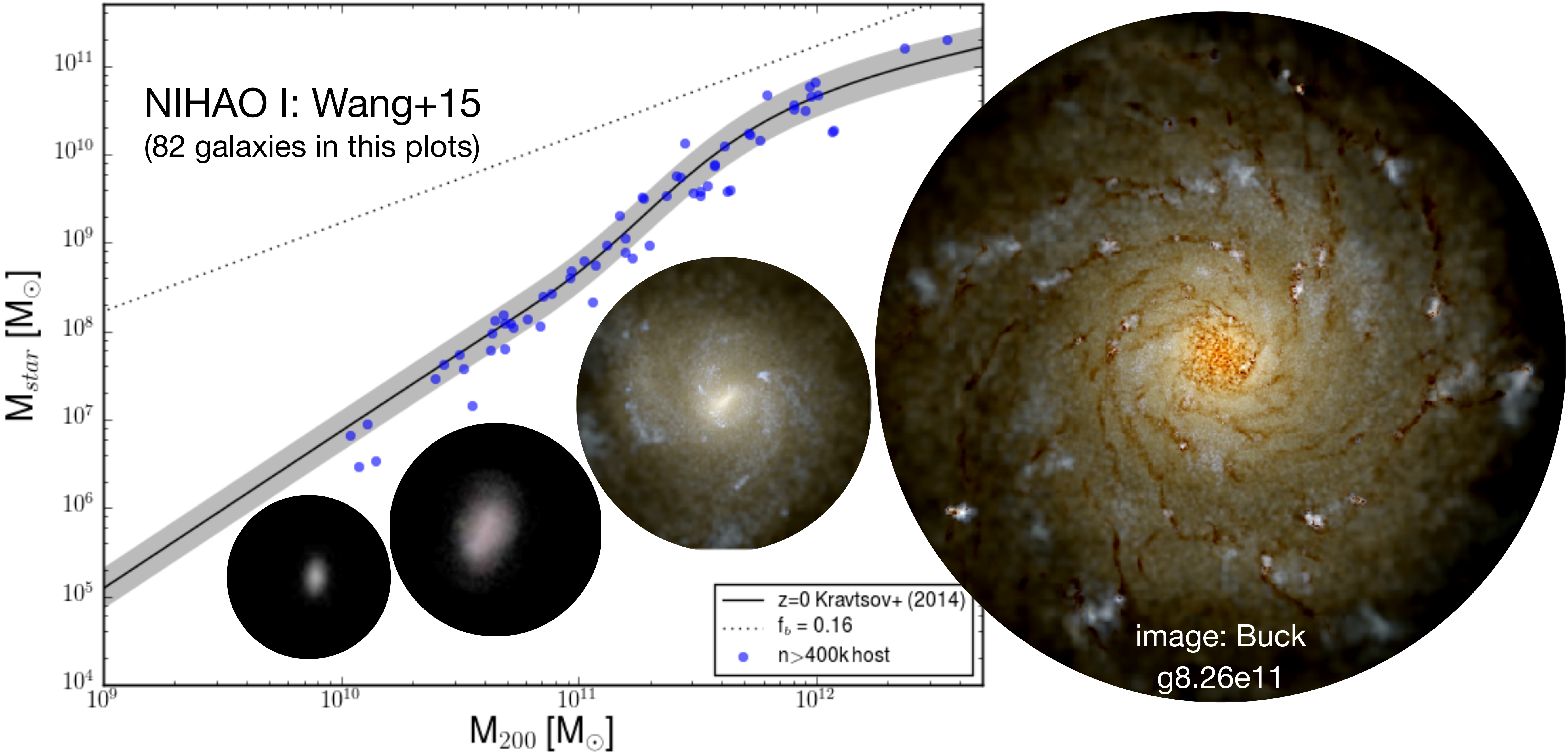
dwarf galaxy population

Numerical Investigation of a Hundred Astronomical Objects

The NIHAO Simulation suite

125 zoom-in simulations from Milky-Way mass to dwarf galaxies scales

SPH - Gasoline2 (Wadsley+2017)



The NIHAO Simulation suite

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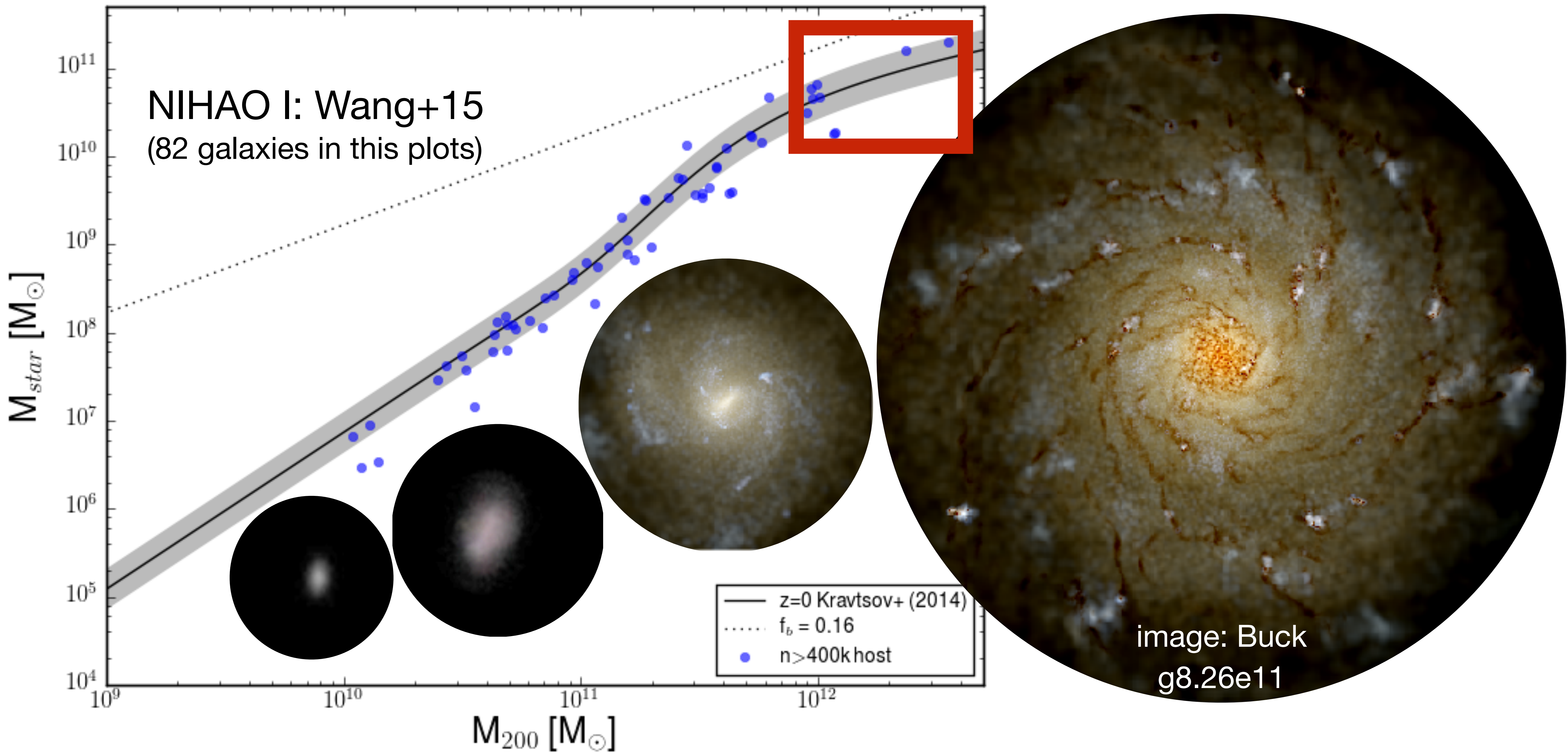
SPH - Gasoline2 (Wadsley+2017)



Simulation Physics

1

GASOLINE2.1

smooth particle hydrodynamics

„modern“ implementation of hydrodynamics, metal diffusion

Wadsley+2017, Keller+2014

2

gas cooling

via hydrogen, helium and various metal lines

gas heating

via Photoionisation from the UV background

Shen+2010, Haardt&Madau 2012

3

self consistent star formation from cold dense gas

n_{th}=10 particles/ccm

Stinson+2006

star formation regions

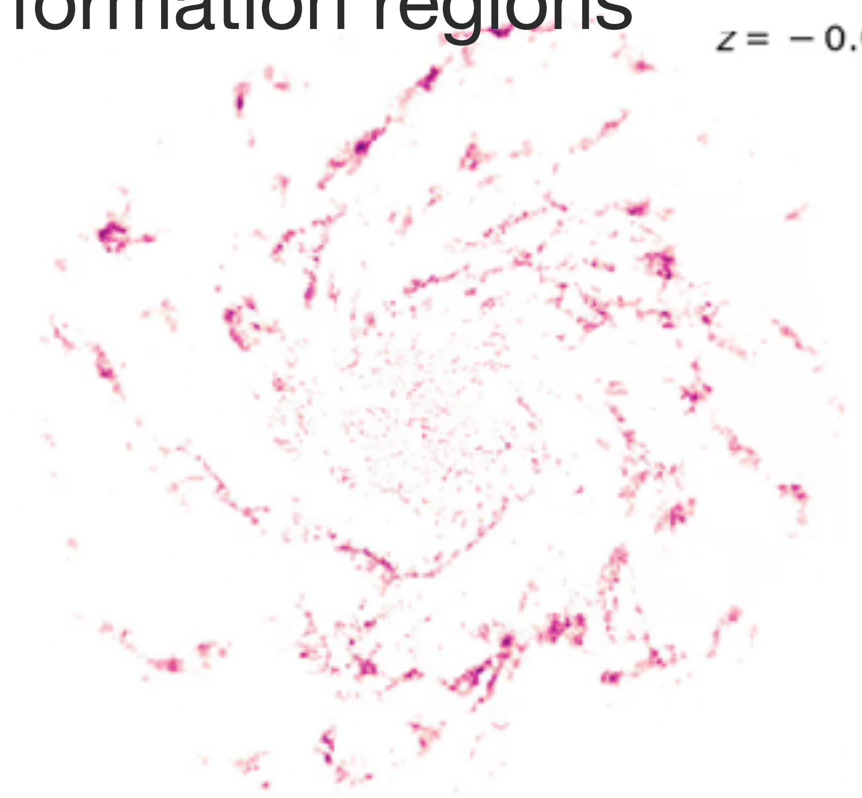


image size: 50x50 kpc

Animation by T. Buck (MPIA, NYUAD) based on NIHAO simulations

4

early stellar feedback and SN feedback (energy + metals)

Stinson+2013

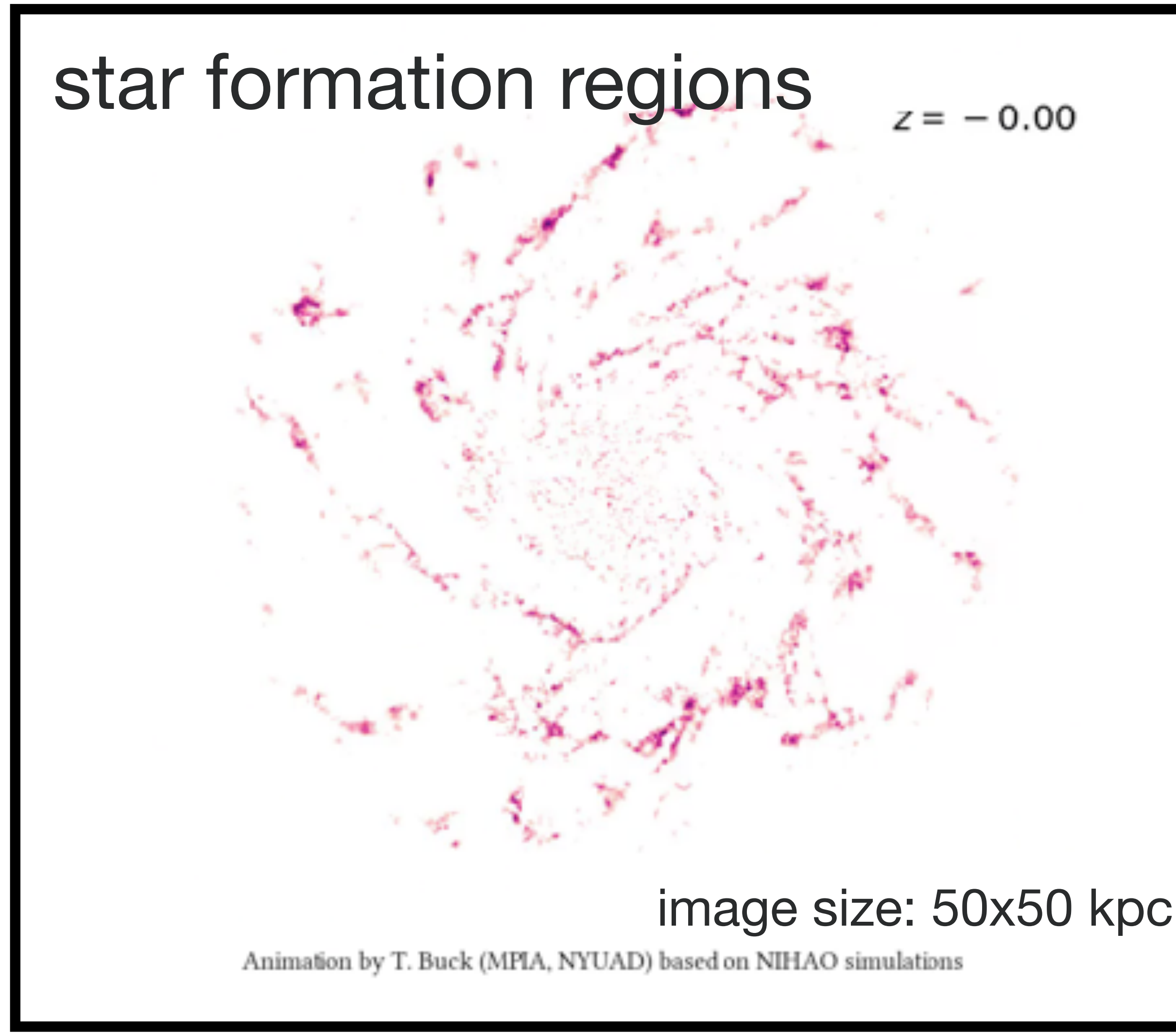
Simulation Physics

1

GASOLINE2.1
smooth particle hydrodynamics

„modern“ implementation of hydrodynamics, metal diffusion

Wadsley+2017, Keller+2014



2

gas cooling

via hydrogen, helium and various metal lines

gas heating

via Photoionisation from the UV background

Shen+2010, Haardt&Madau 2012

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self consistent star formation from cold dense gas
n_{th}=10 particles/ccm

Stinson+2006

4

early stellar feedback and SN feedback (energy + metals)

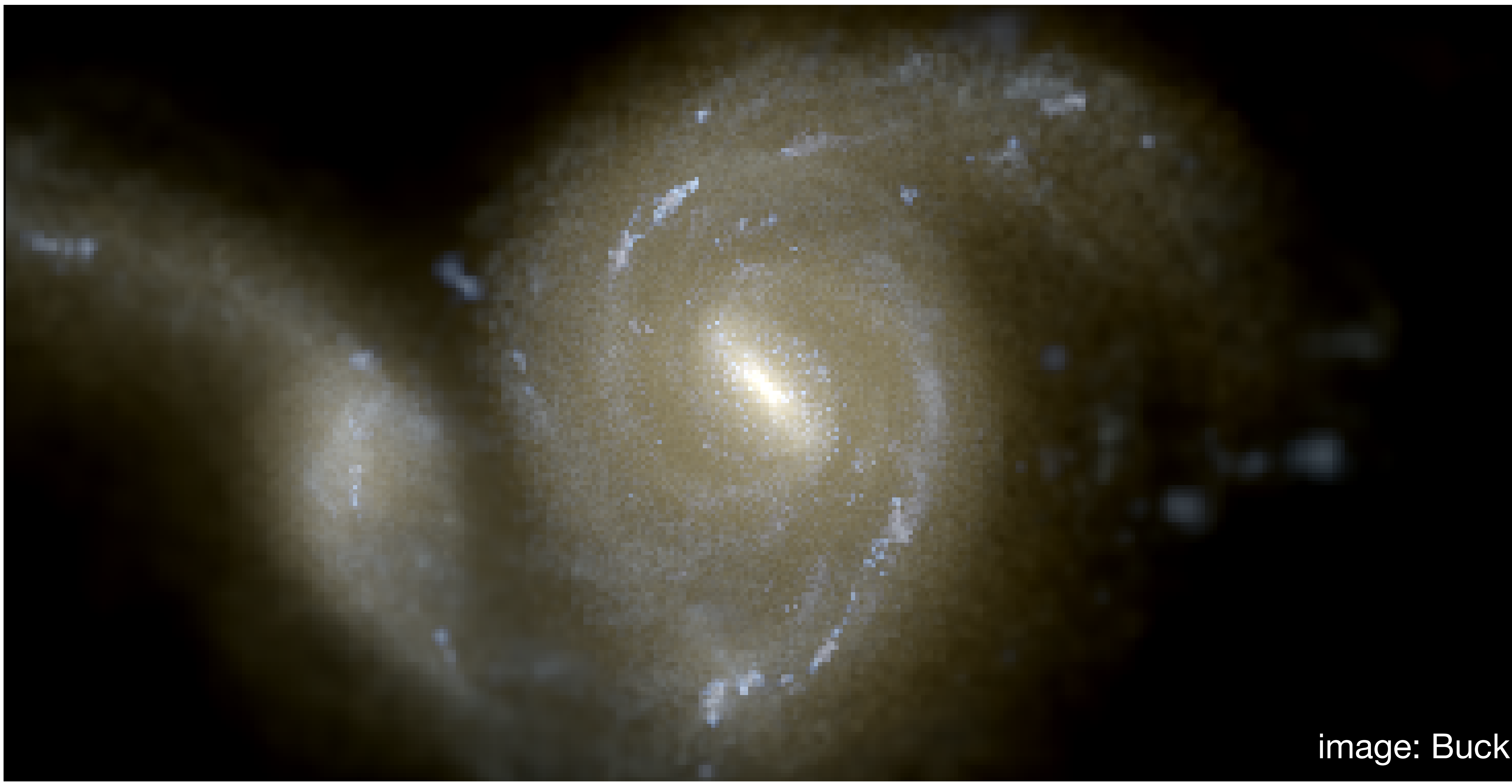
Stinson+2013

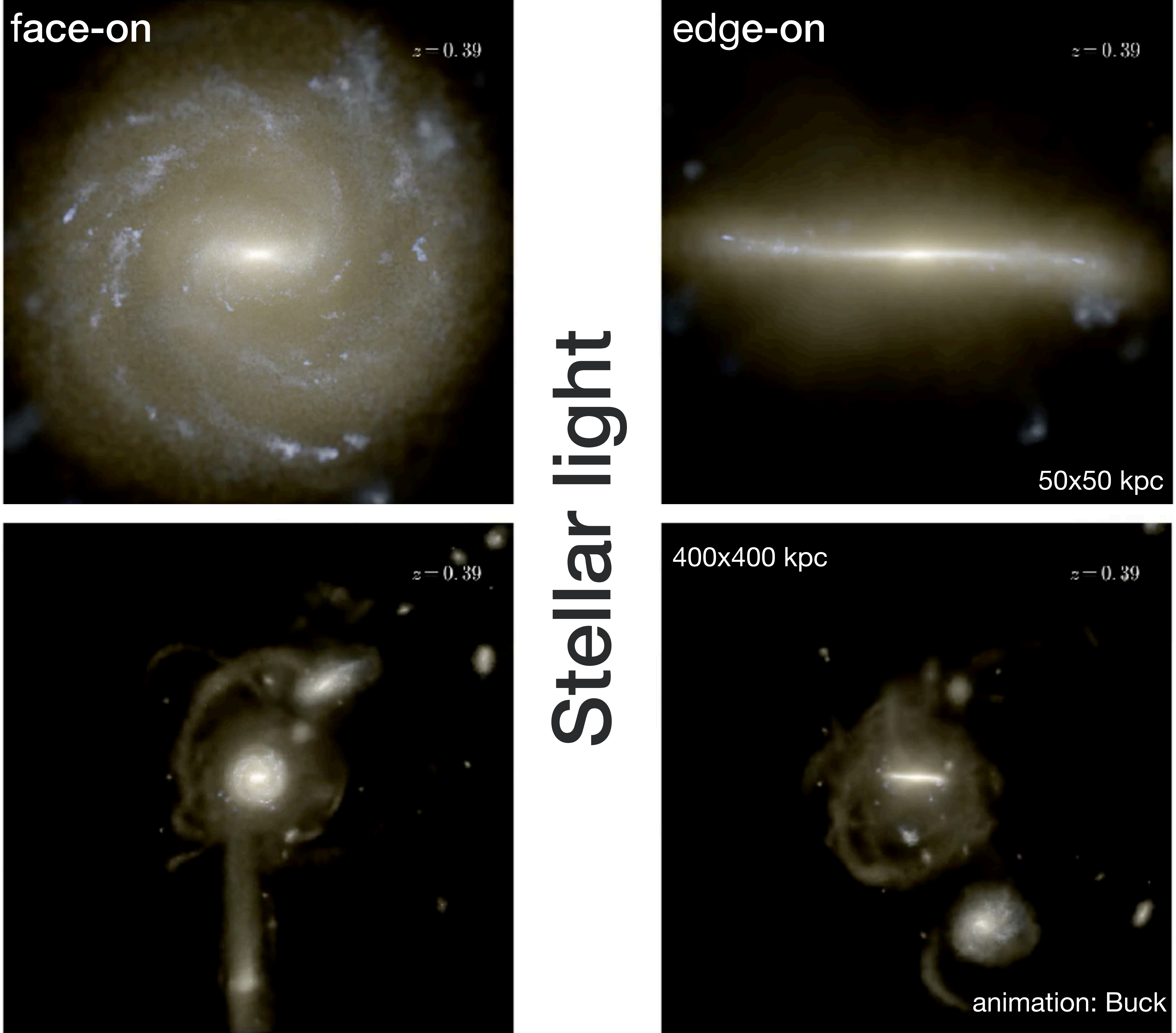
High-resolution hydro simulations of MW mass galaxies

Why fully cosmological, high-resolution, hydro simulations?

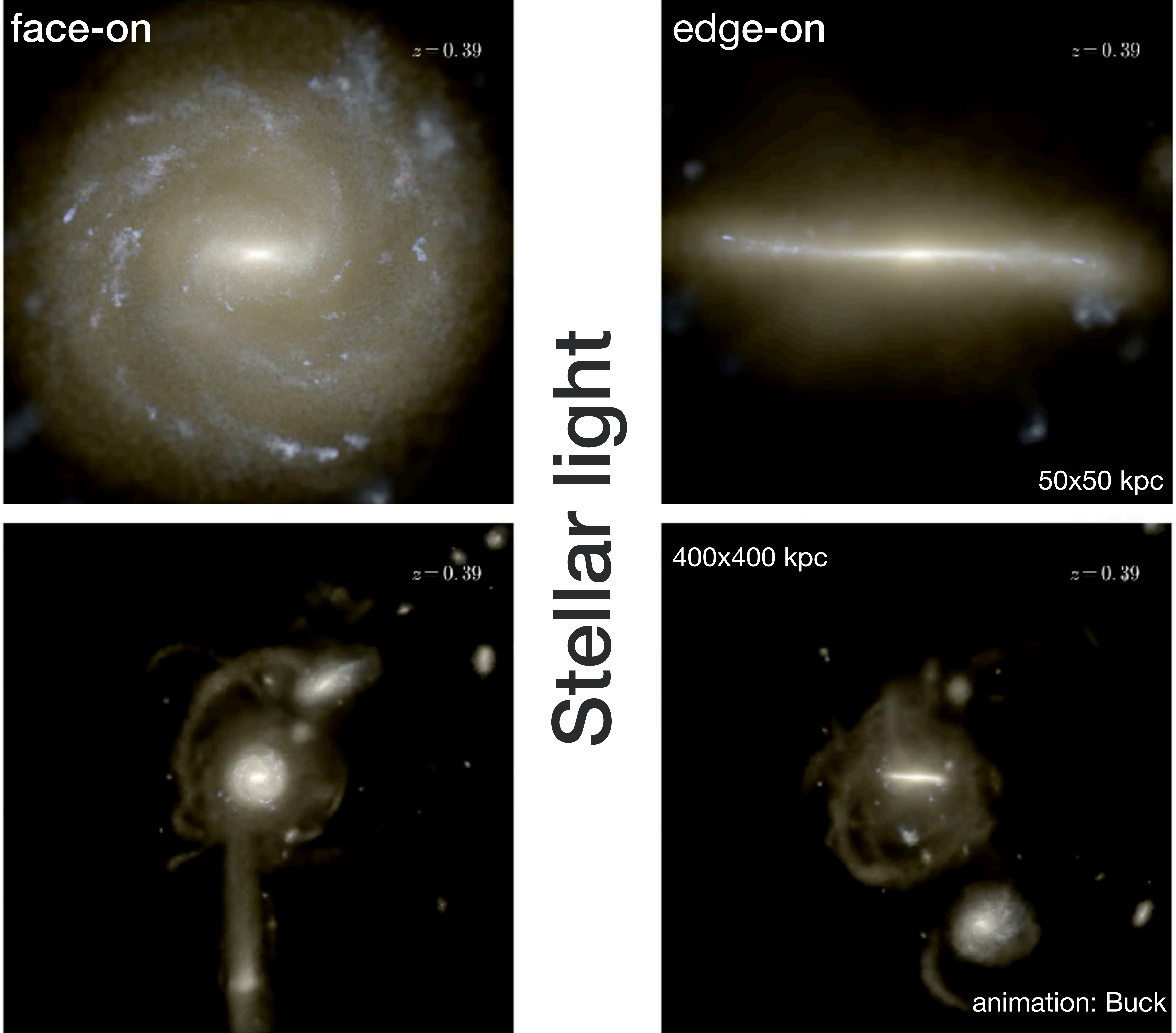
A: dwarf galaxy population

B: stellar disc structure




face-on
$z = 0.39$
edge-on
$z = 0.39$
50x50 kpc
Stellar light
$z = 0.39$
400x400 kpc
$z = 0.39$
animation: Buck

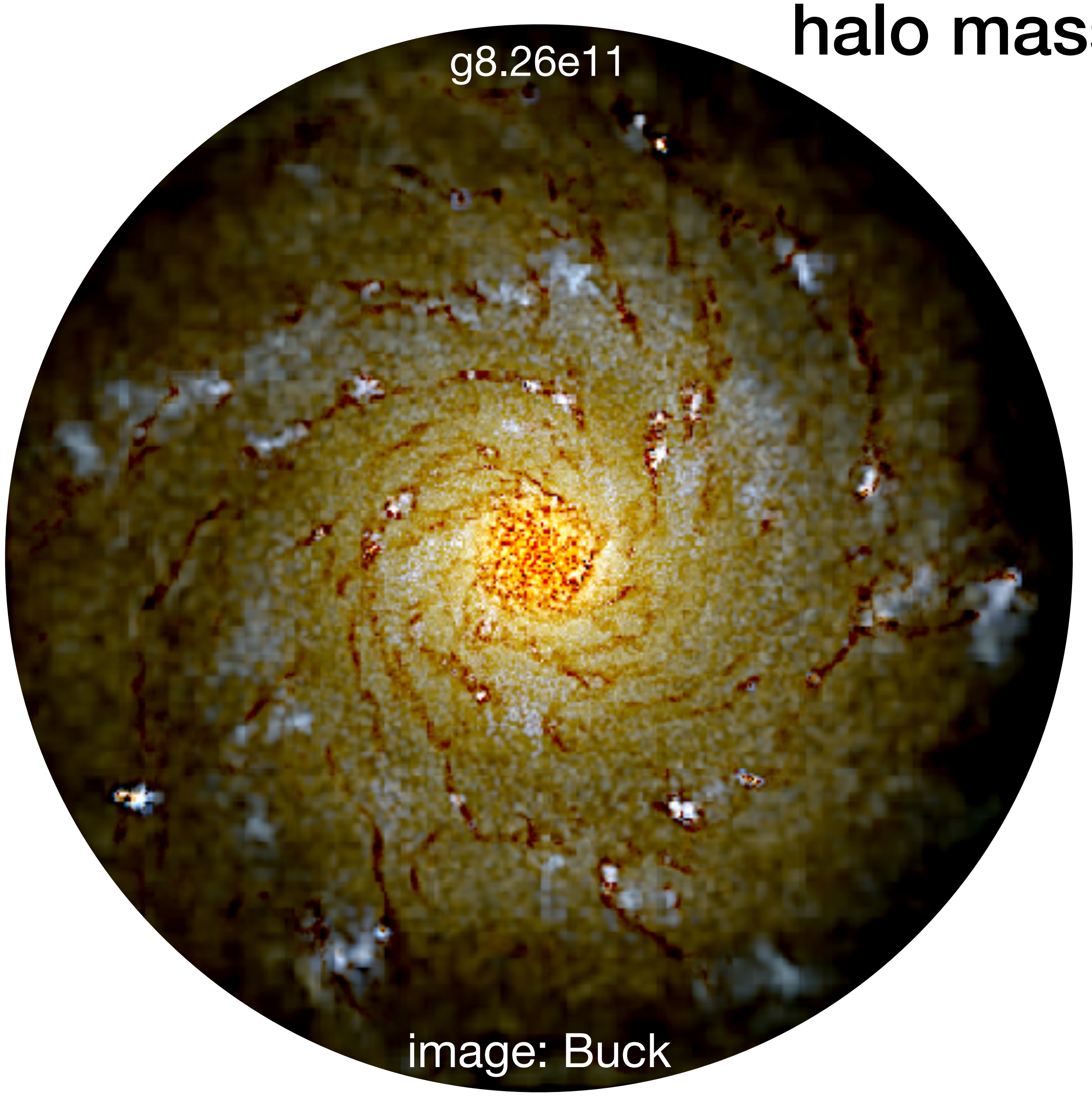
Stellar light



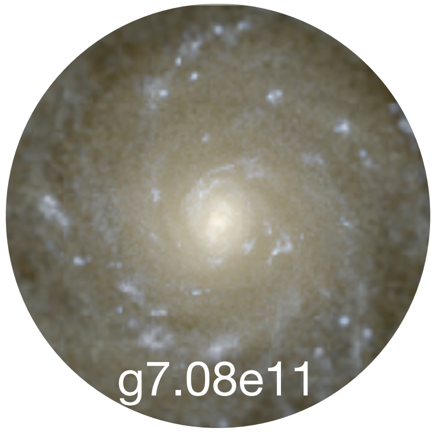
High-resolution Simulations

7 Zoom-in simulations: 4 done, 3 at z=1
and more to come

halo masses: 5 x 10^{11} to 2.8 x 10^{12} $M_\odot$

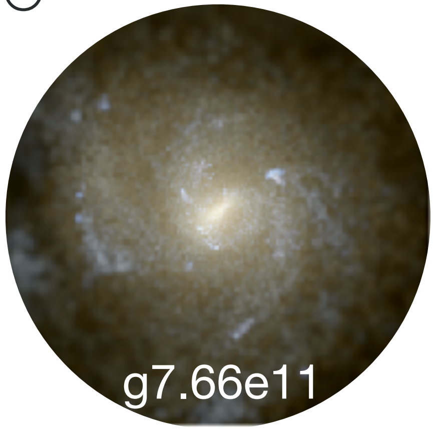


~ 3 x 10^7 particles
~ 8 x 10^6 star particles
~ 10^7 gas particles



Gravitational softening and particle masses:

- dark matter: 400 pc, 1.5 x 10^5 $M_\odot$
- gas: 180 pc, 2.8 x 10^4 $M_\odot$
- stars: 180 pc, 9300 $M_\odot$



similar zoom-in projects: Aumer+2013, Latte-project (Wetzel+2016), Apostle (Sawala+2016), Auriga (Grand+2017)

the stellar disc

- structure in position and abundance space
- thin and thick disc

the peanut bulge

- morphology, kinematics
- formation

How did the Milky Way form?

- high-redshift clumpy galaxies

The early stellar disc

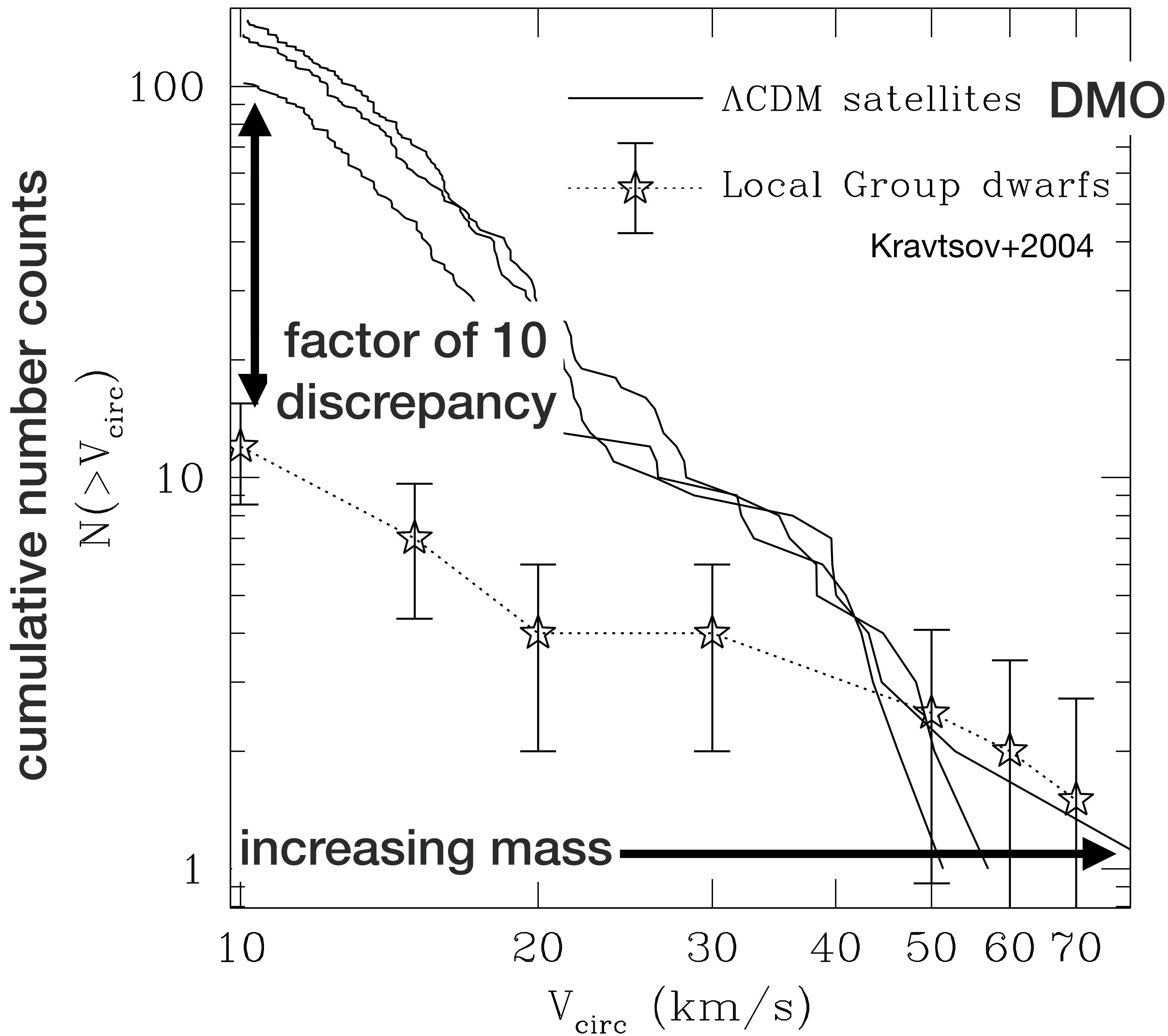
- spatial distribution
- environmental effects

dwarf galaxy population

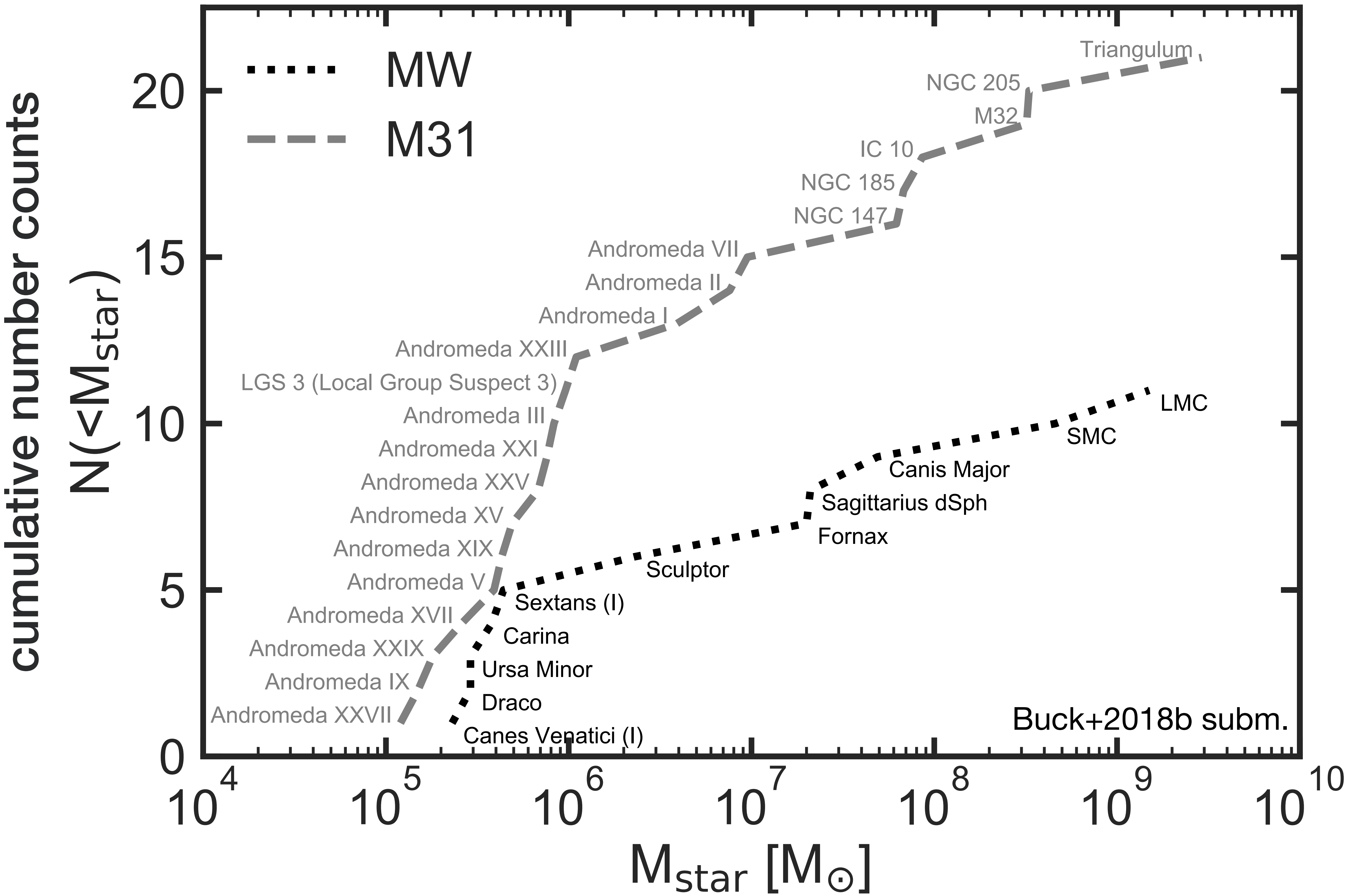
High-resolution hydro simulations of MW mass galaxies:

Can we reproduce the Local Group dwarf galaxy population?

The missing satellites problem

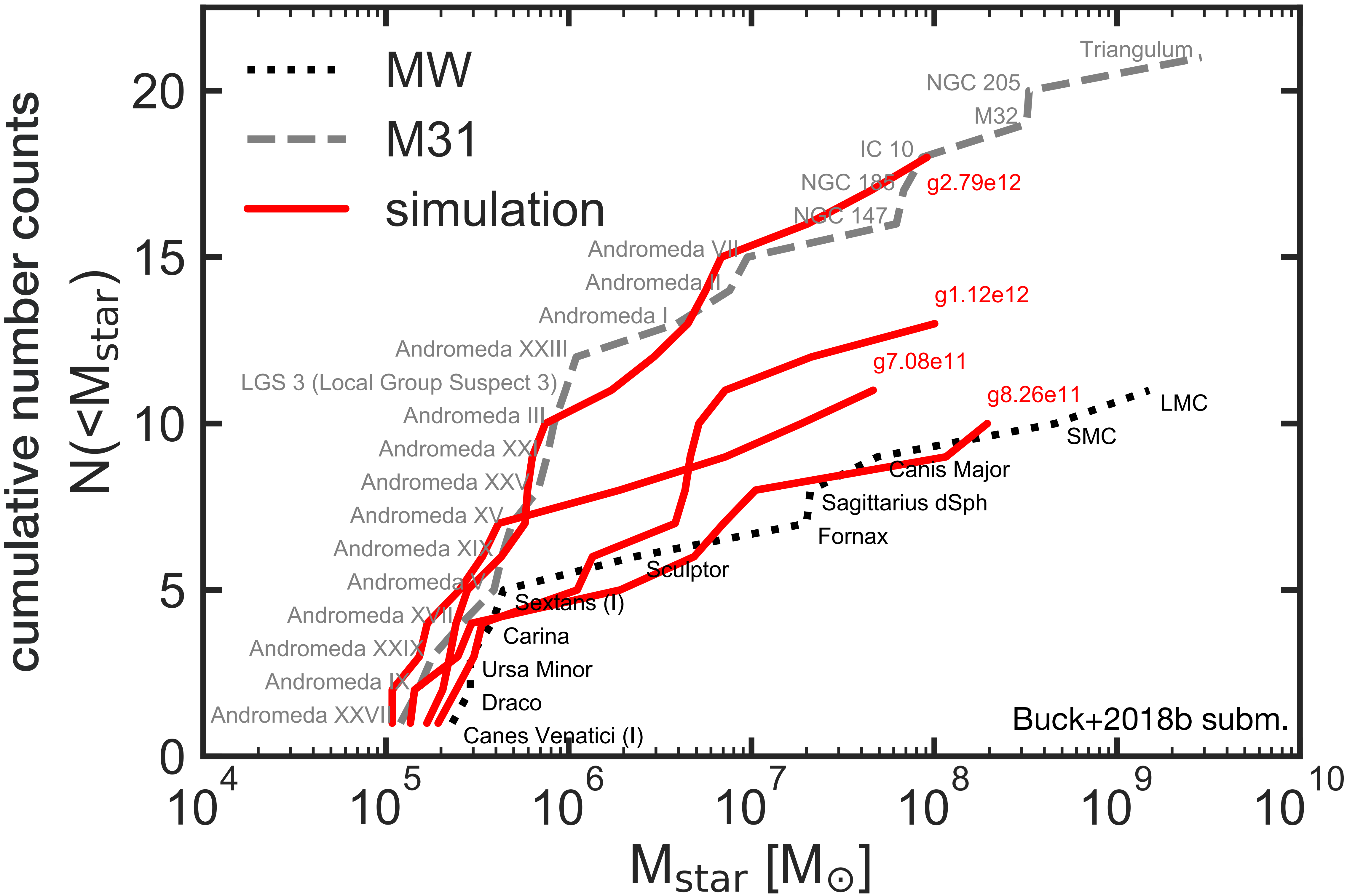


Satellite stellar mass function



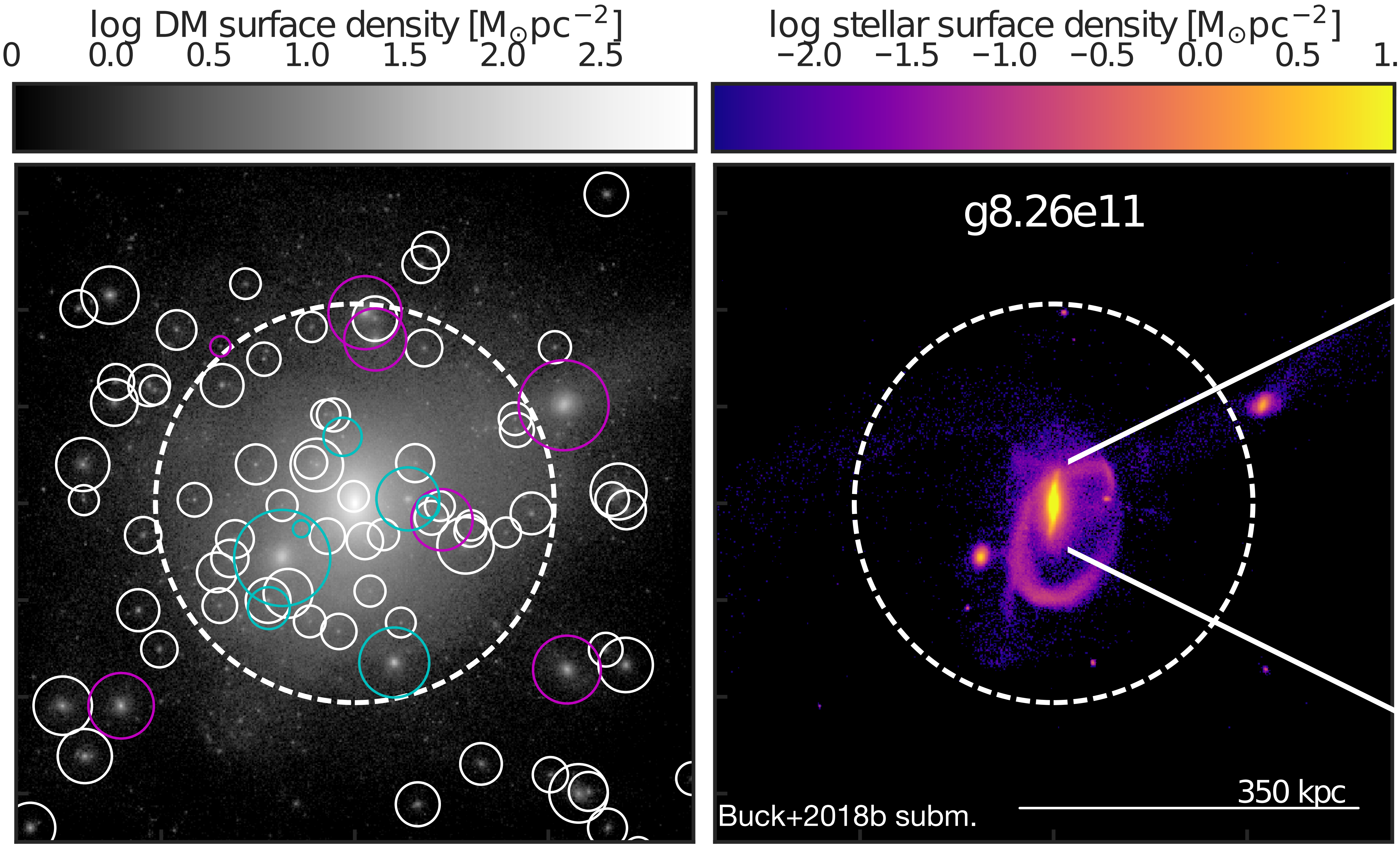
see also: Sawala+2015, Simpson+2017, Despali&Vegetti 2017 (baryonic modification of the mass function)

No missing satellites problem here!



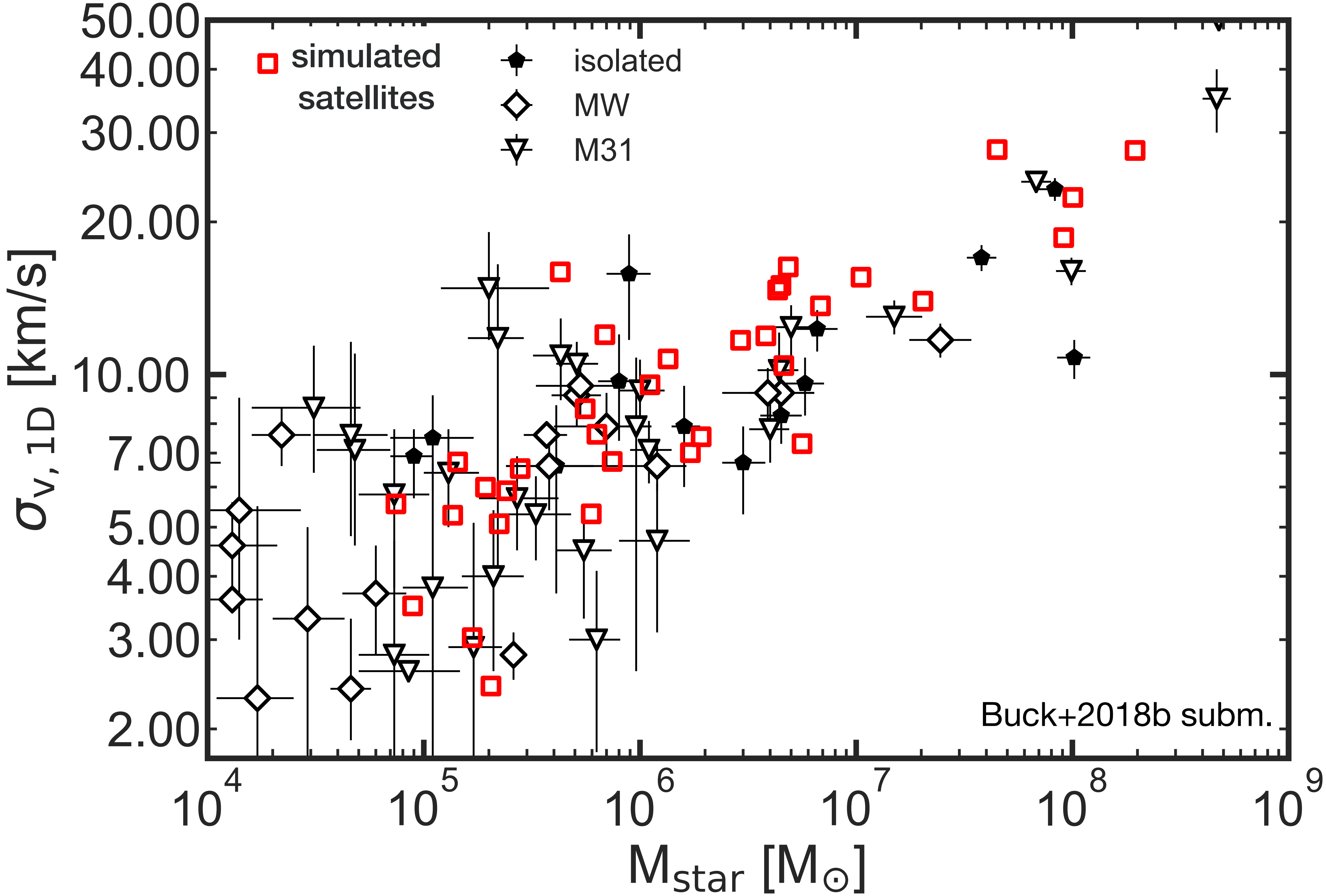
see also: Sawala+2015, Simpson+2017, Despali&Vegetti 2017 (baryonic modification of the mass function)

Baryonic effects leave haloes dark



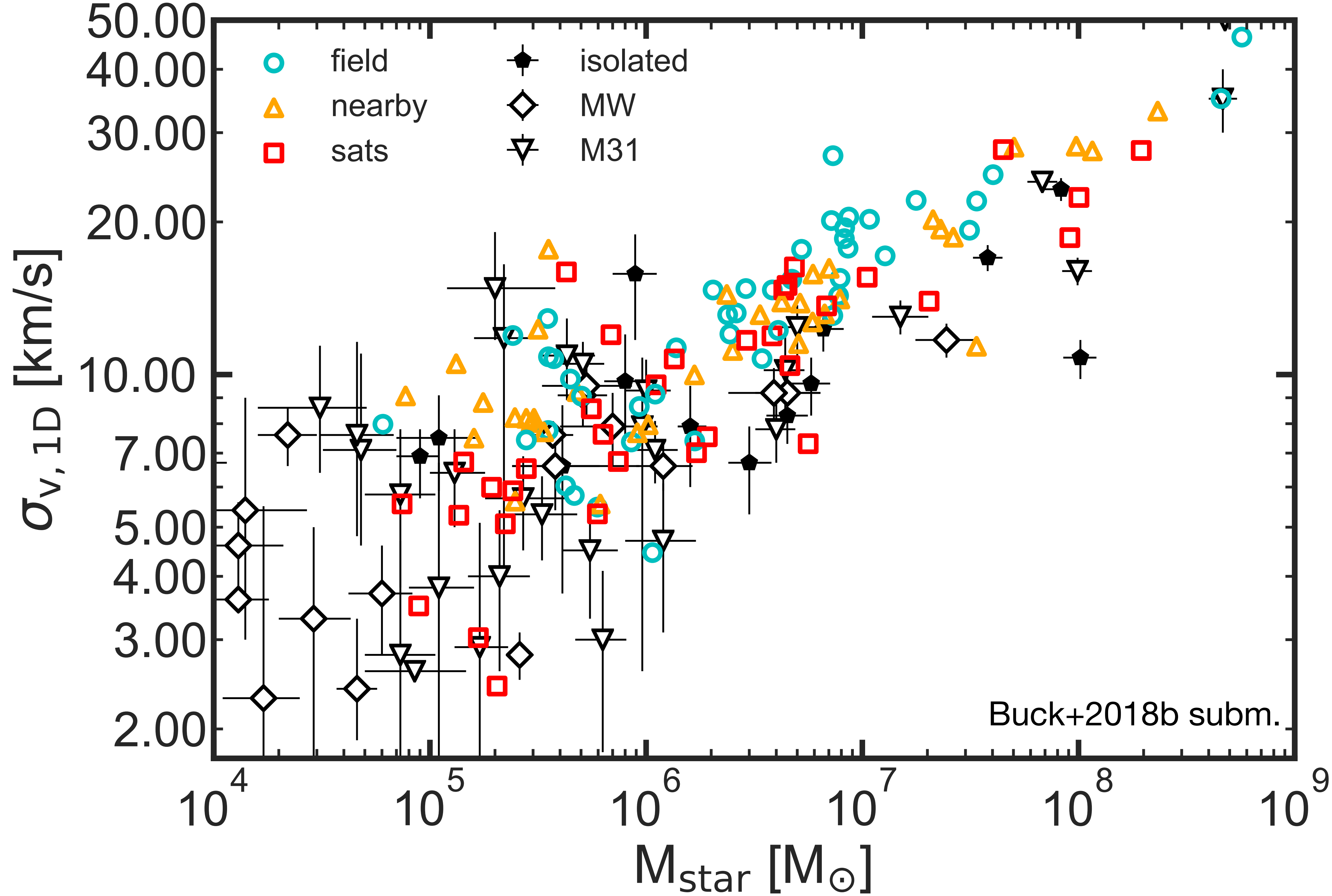
see also: Simpson+ 2017, Sawala+2016, Wetzel+2016,

Line-of-sight velocity dispersions of simulations and observations agree



also: Macciò+(incl. TB) 2017, Frings+(incl. TB) 2017

Line-of-sight velocity dispersions of simulations and observations agree



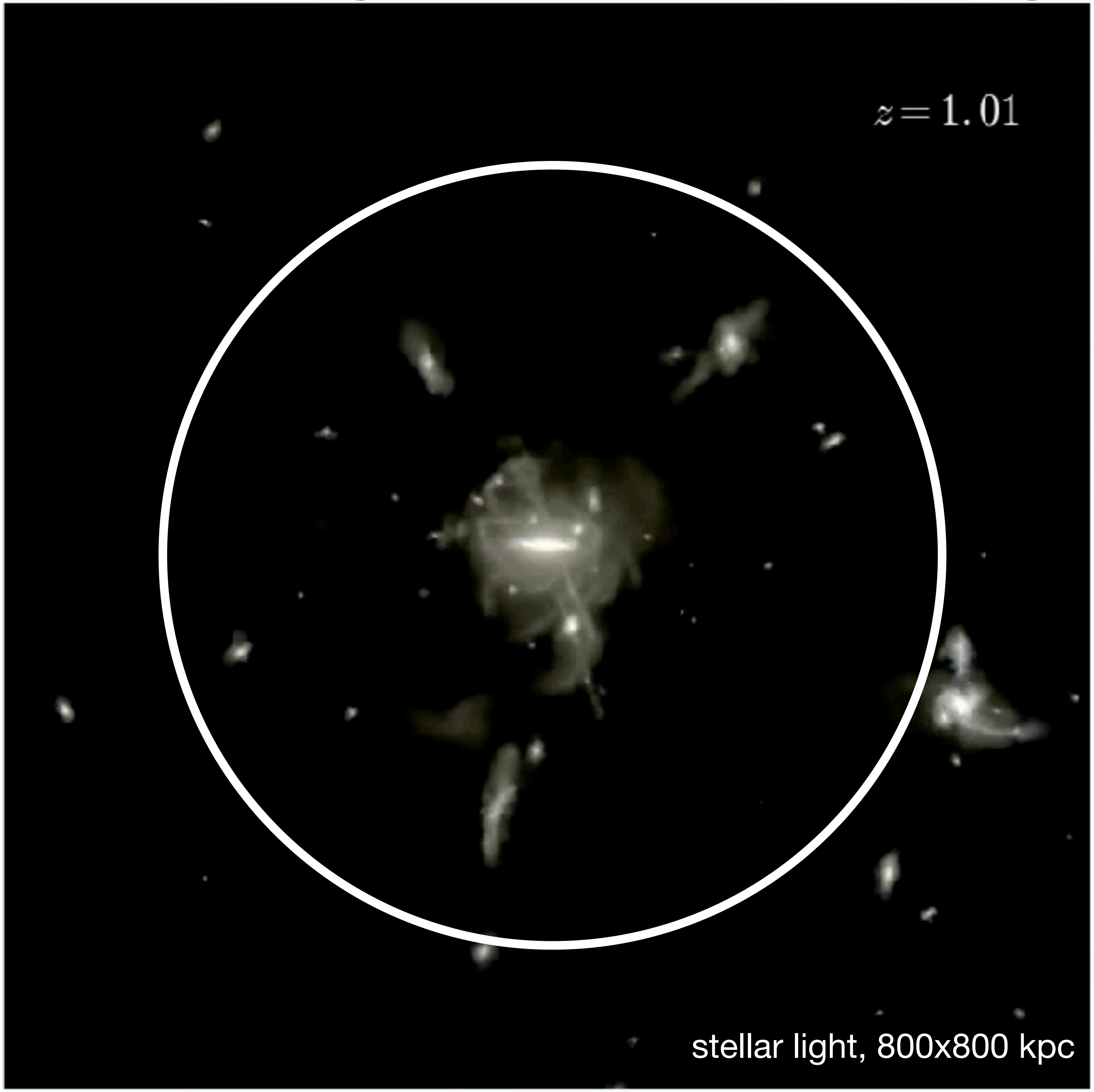
also: Macciò+(incl. TB) 2017, Frings+(incl. TB) 2017

Can we reproduce the Local Group dwarf galaxy population?

YES!

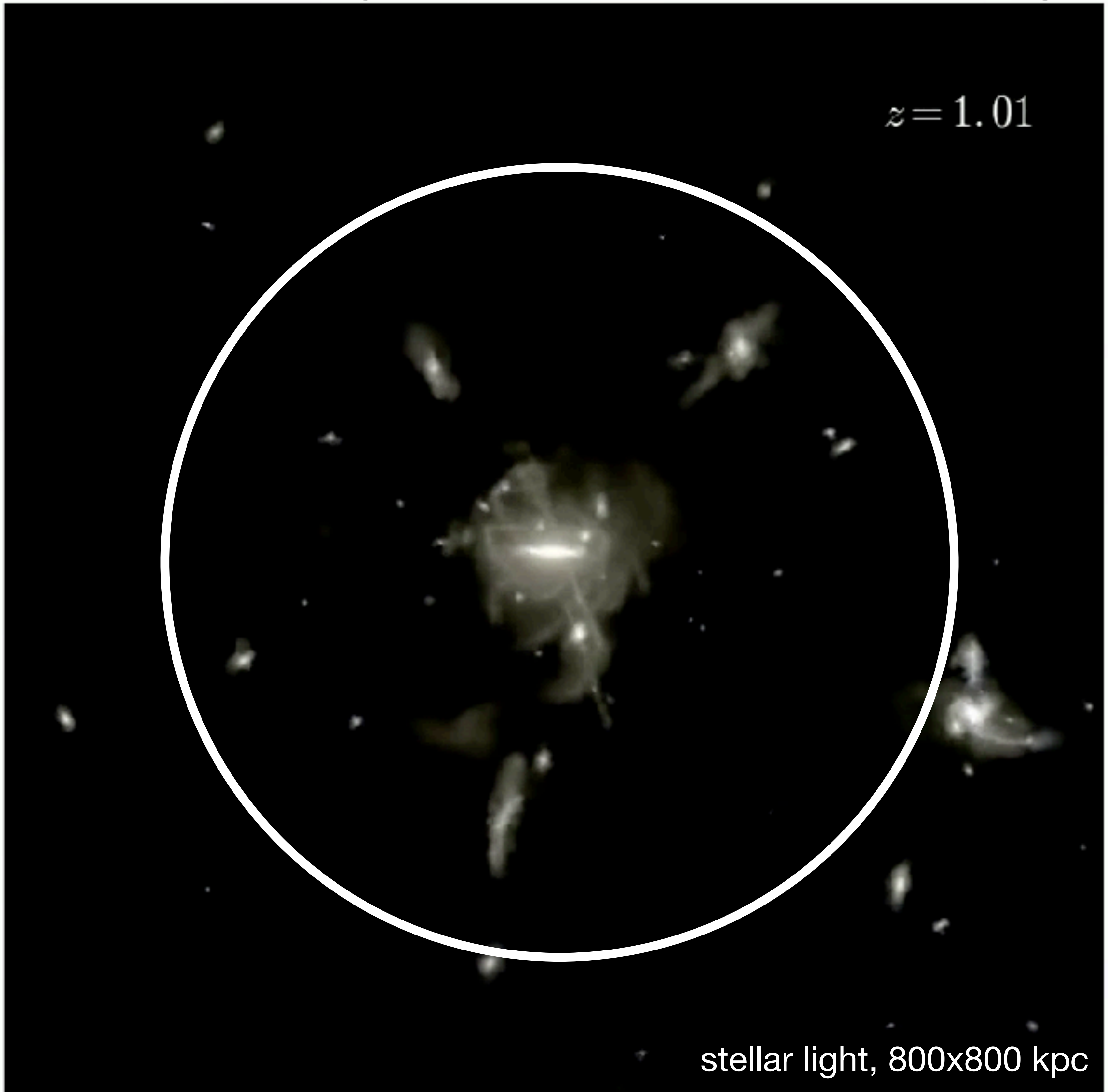
What can we learn from these simulations about Local Group dwarf galaxies?

Can we identify backsplash galaxies



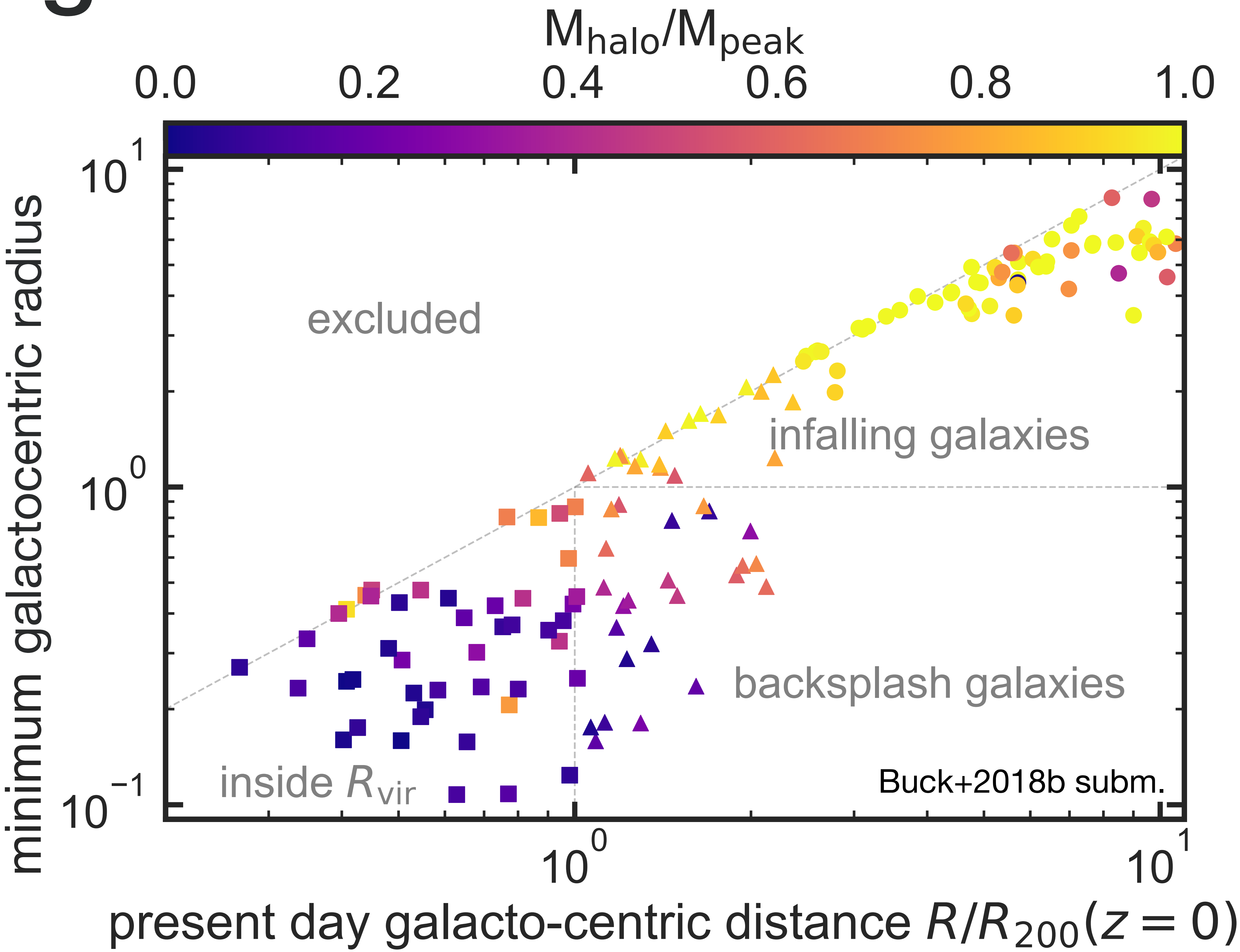
Animation by T. Buck (MPIA, NYUAD) based on NIHAO simulations

Can we identify backsplash galaxies



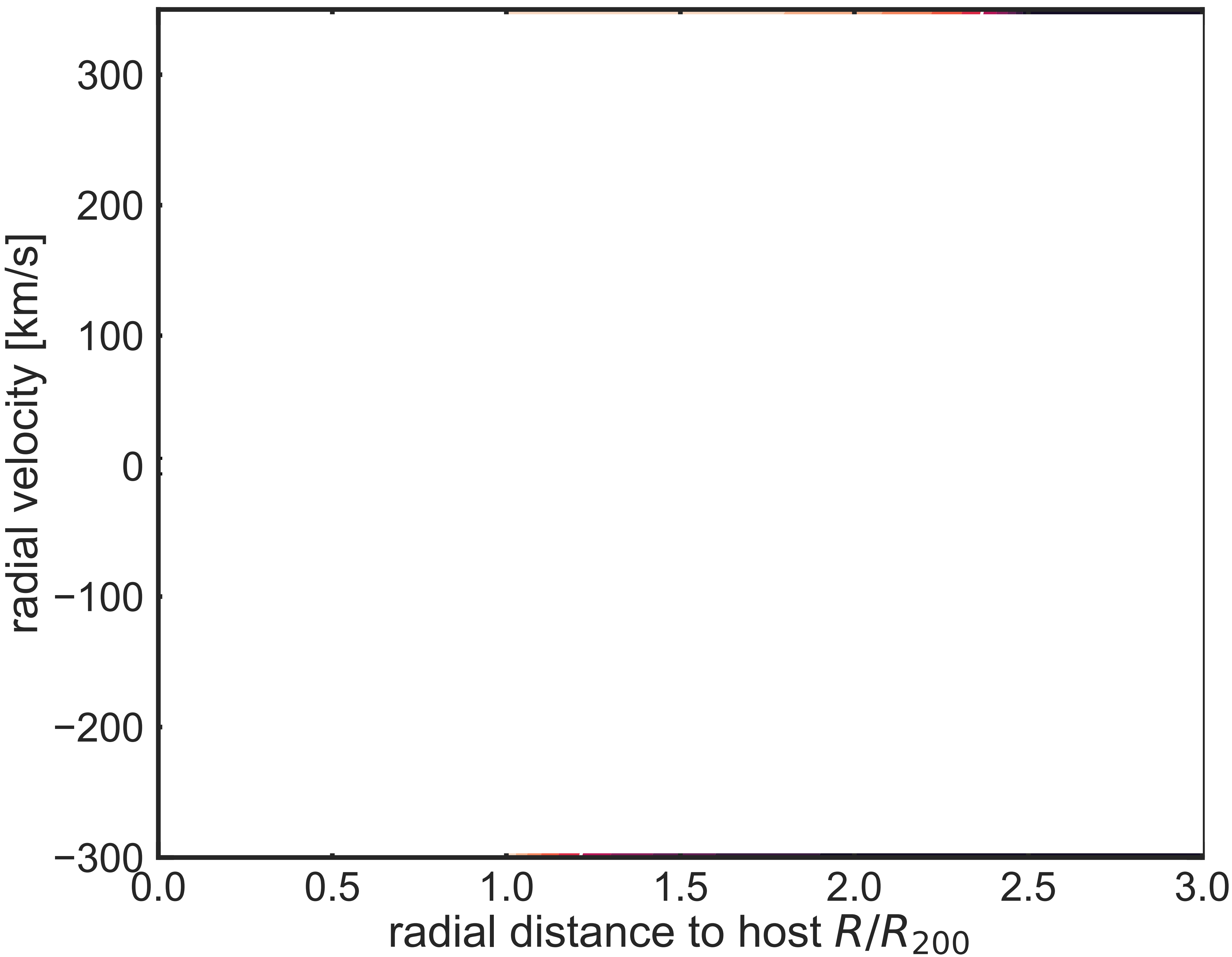
Animation by T. Buck (MPIA, NYUAD) based on NIHAO simulations

Backsplash galaxies lost mass during the close encounter with MW



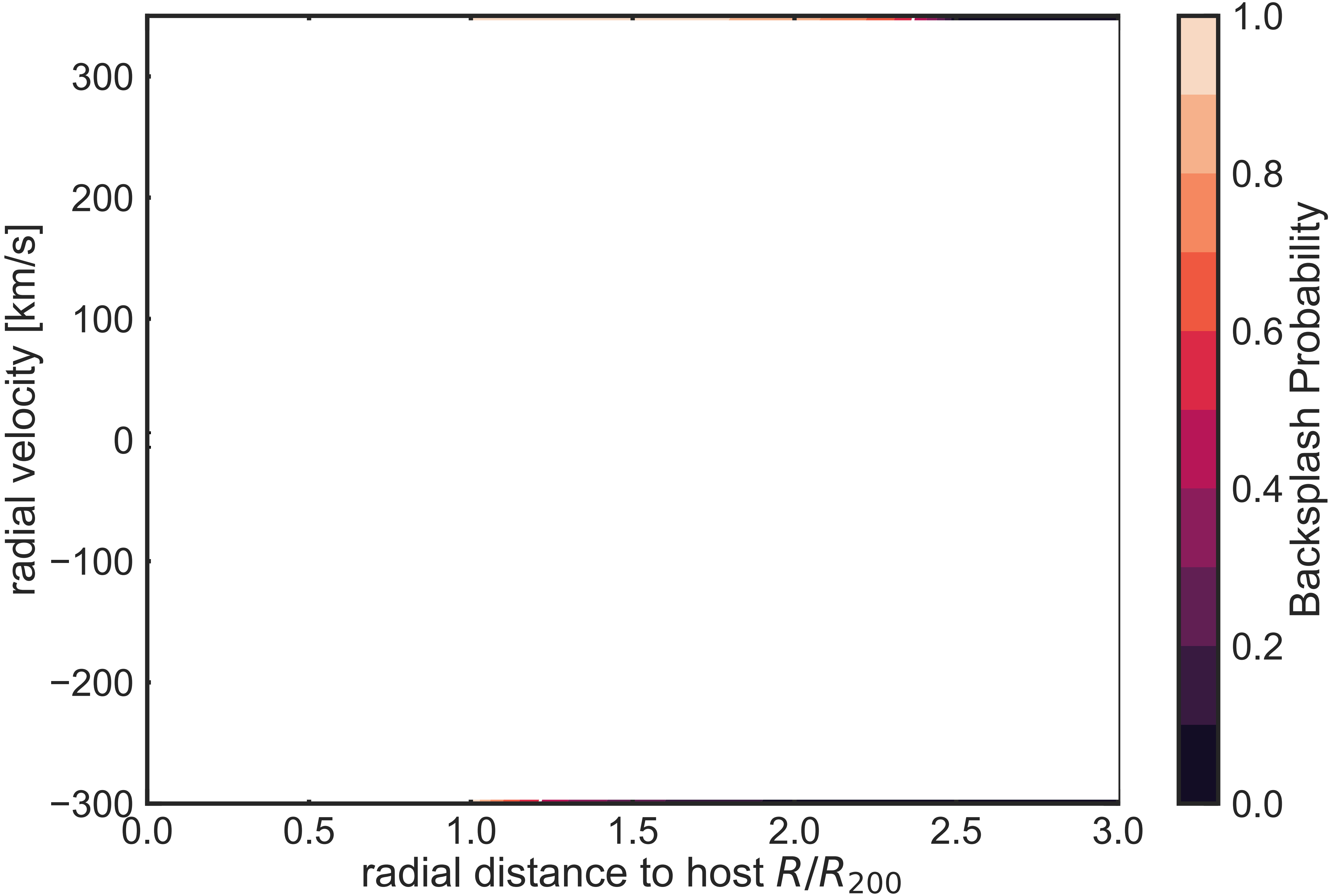
see also:
Knebe+ 2011

Can we identify backsplash galaxies



see also: Teyssier+ 2012

Can we identify backsplash galaxies



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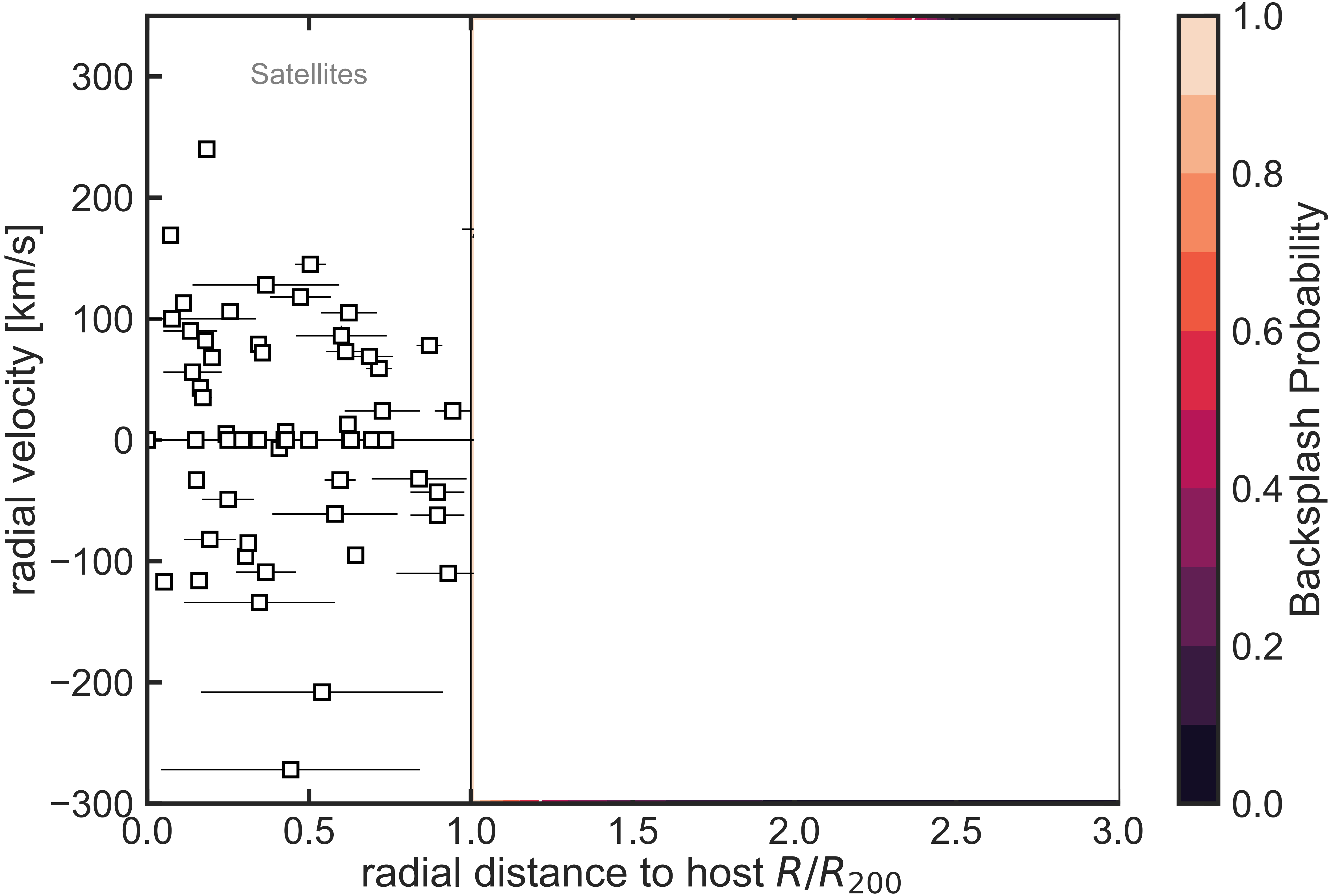
Can we identify backsplash galaxies



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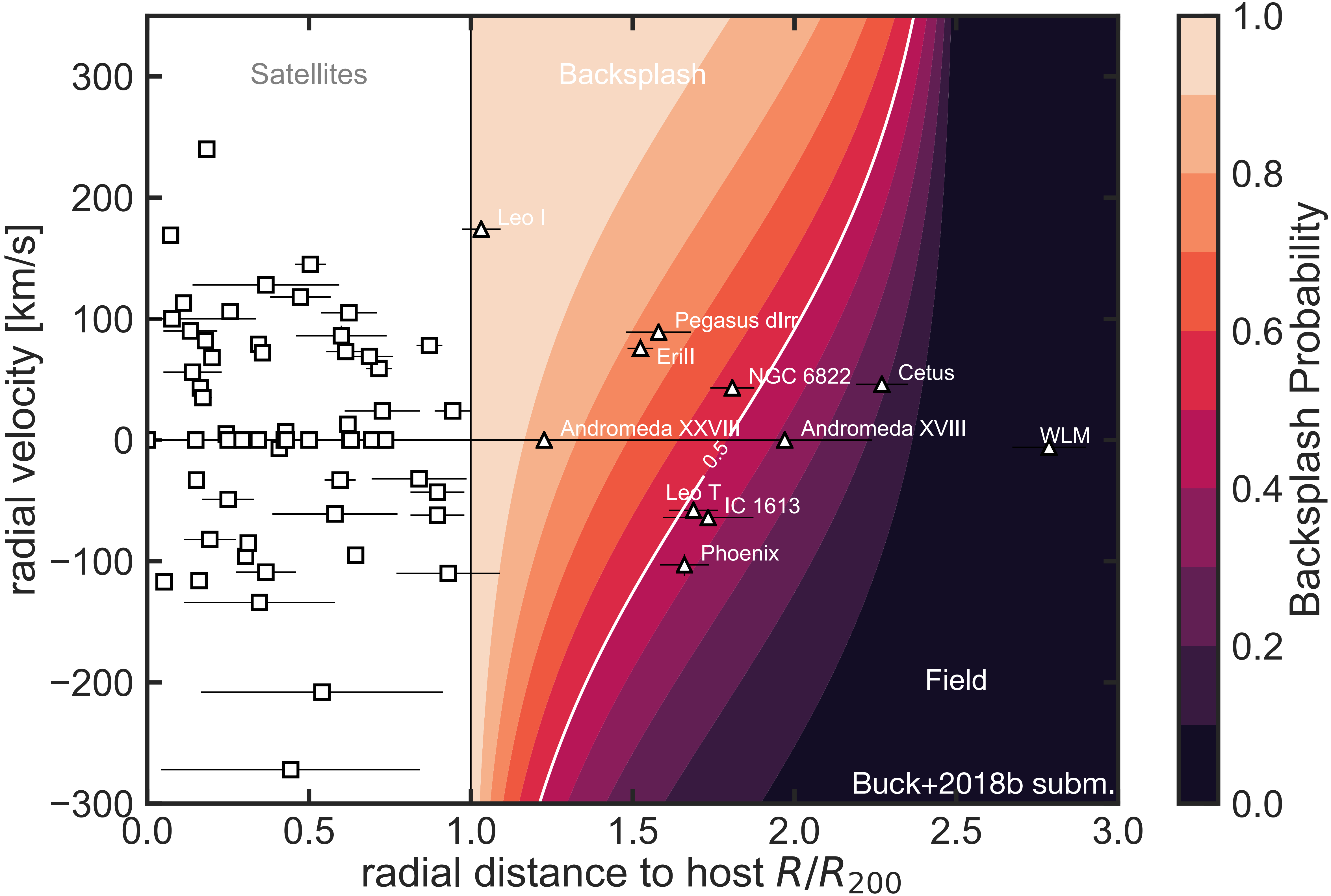
Can we identify backsplash galaxies



see also: Teyssier+ 2012

Reproducing the Local Group dwarf galaxy population

- number, mass and structure of simulated dwarf galaxies agree well with observed relations
- backsplash galaxies are common and they can be strongly affected by the host
- Identification of backsplash galaxies possible e.g. via distance and radial velocity

How did the Milky Way form?

the stellar disc

- structure in position and abundance space
- thin and thick disc

the peanut bulge

- morphology, kinematics
- formation

- high-redshift clumpy galaxies

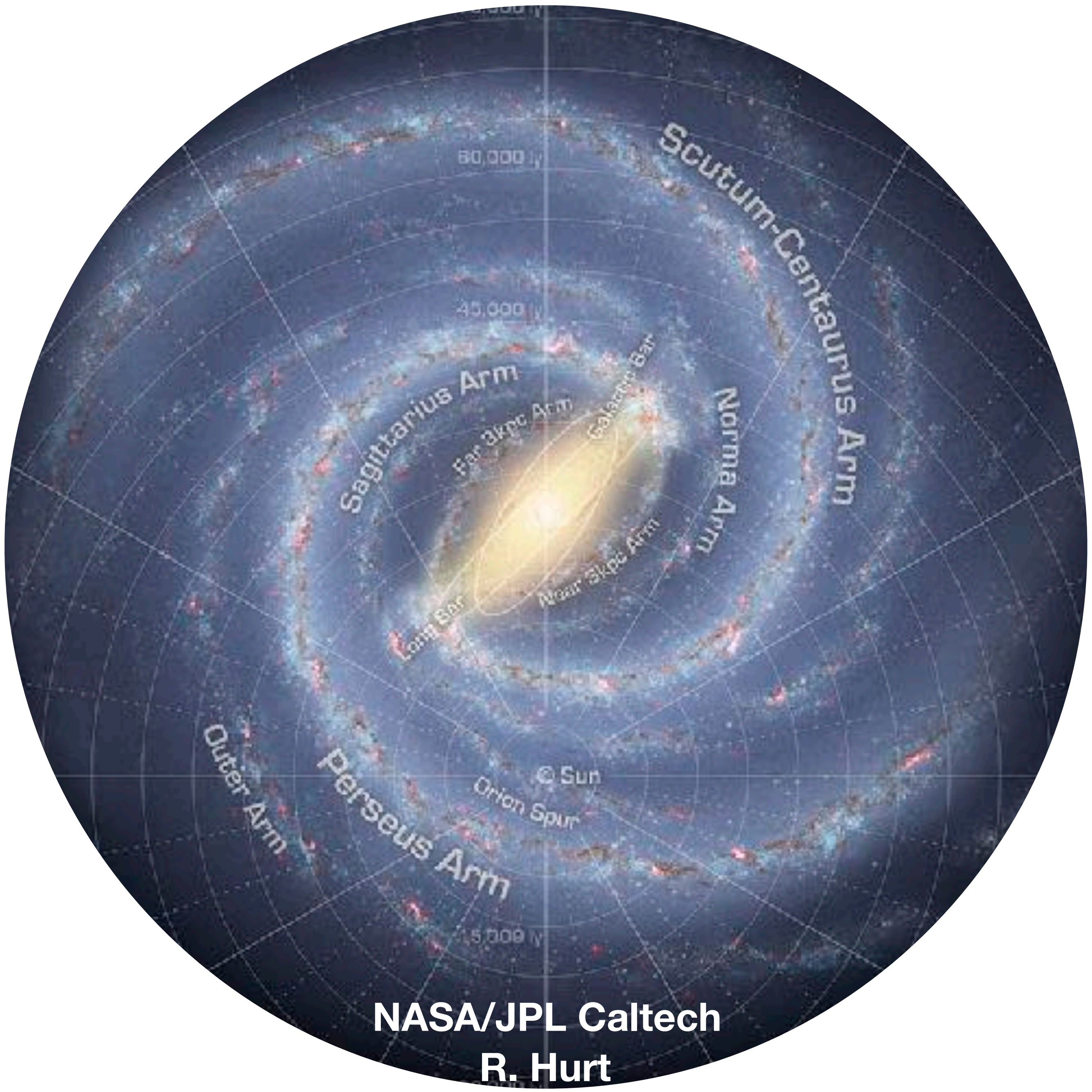
The early stellar disc

- spatial distribution
- environmental effects

dwarf galaxy population

Reproducing the central region of the Milky Way: the peanut-shaped bulge

The peanut-shaped bulge is caused by the bar seen edge-on!



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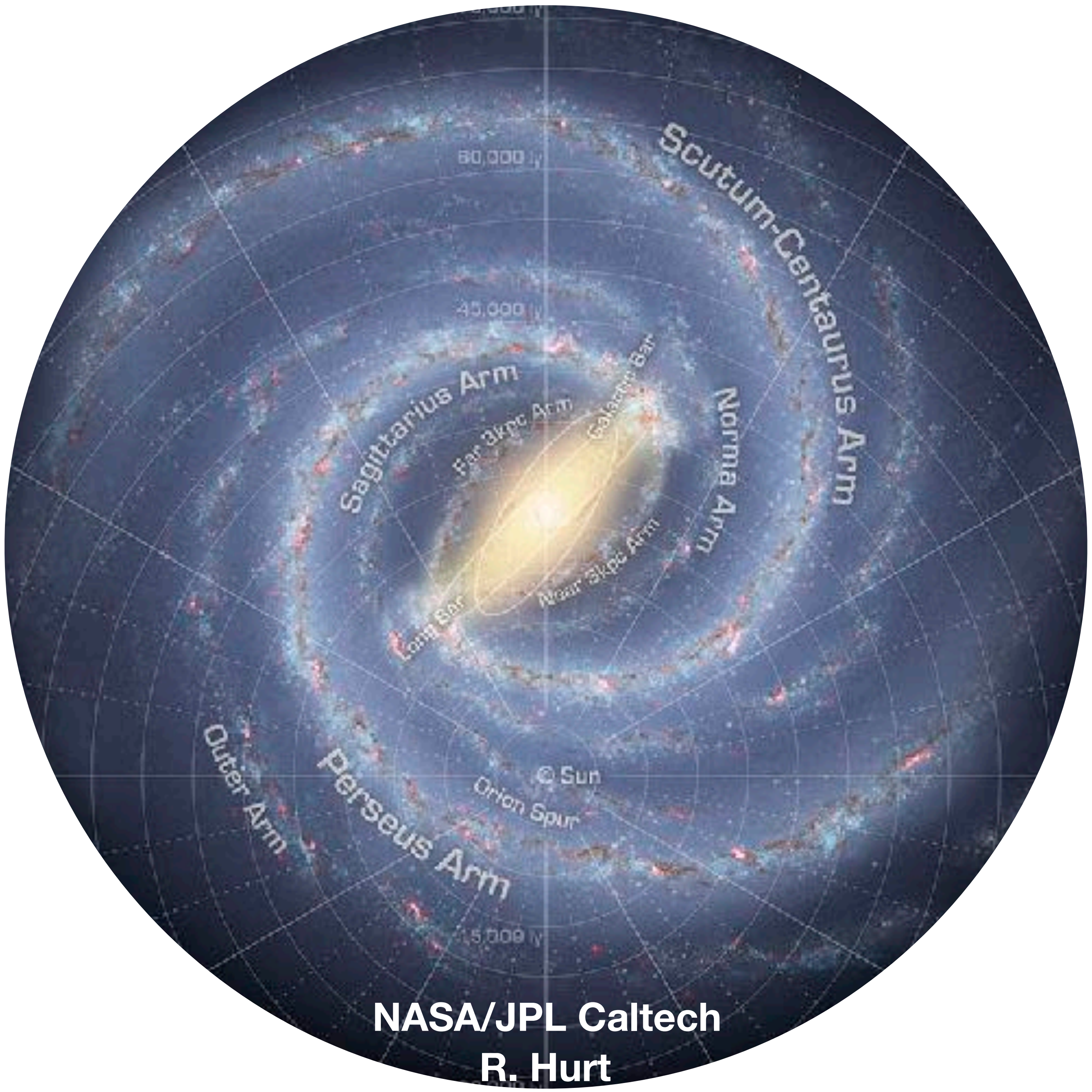

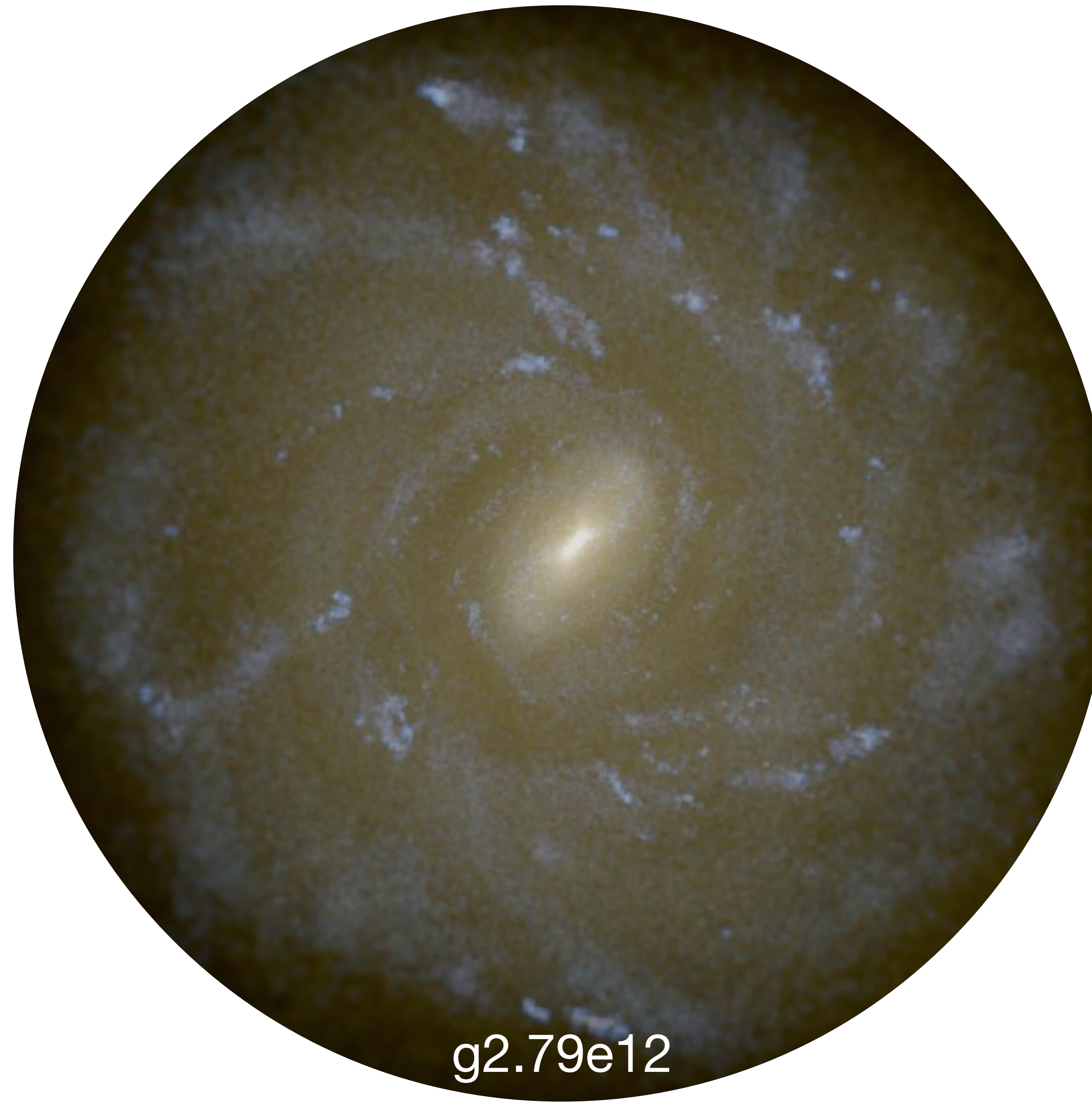

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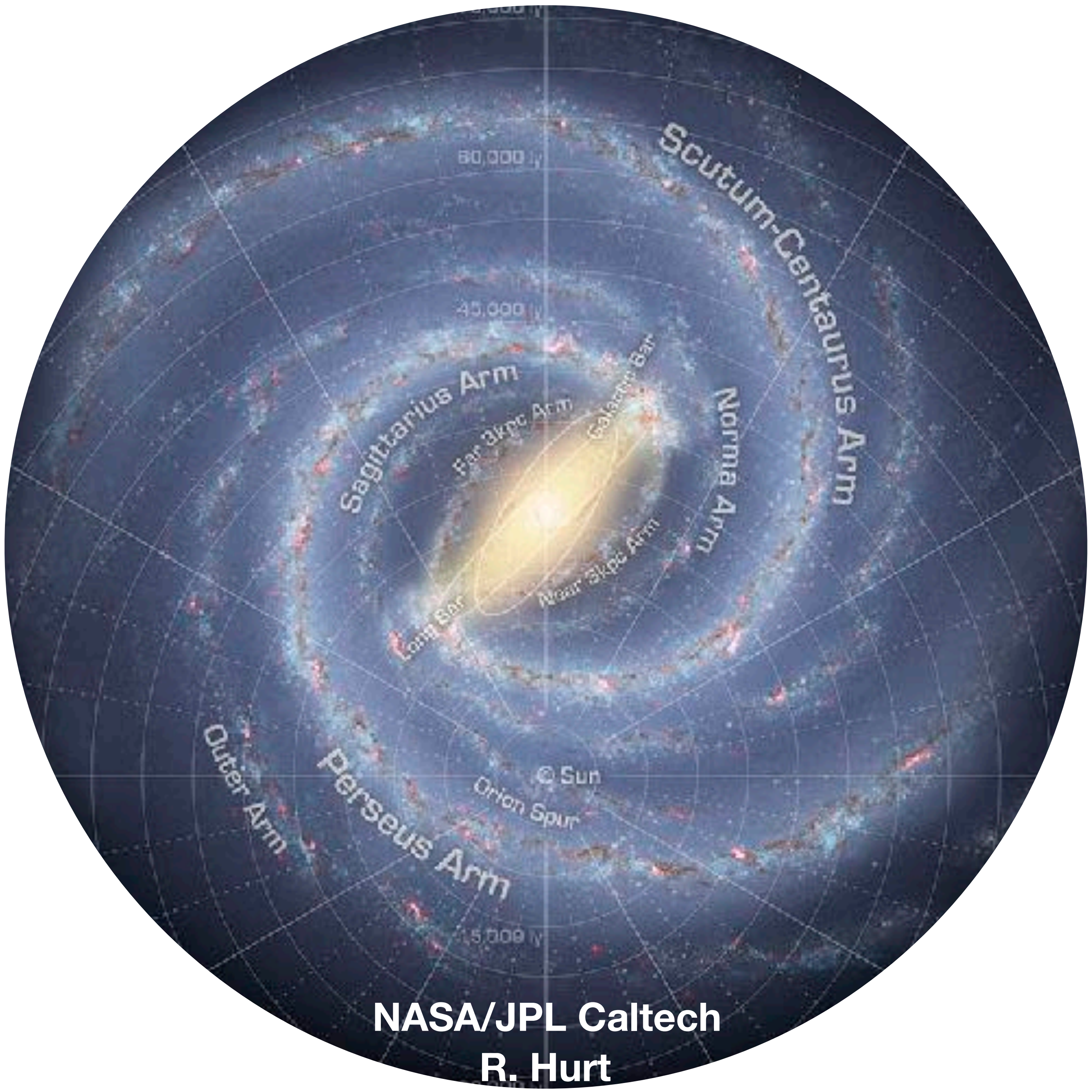

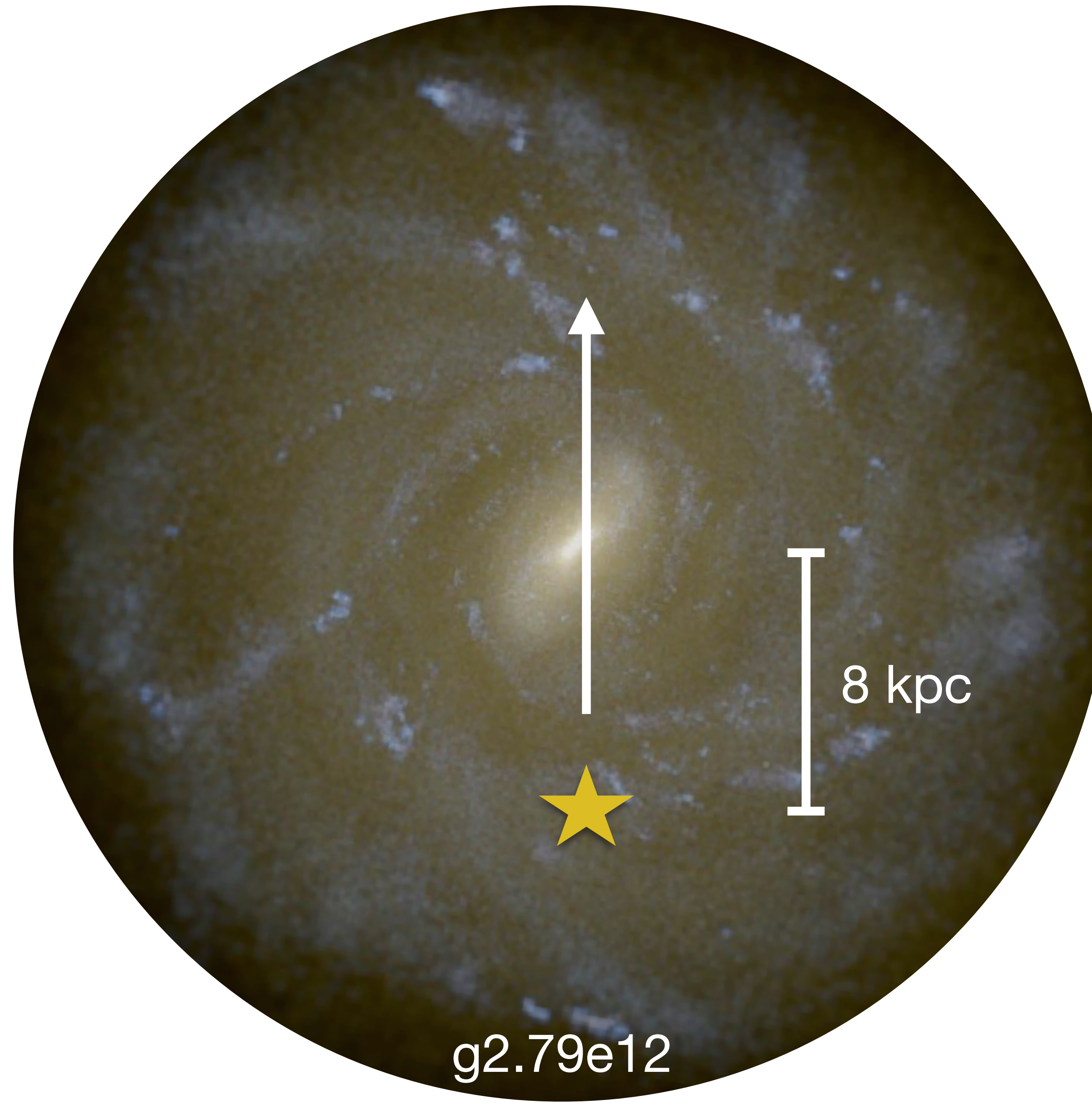

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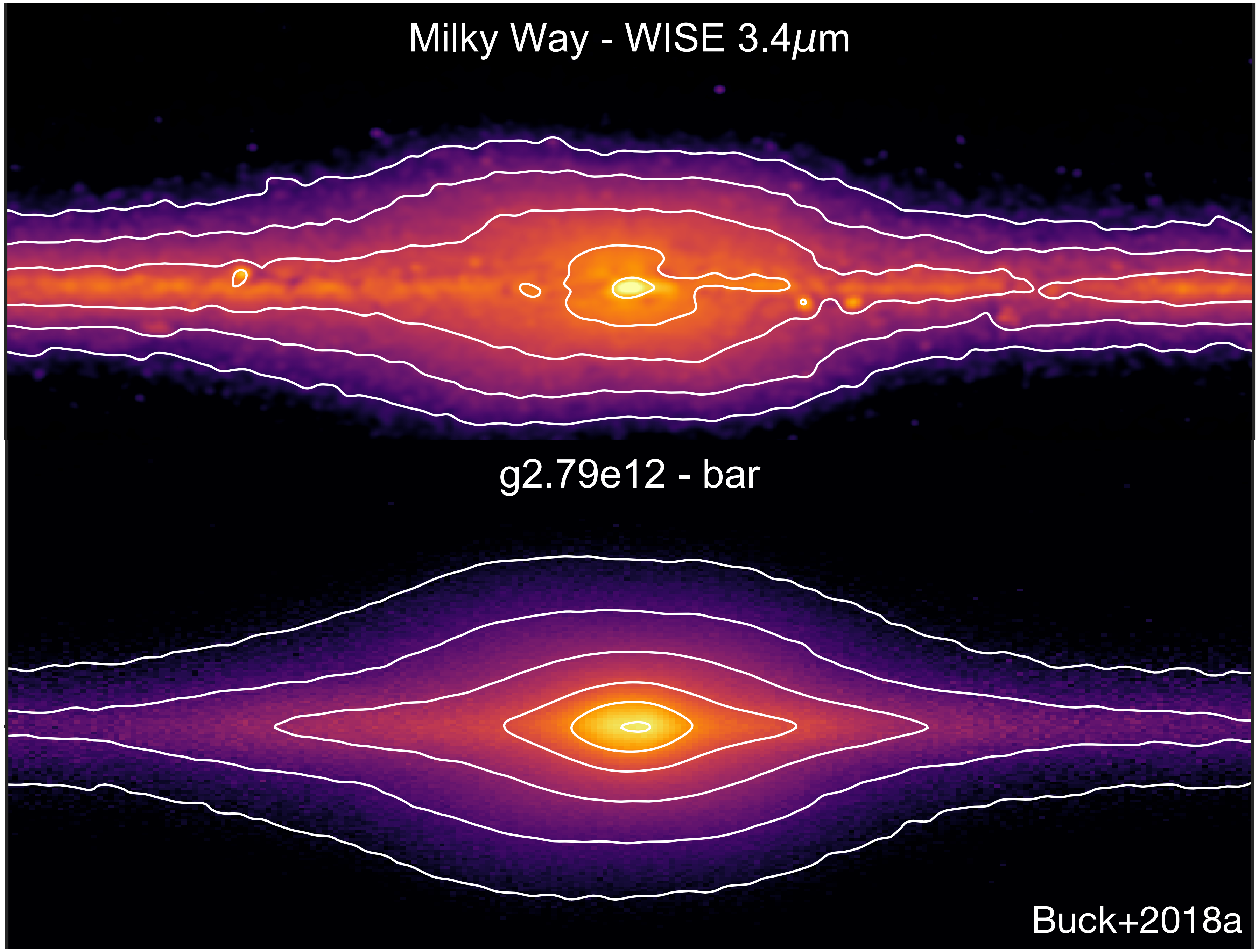
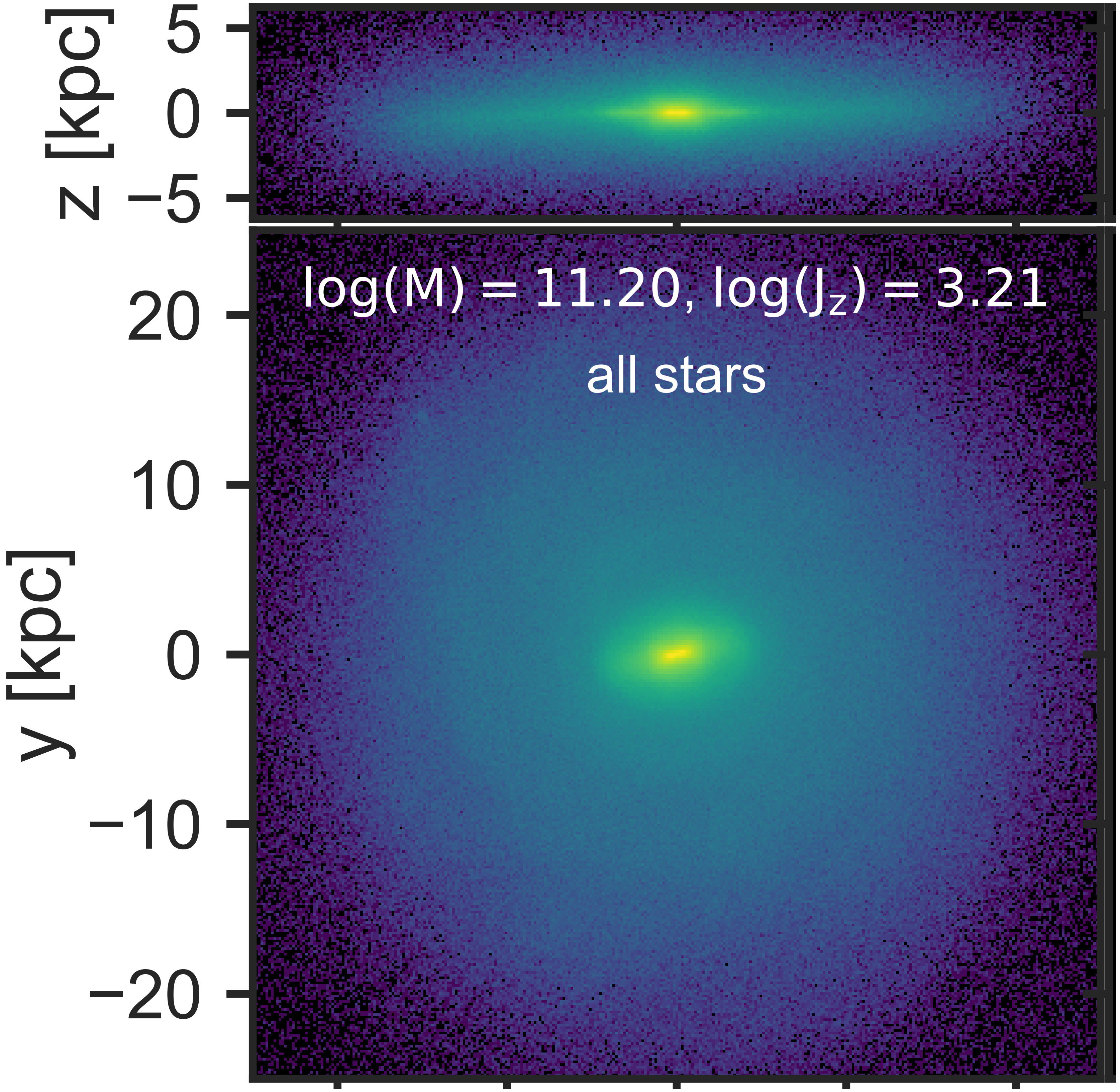


image field of view:
80x40 degree

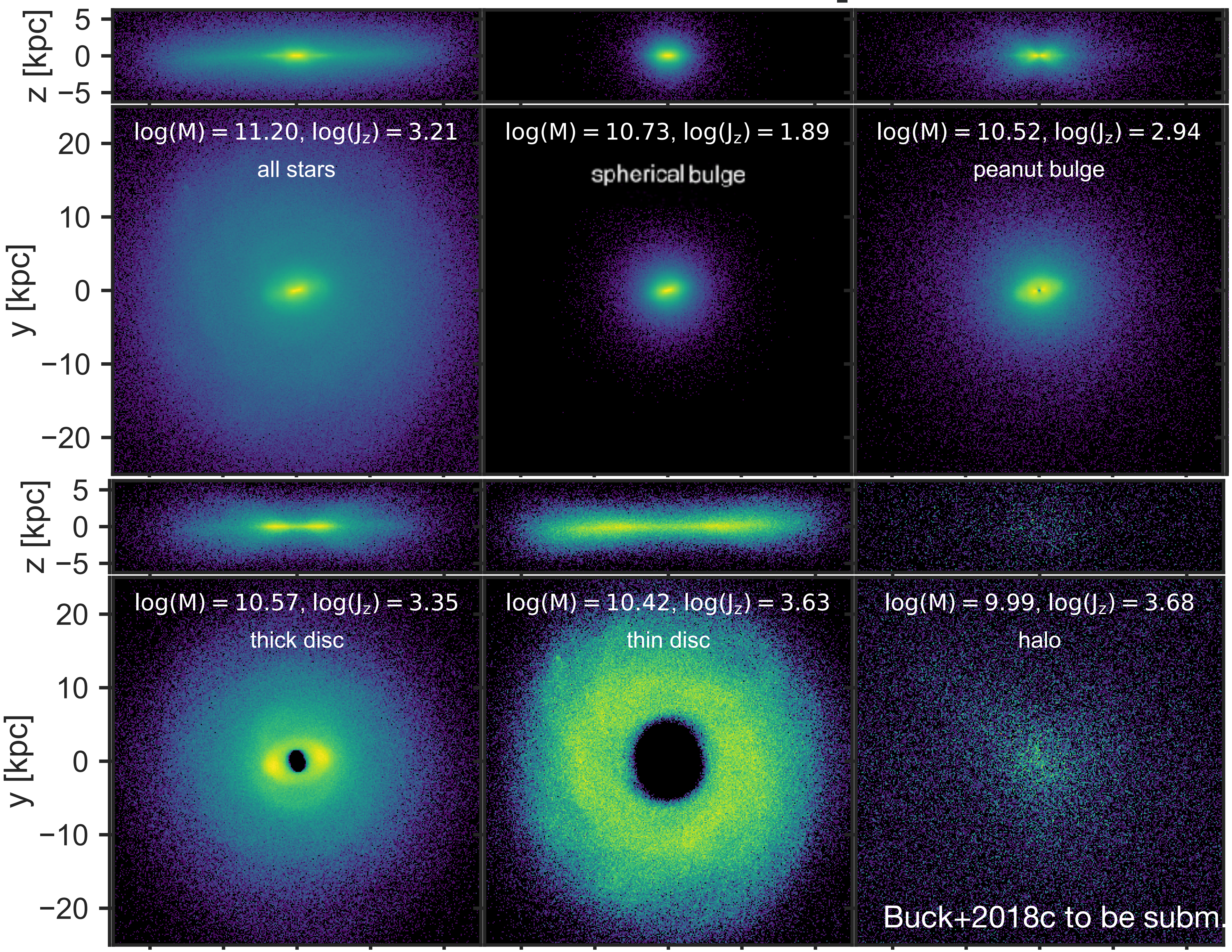
The formation scenario of the peanut bulge!

Kinematic Decomposition



decomposition: Obreja+(incl. Buck) 2018

Kinematic Decomposition



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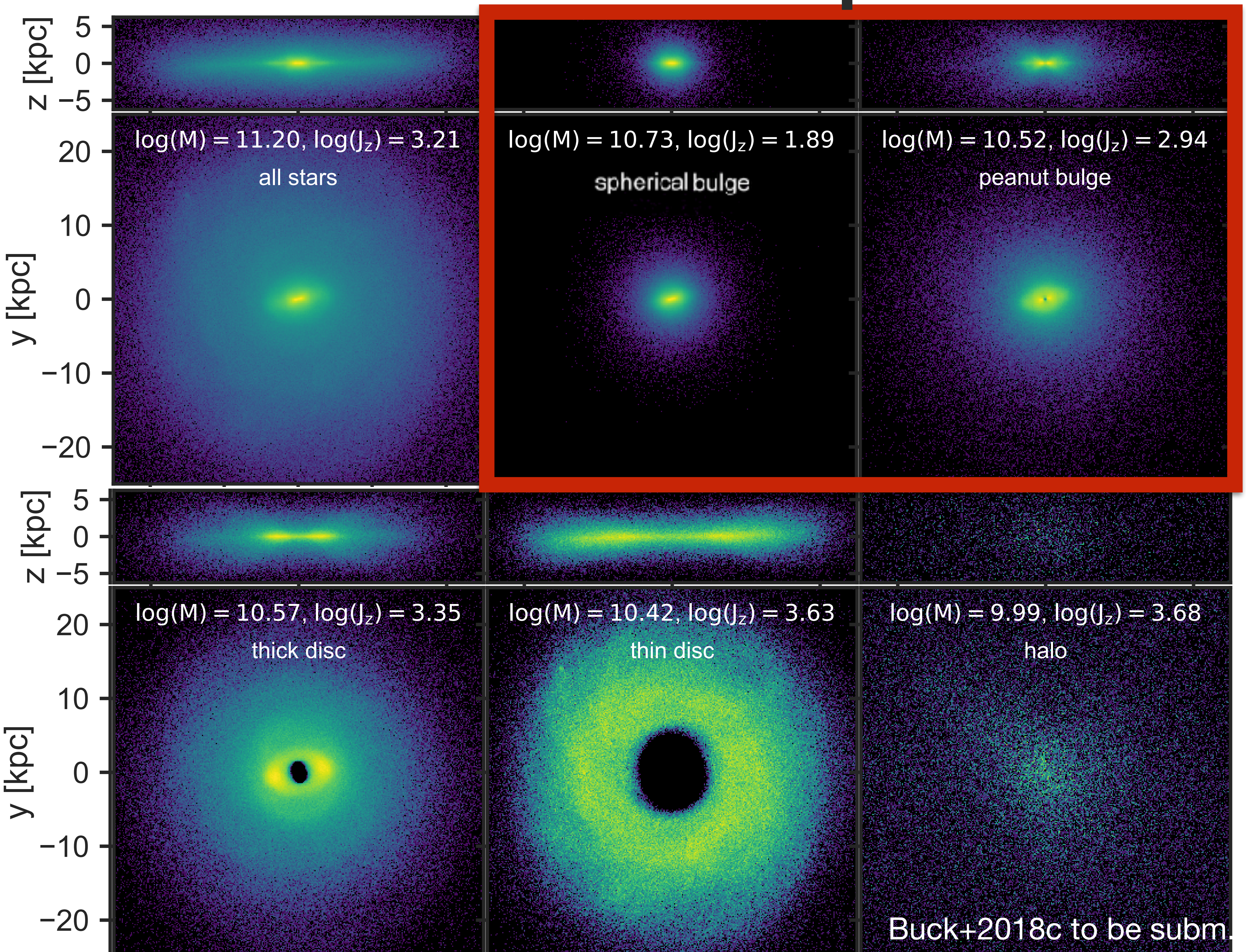
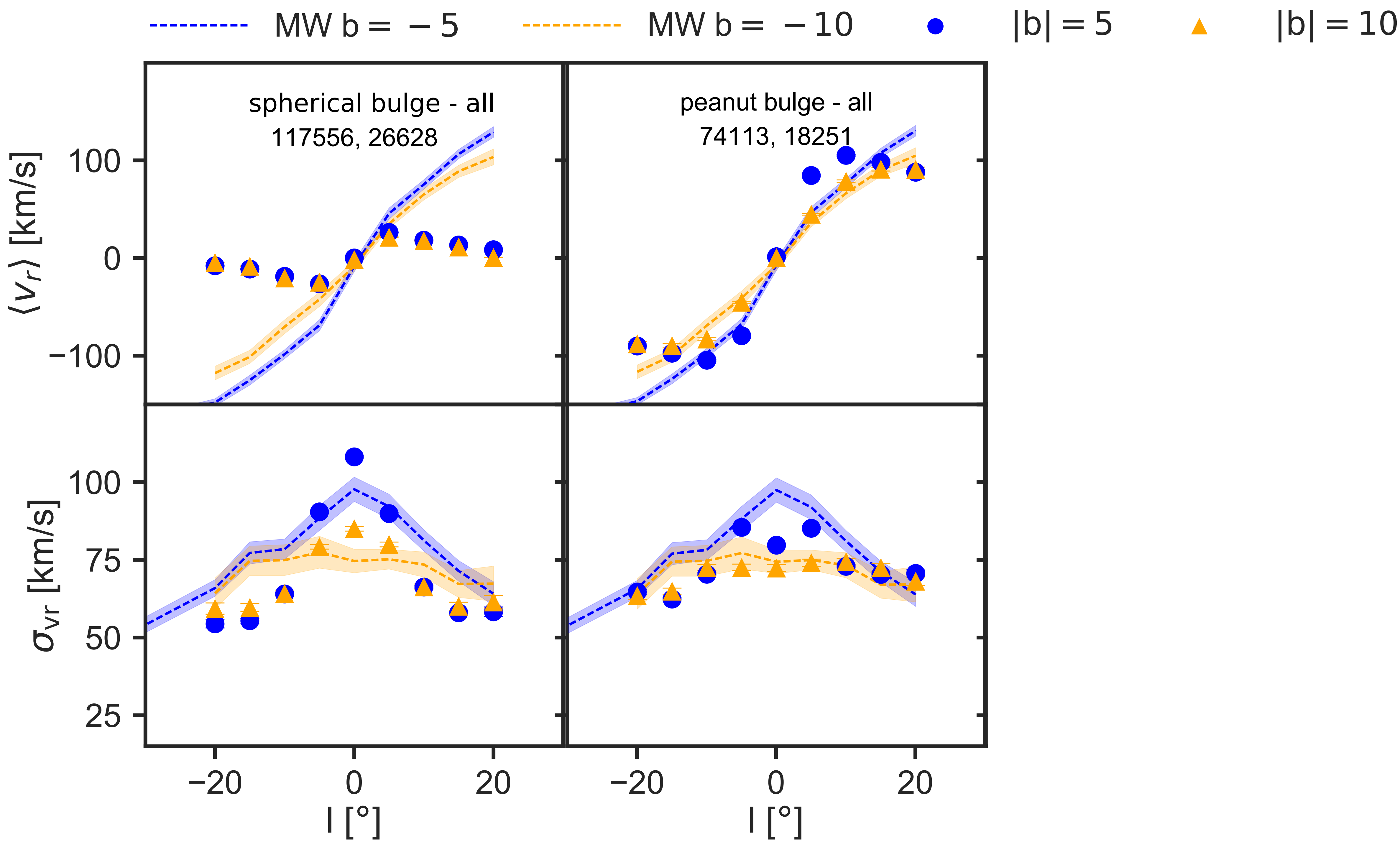
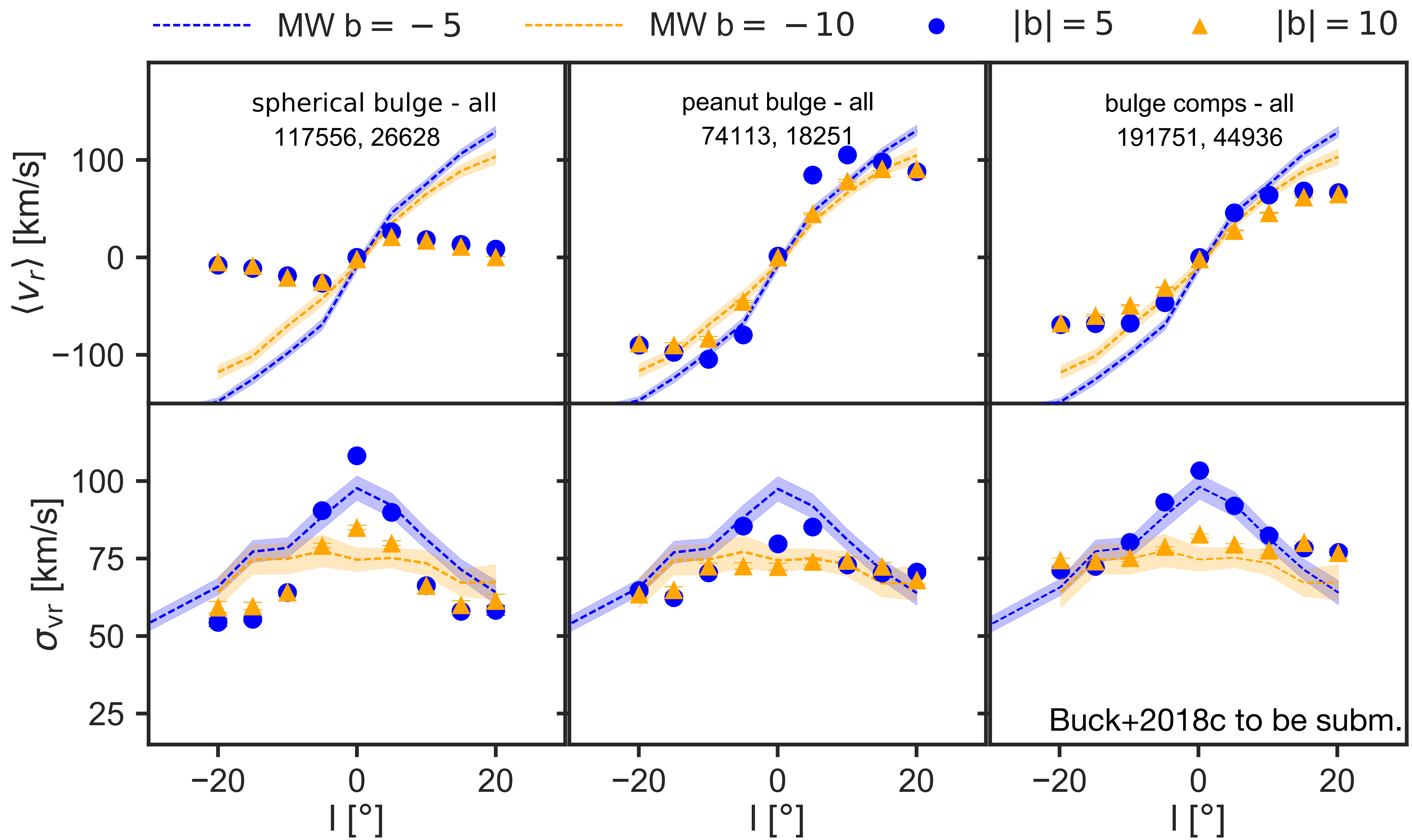


decomposition: Obreja+(incl. Buck) 2018

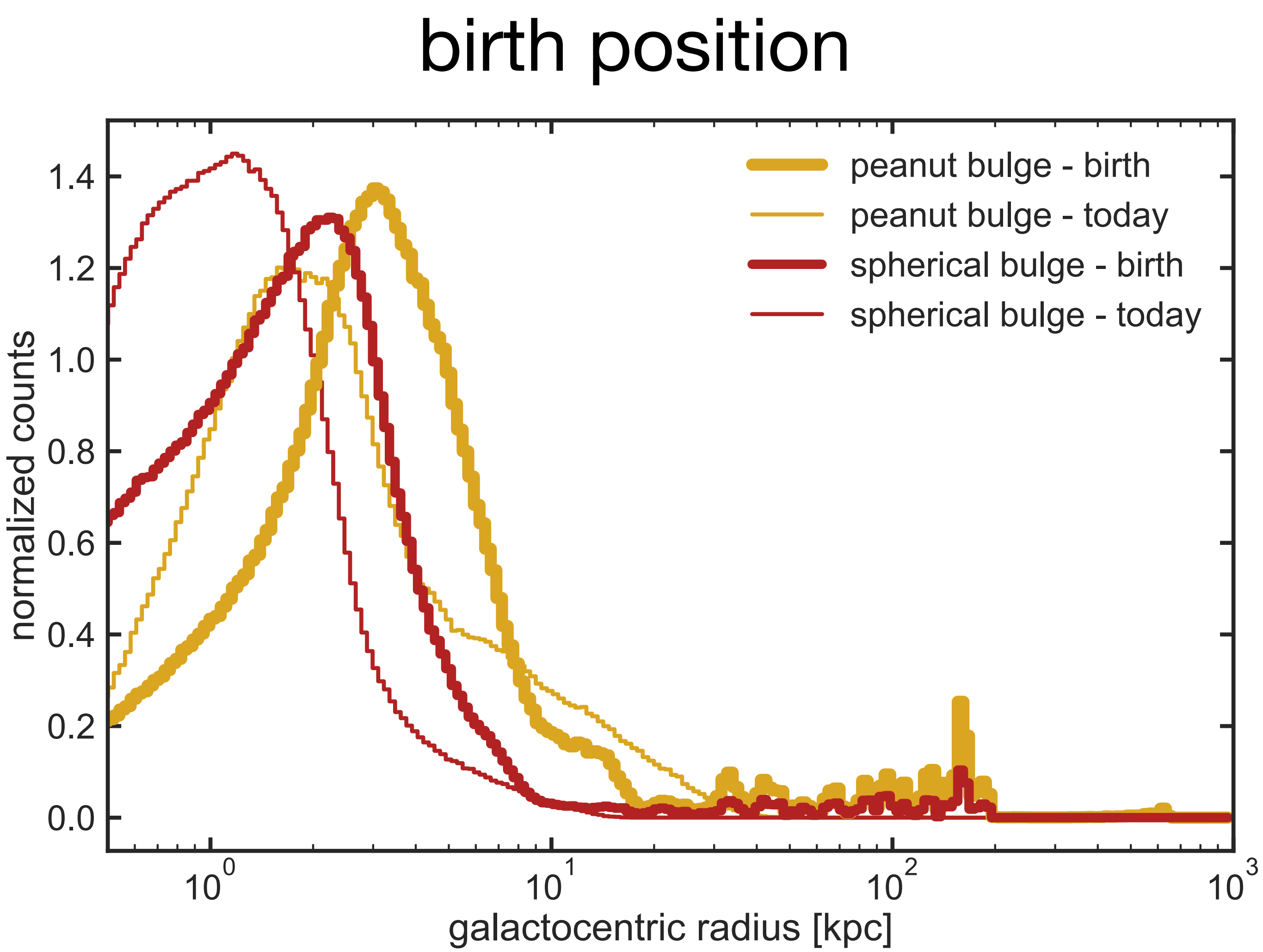
Different properties for peanut and spherical component

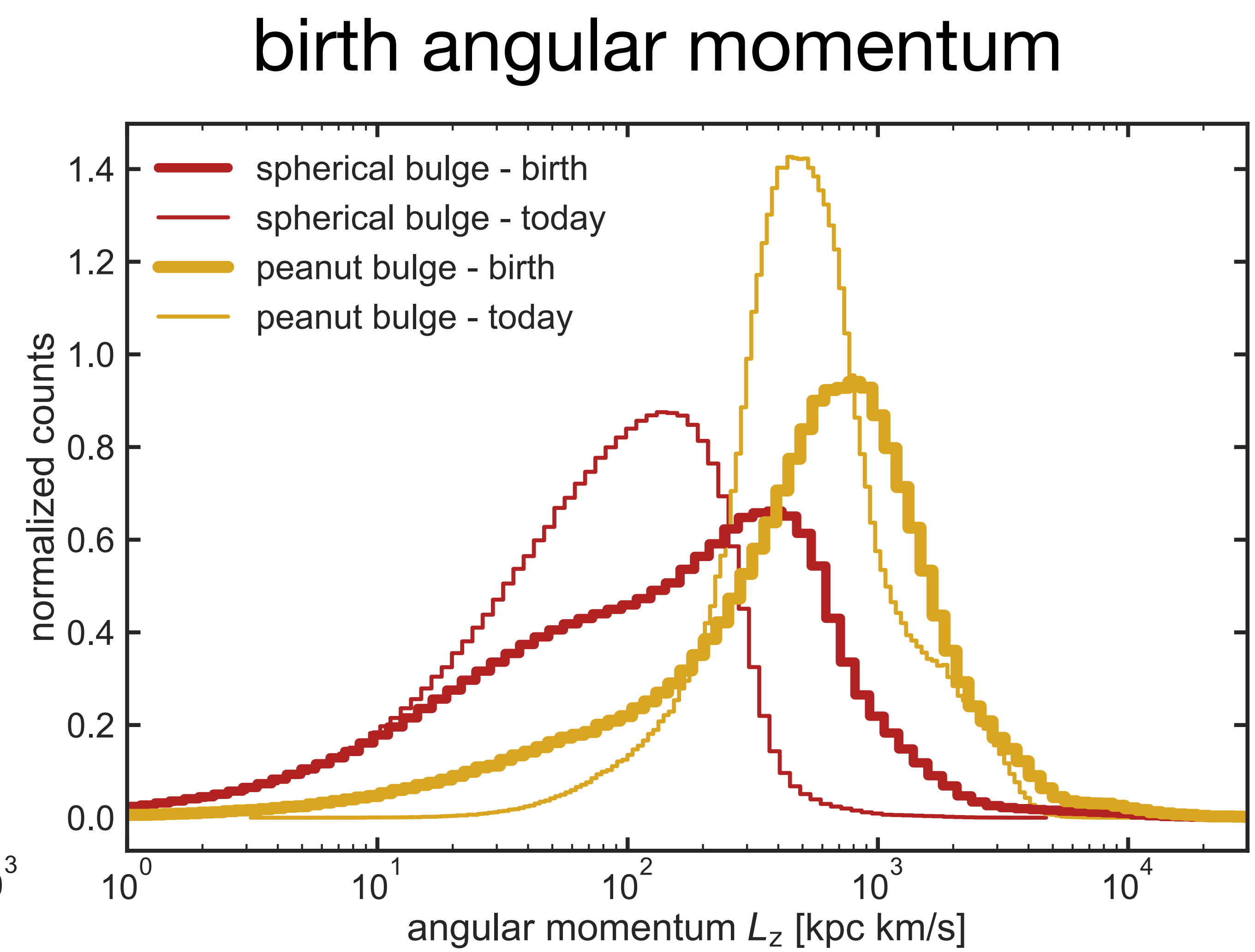


Different properties for peanut and spherical component



Birth properties of peanut and spherical bulge stars are different





Buck+2018c to be subm.

Reproducing the peanut shaped bulge of the MW

- first cosmo sim to reproduce key features of the peanut shaped bulge of the MW
- morphology and kinematics are well in agreement with observations of the MW
- Prediction: two kinematically different bulge components present in the MW
- peanut bulge stars have on av. higher birth angular momentum and larger birth radii

the stellar disc

the peanut bulge

How did the Milky Way form?

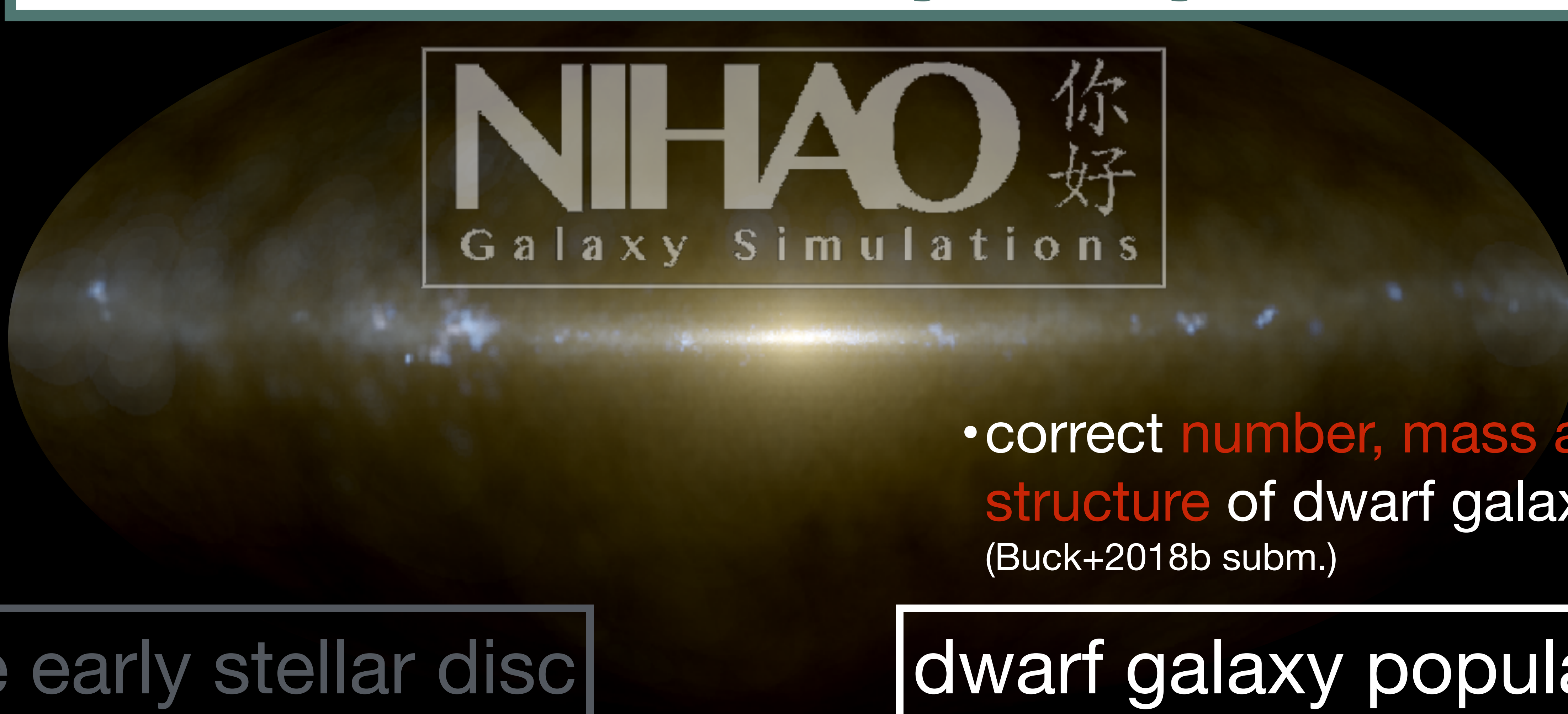
The early stellar disc

dwarf galaxy population

the stellar disc

the peanut bulge

How did the Milky Way form?



- correct number, mass and structure of dwarf galaxies (Buck+2018b subm.)

The early stellar disc

dwarf galaxy population

the stellar disc

the peanut bulge

- first cosmo sim reproducing MW bulge (Buck+2018a, Buck+2018c to be subm.)
- 2 kinematically distinct bulge comps.

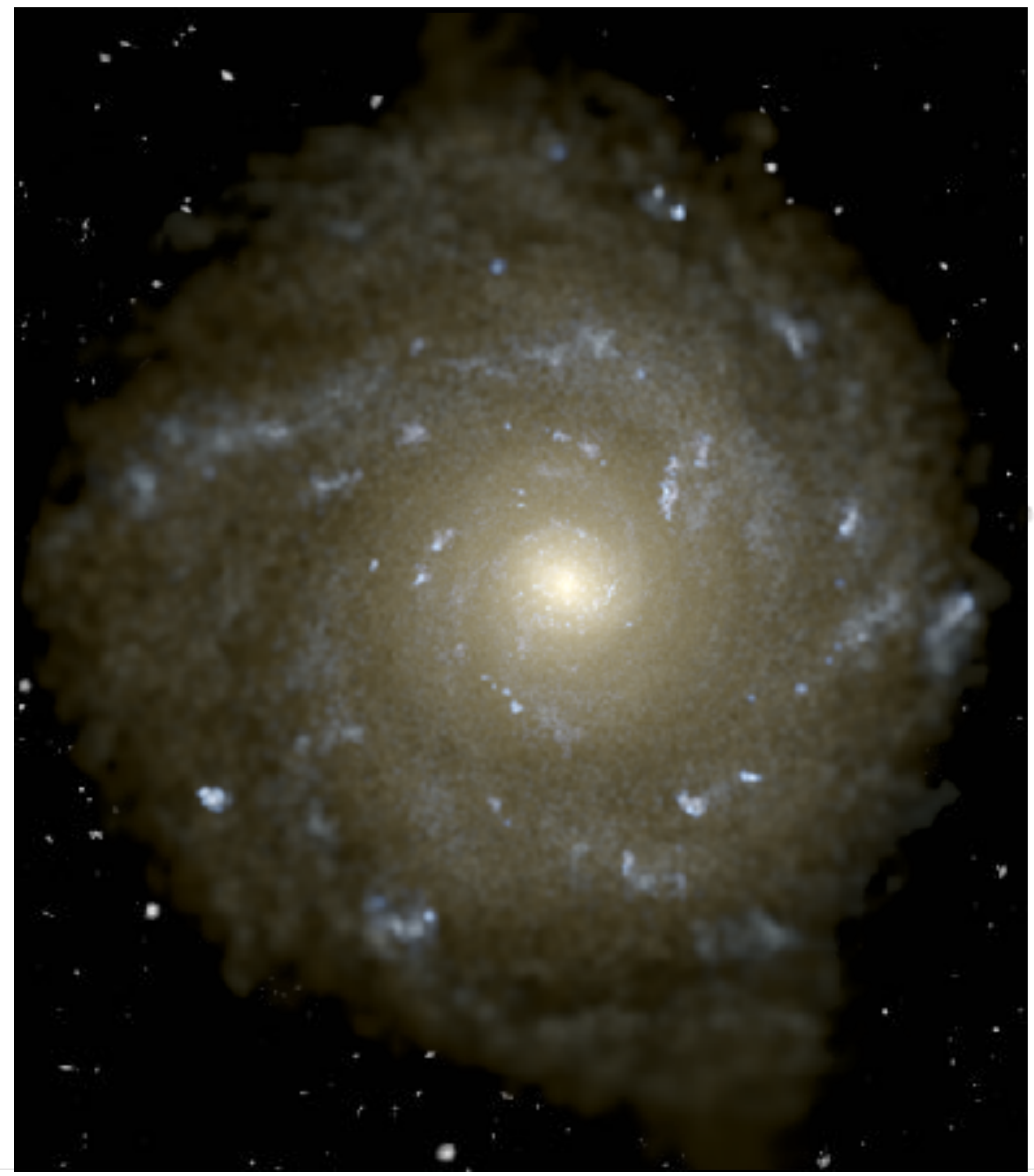
How did the Milky Way form?

- correct number, mass and structure of dwarf galaxies (Buck+2018b subm.)

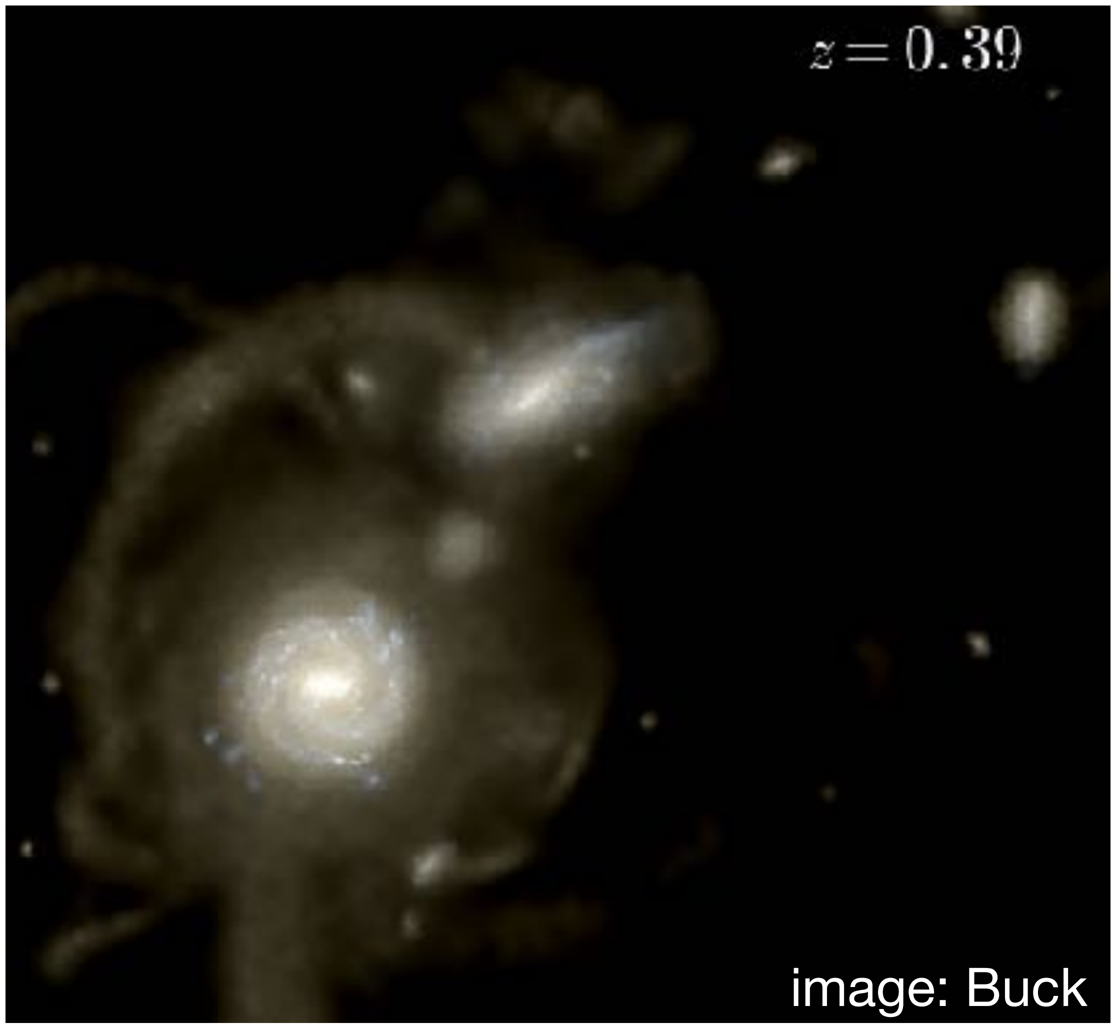
The early stellar disc

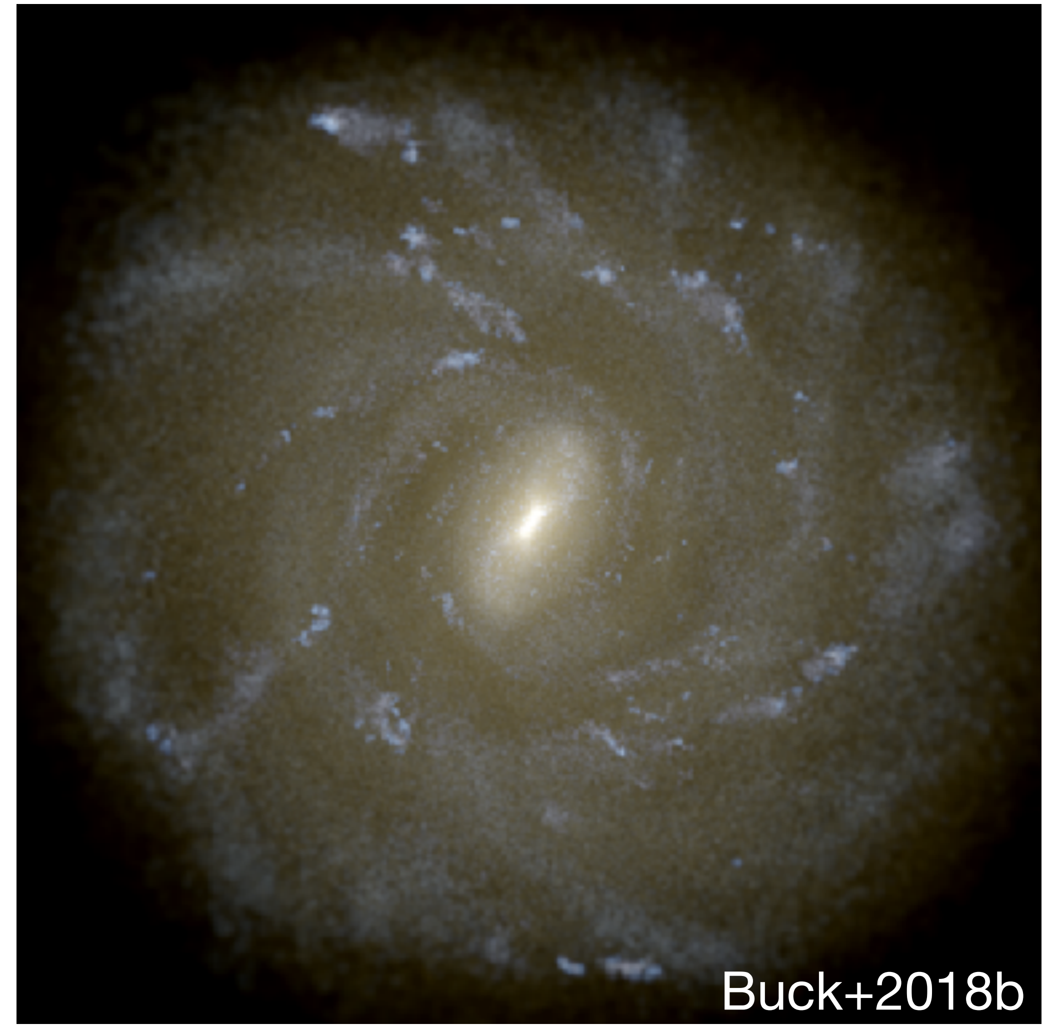
dwarf galaxy population

State of the art simulations: realistic! Use them with up-coming Galactic surveys!



Which information can we extract from the structure of the stellar disc?





Questions:

- What is the influence of (internal) secular evolution as opposed to (external) environmental effects?

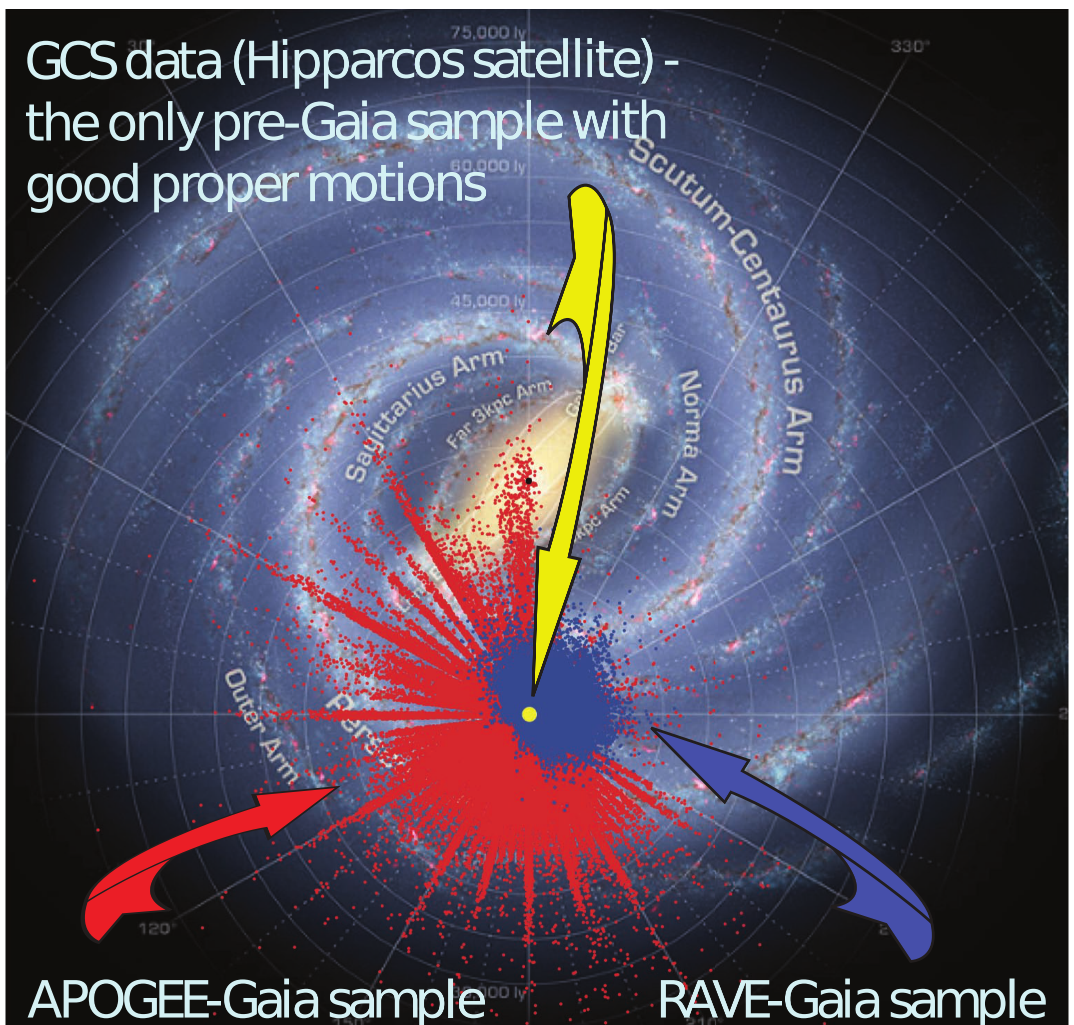
see also: Aumer+2014 (simulations), Terrazas+2016 (semi-analytic models)

The structure of the whole MW stellar disc will be measured

Gaia ⟶ 5+1D phase space coordinates (25th of April 2018)

APOGEE2 + 4MOST + Galah ⟶ chemical abundances

KEPLER + APOGEE (Cannon) ⟶ ages



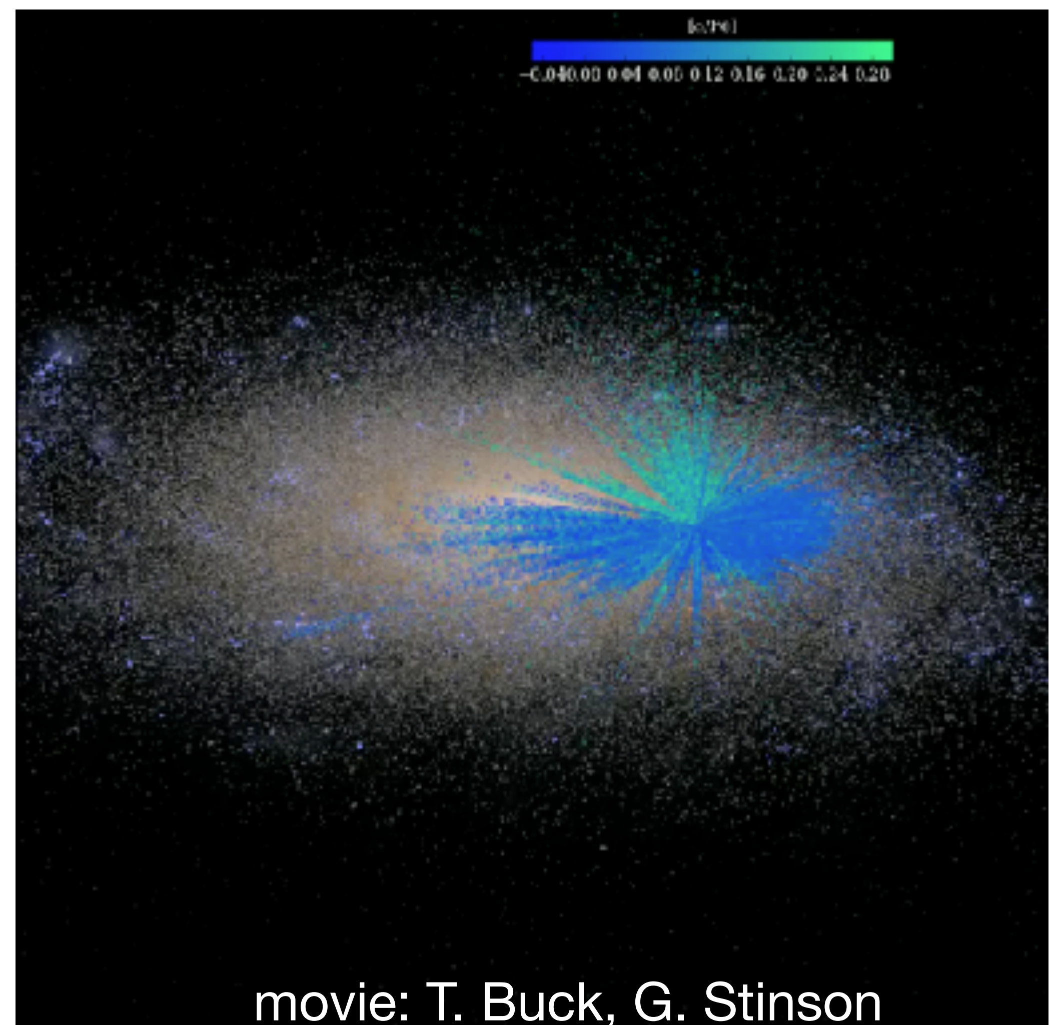


image credit: Ivan Minchev

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APOGEE2 + 4MOST + Galah ⟶ chemical abundances

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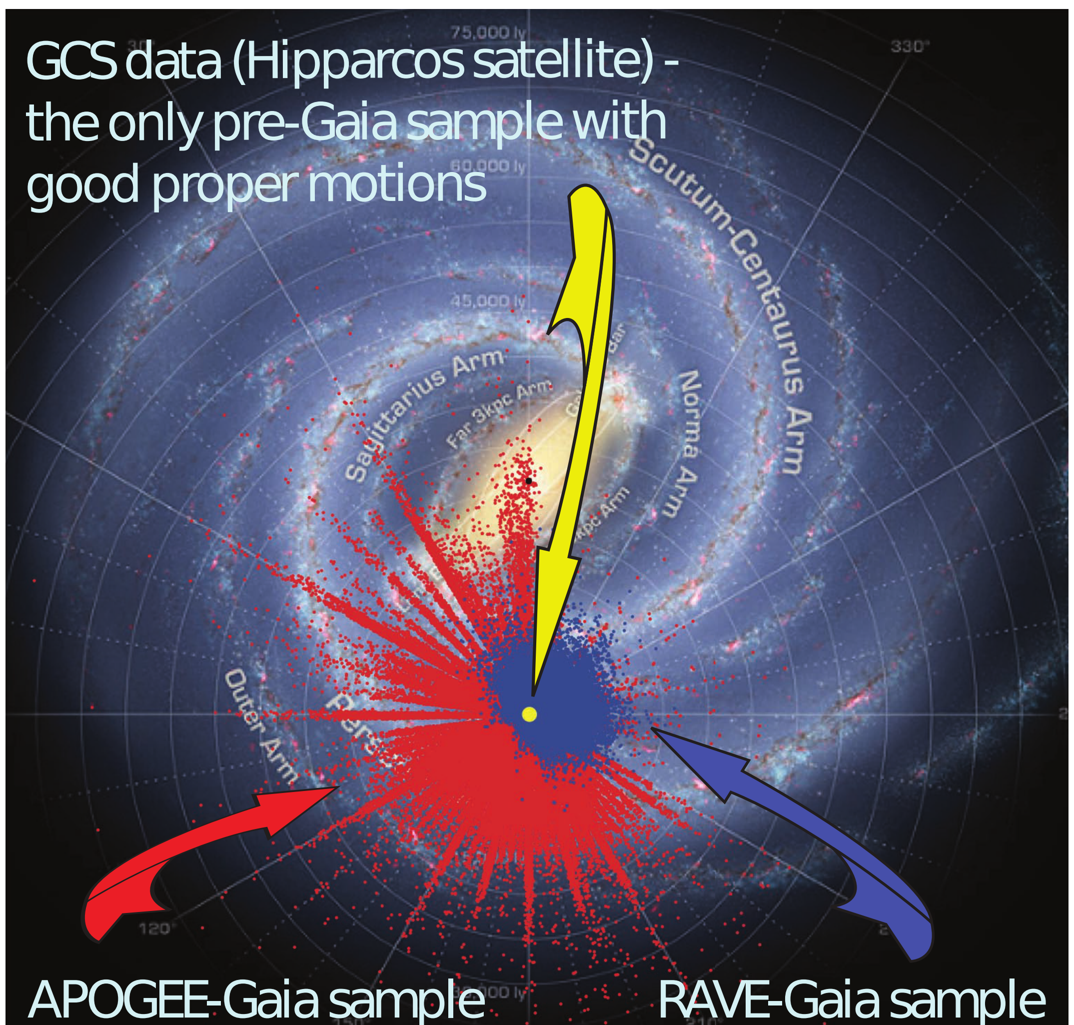


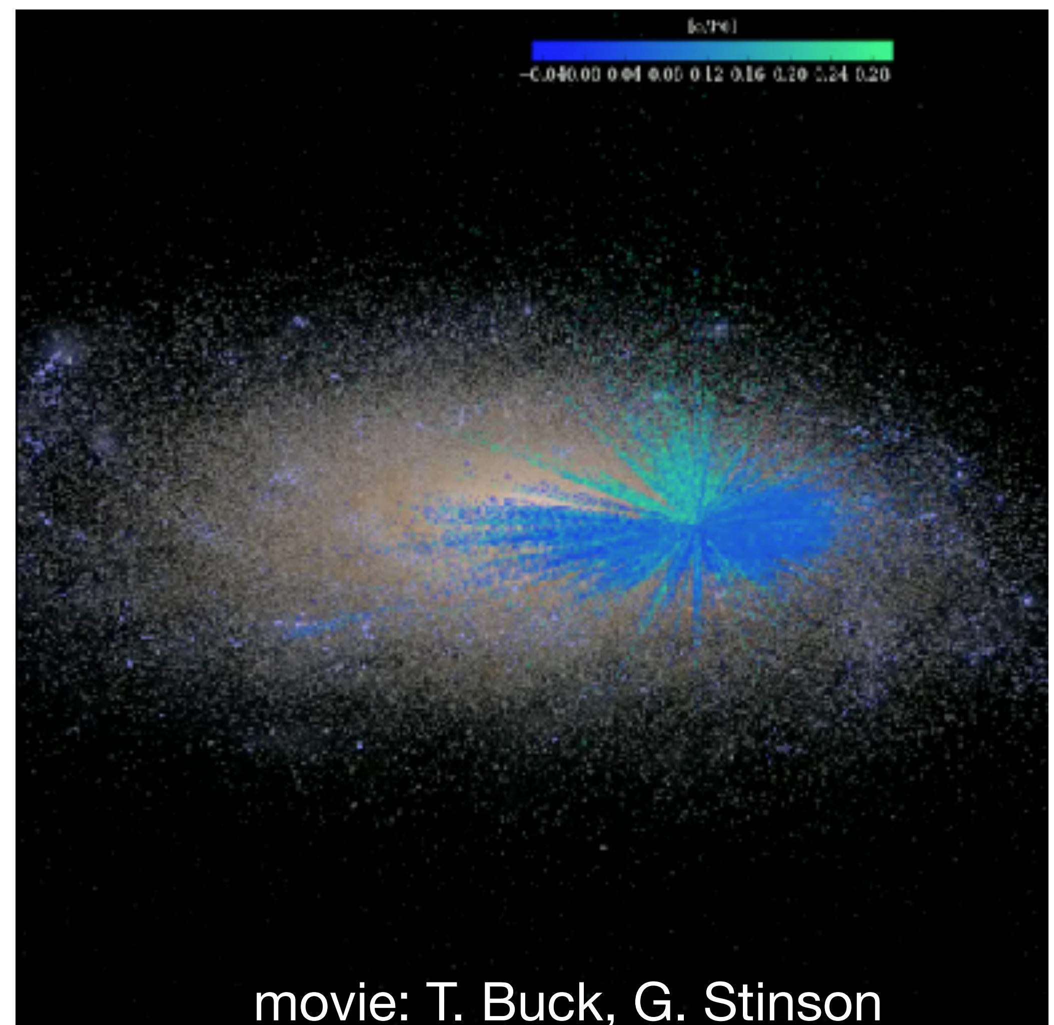


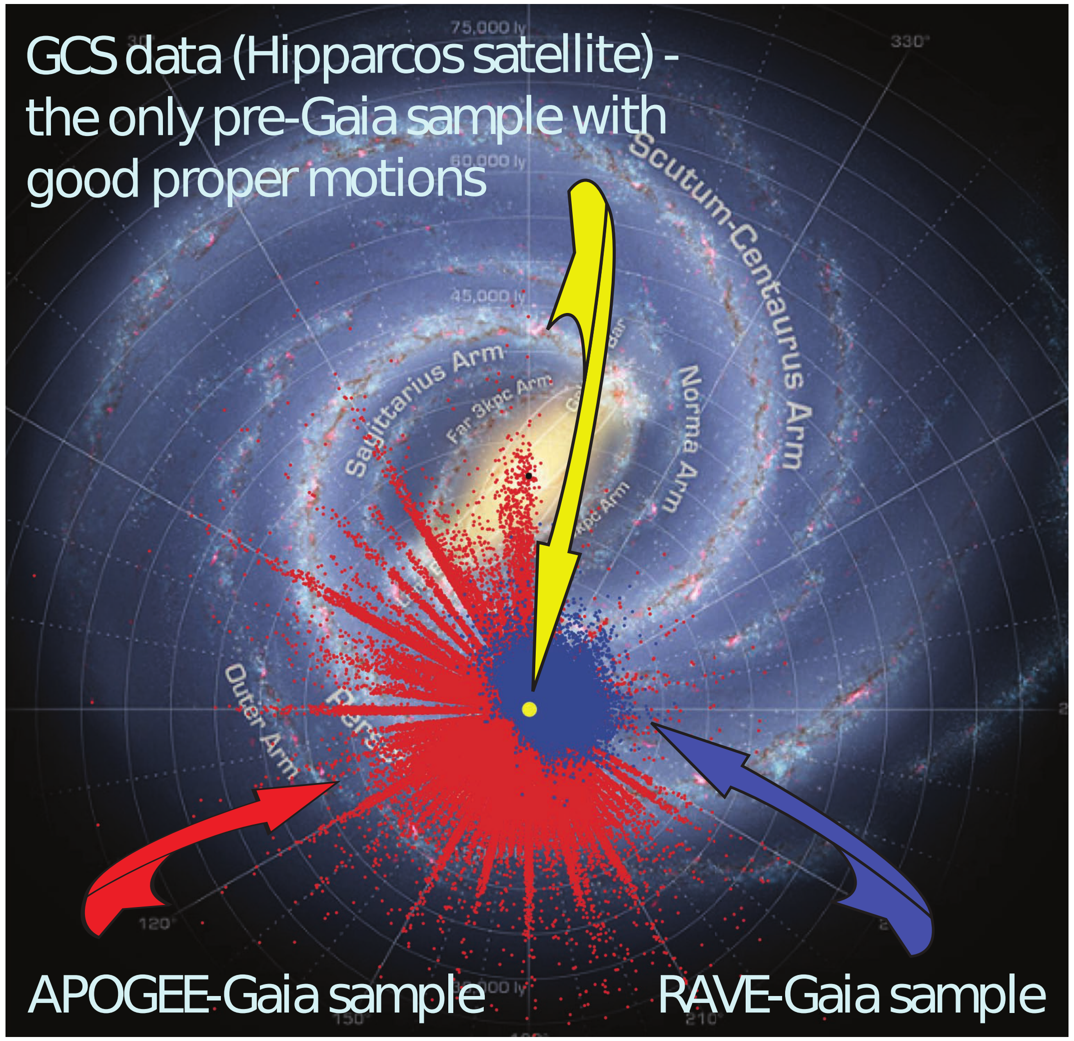
image credit: Ivan Minchev

The structure of the whole MW stellar disc will be measured

Gaia → 5+1D phase space coordinates (25th of April 2018)

APOGEE2 + 4MOST + Galah → chemical abundances

KEPLER + APOGEE (Cannon) → ages



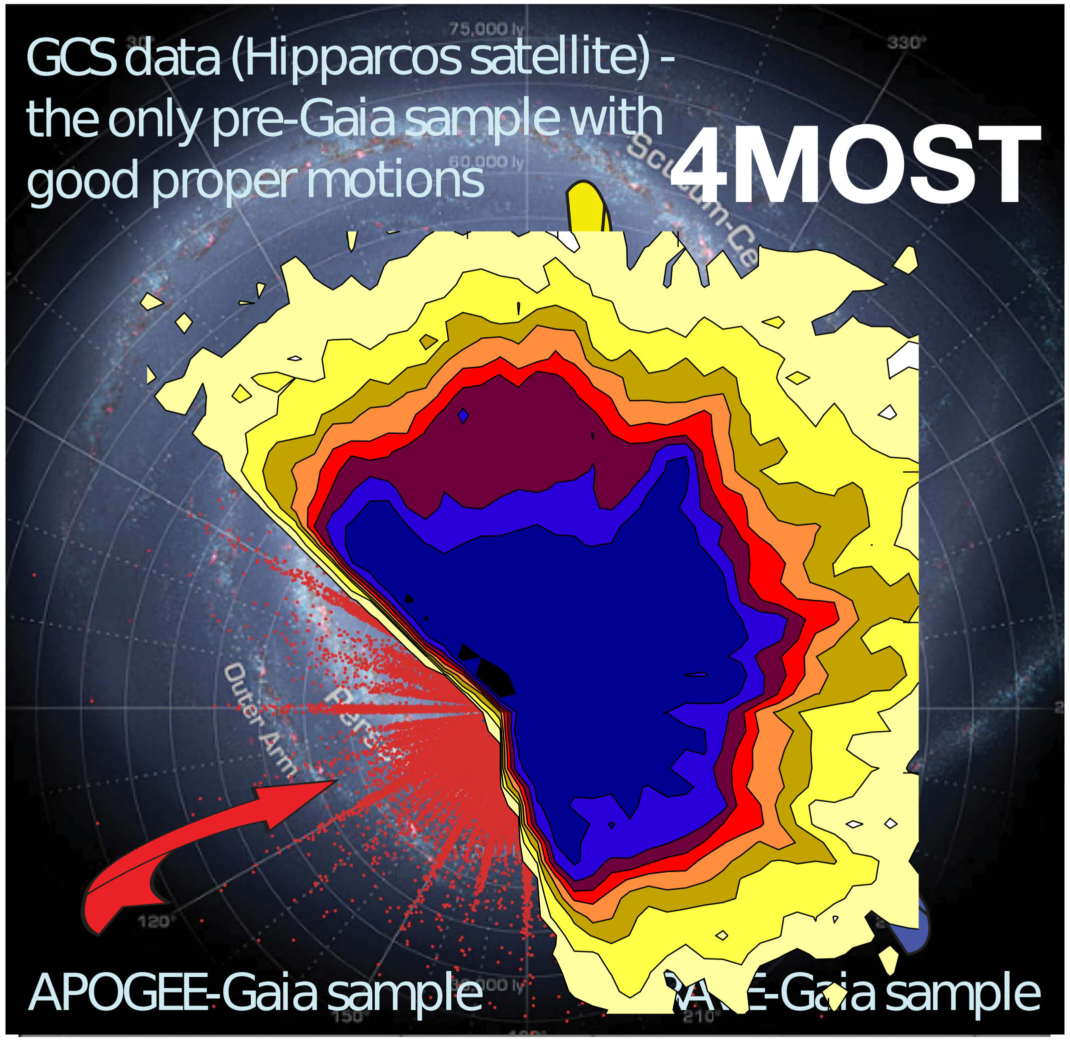
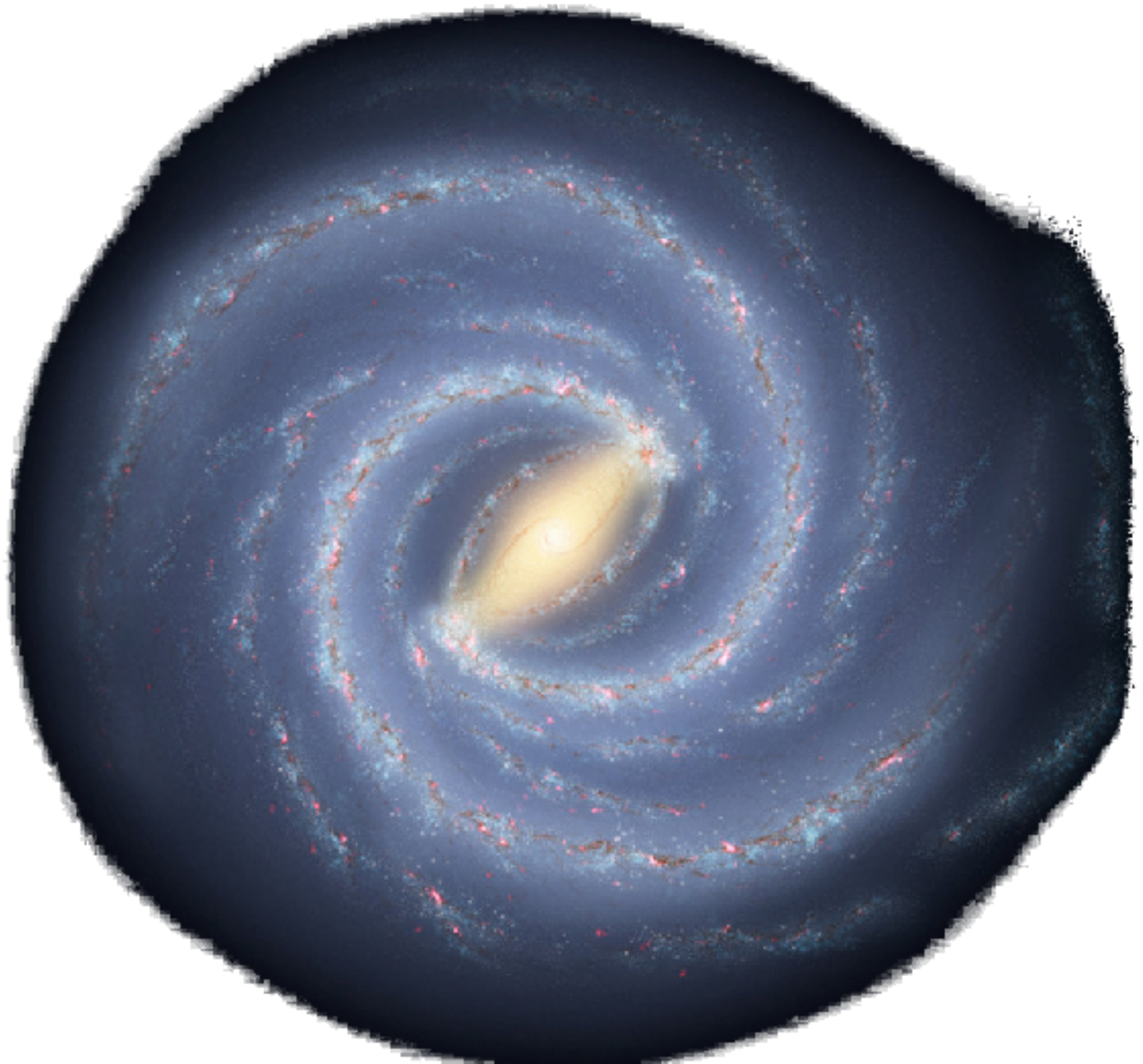
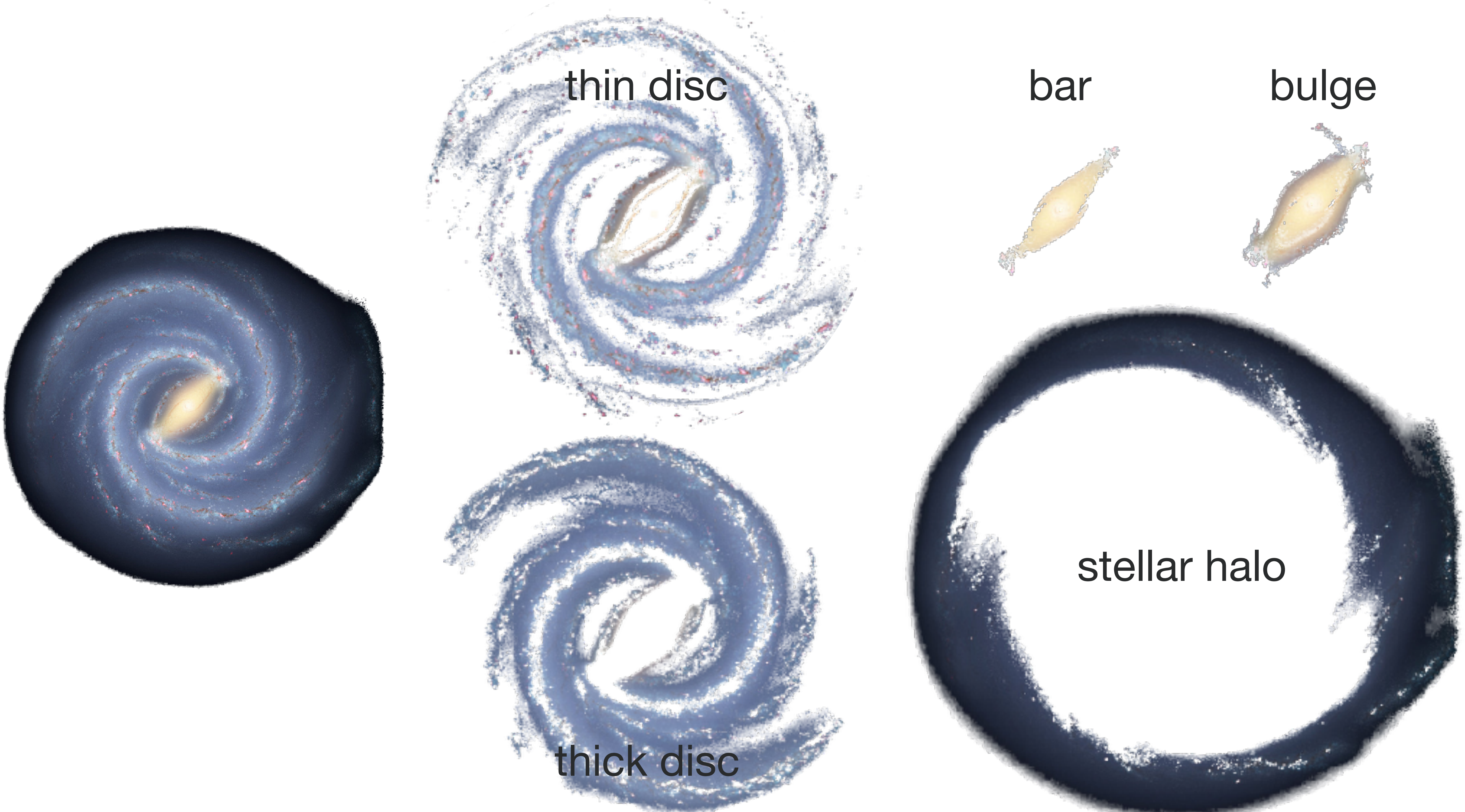


image credit: Ivan Minchev

The structure of the whole MW can be kinematically defined and studied



The structure of the whole MW can be kinematically defined and studied



How did the Milky Way form?

the stellar disc

the peanut bulge

The early stellar disc

dwarf galaxy population

the stellar disc

the peanut bulge

How did the Milky Way form?

- correct number, mass and structure of dwarf galaxies
  (Buck+2018b subm.)

The early stellar disc

dwarf galaxy population

How did the Milky Way form?

the stellar disc

the peanut bulge

- first cosmo sim reproducing MW bulge (Buck+2018a, Buck+2018c to be subm.)
- 2 kinematically distinct bulge comps.

- correct number, mass and structure of dwarf galaxies (Buck+2018b subm.)

The early stellar disc

dwarf galaxy population

How did the Milky Way form?

the stellar disc

- realistic stellar discs
- great potential combined with upcoming surveys

the peanut bulge

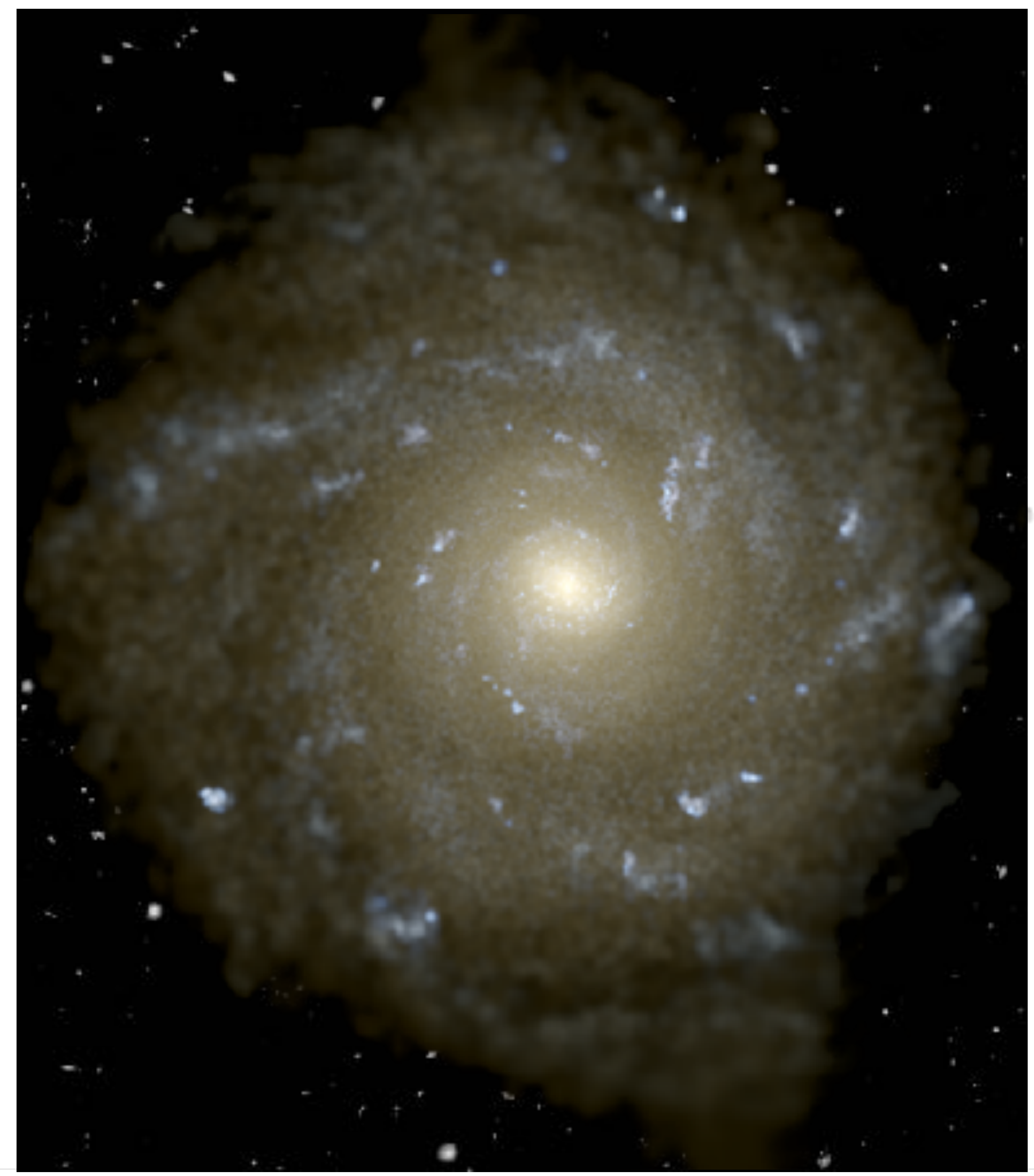
- first cosmo sim reproducing MW bulge (Buck+2018a, Buck+2018c to be subm.)
- 2 kinematically distinct bulge comps.

- correct number, mass and structure of dwarf galaxies (Buck+2018b subm.)

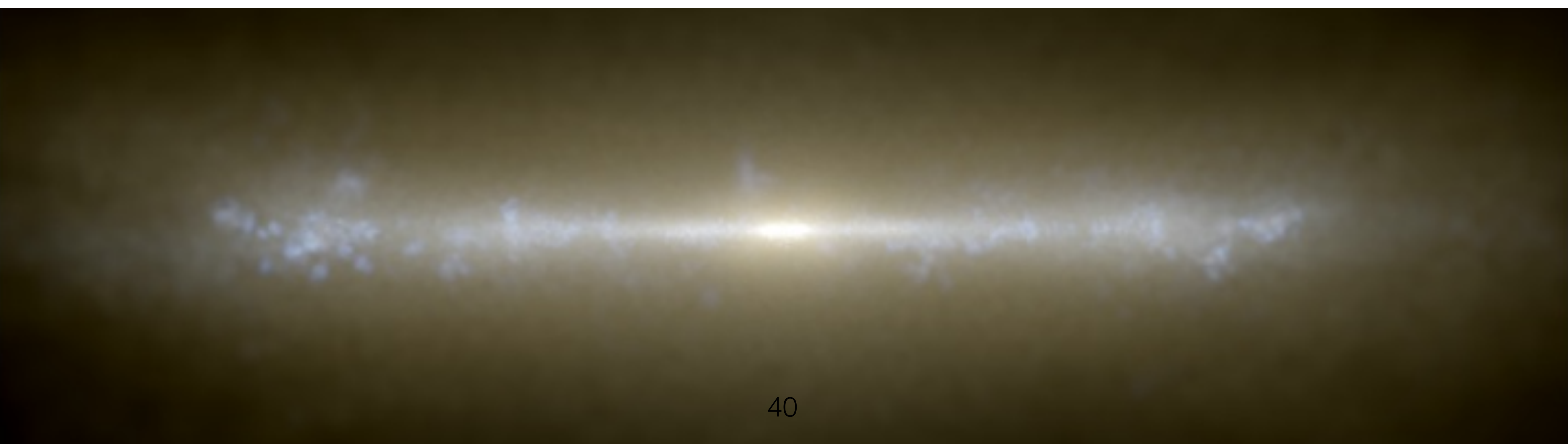
dwarf galaxy population

The early stellar disc

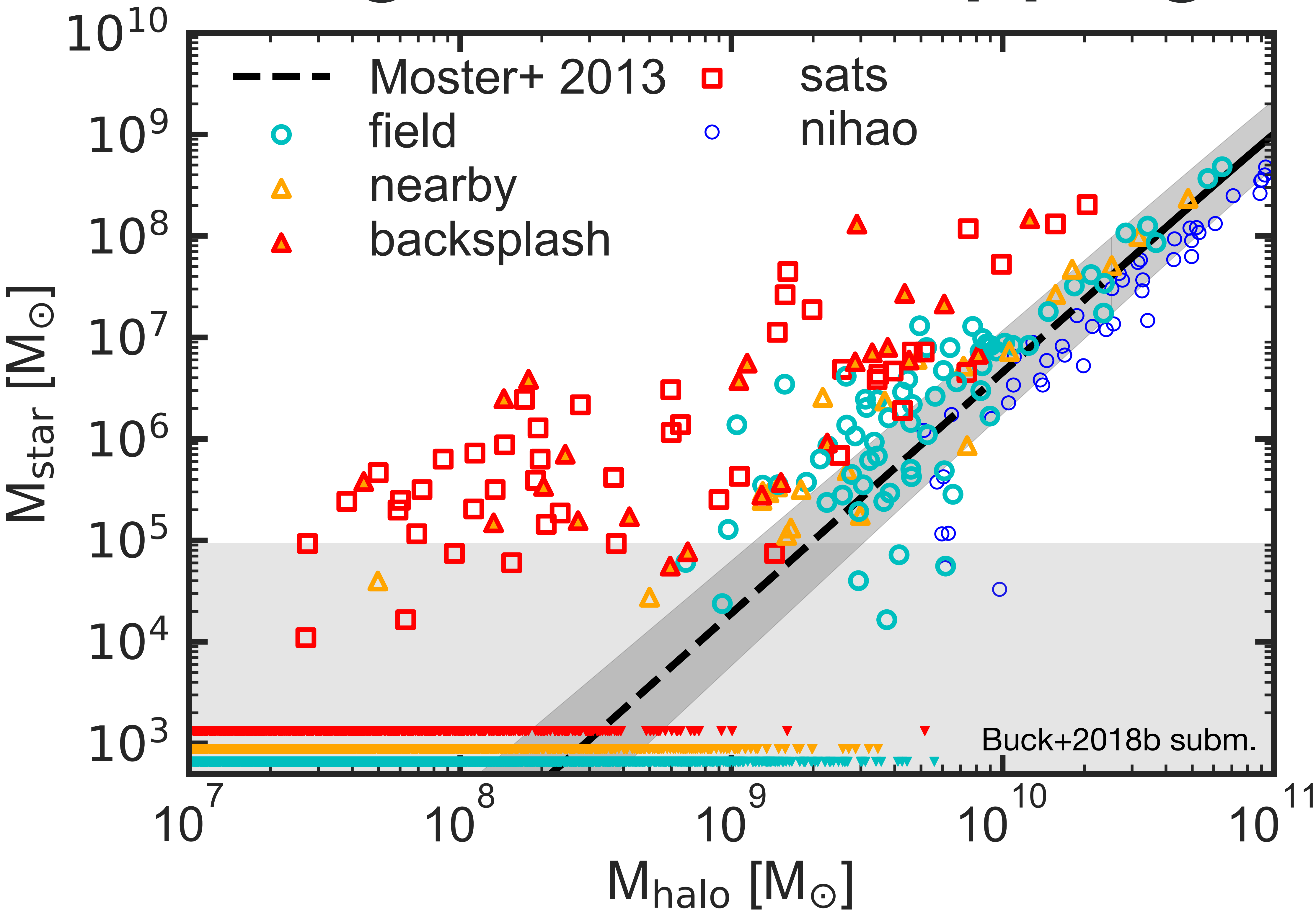
State of the art simulations: realistic!
Use them with up-coming Galactic surveys!



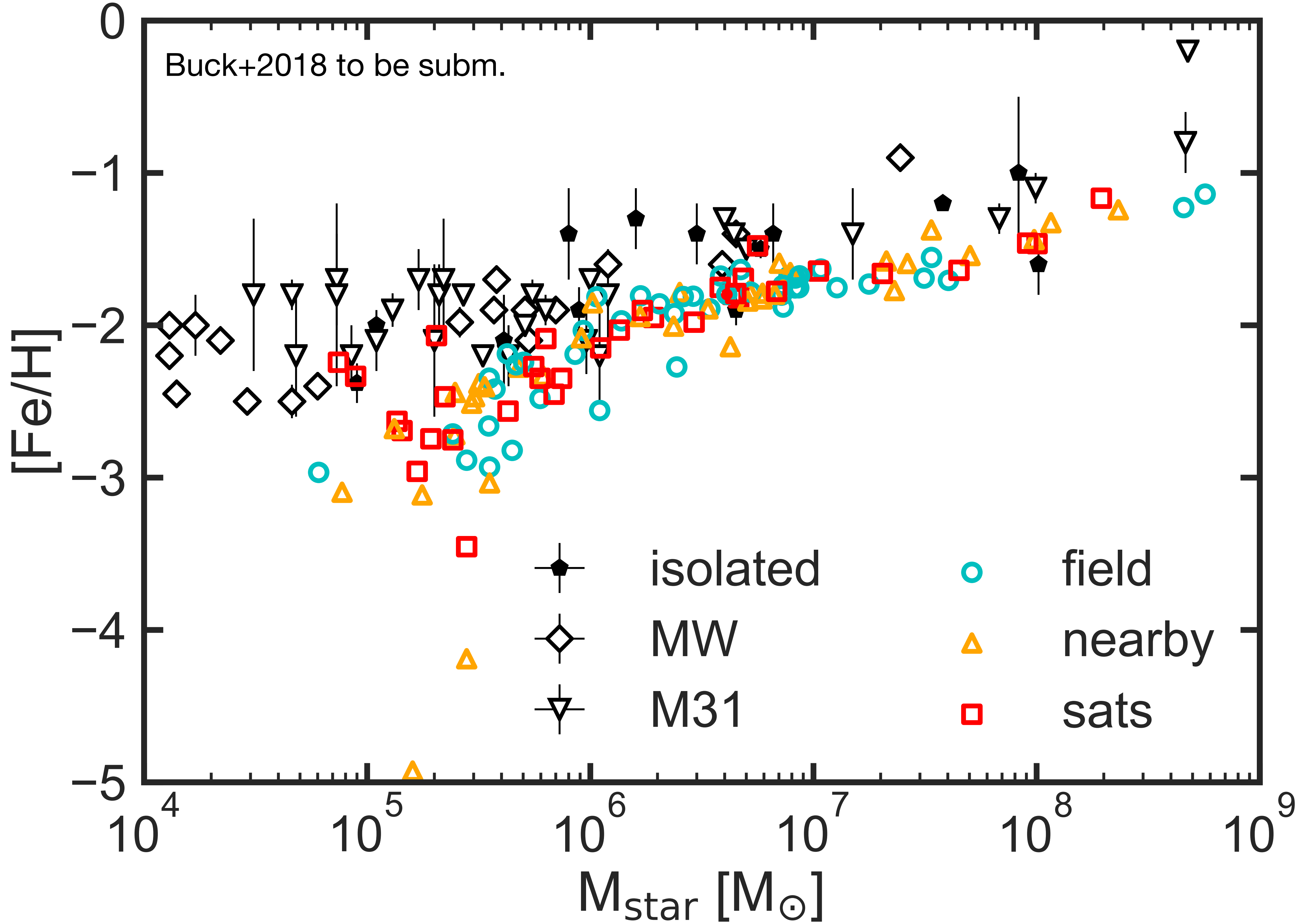
Extra Material



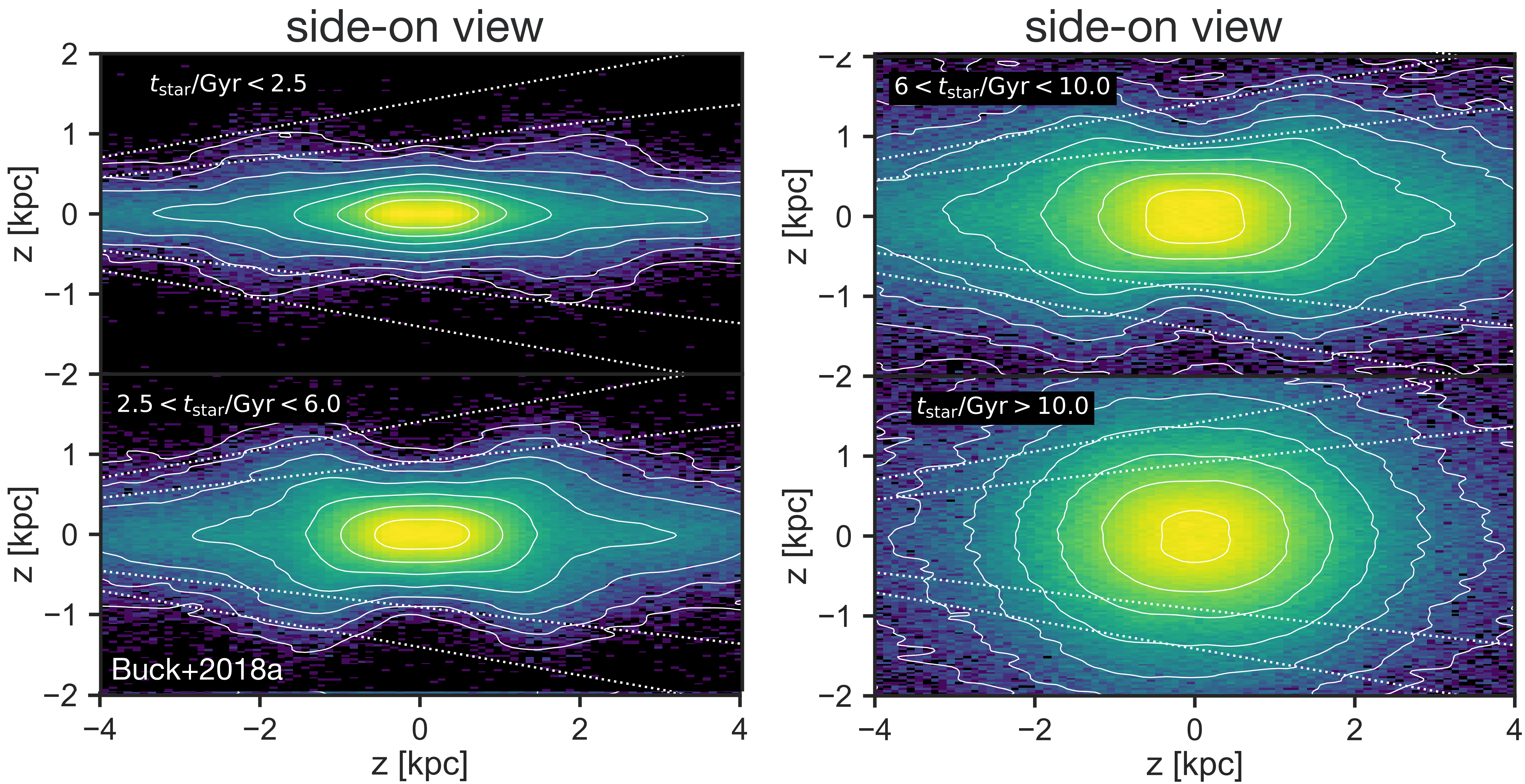
Stellar mass-halo mass relation: the signature of stripping



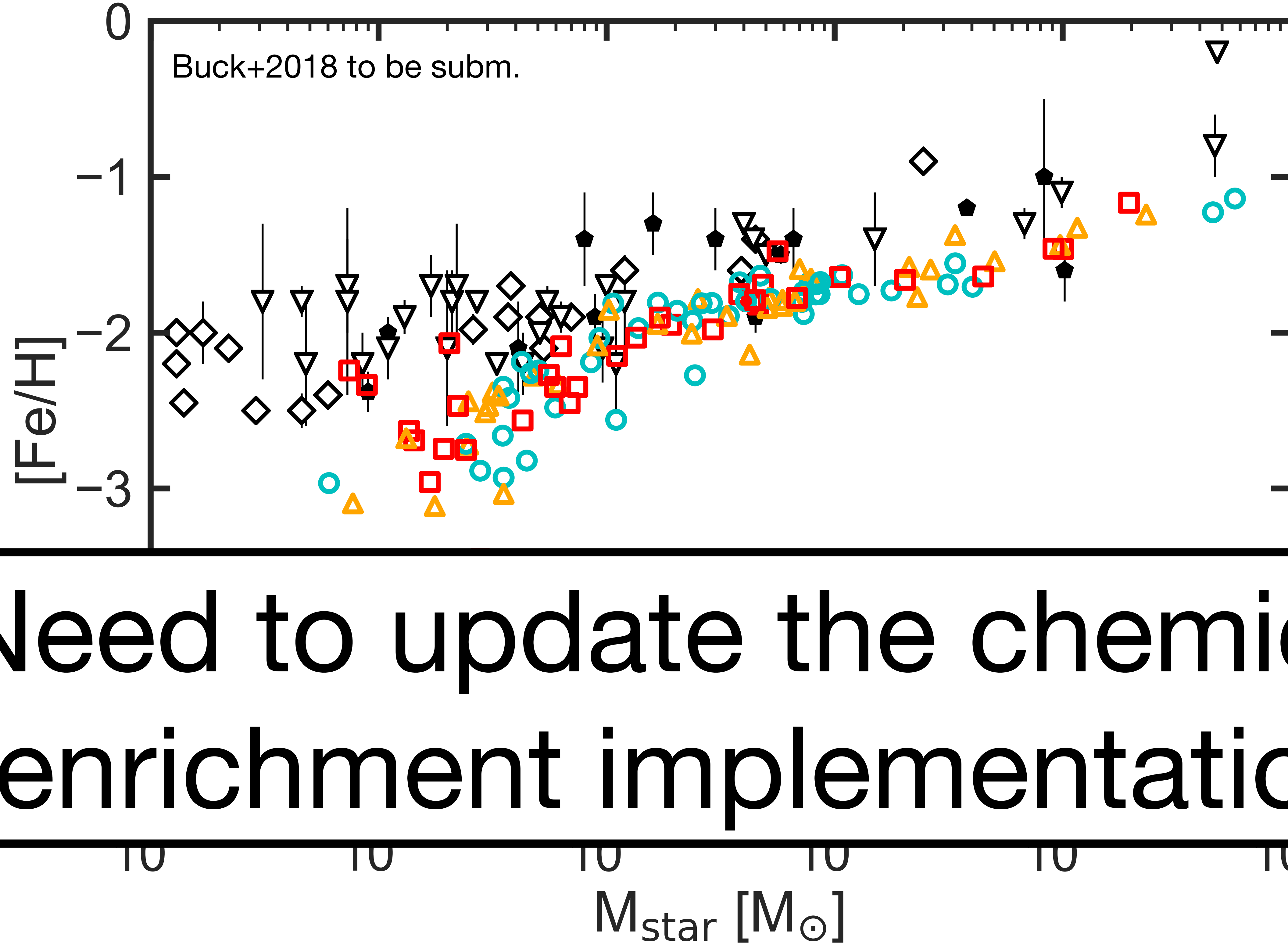
Mass-metallicity relation of dwarf galaxies:



The peanut/X-shaped morphology shows strong age dependence

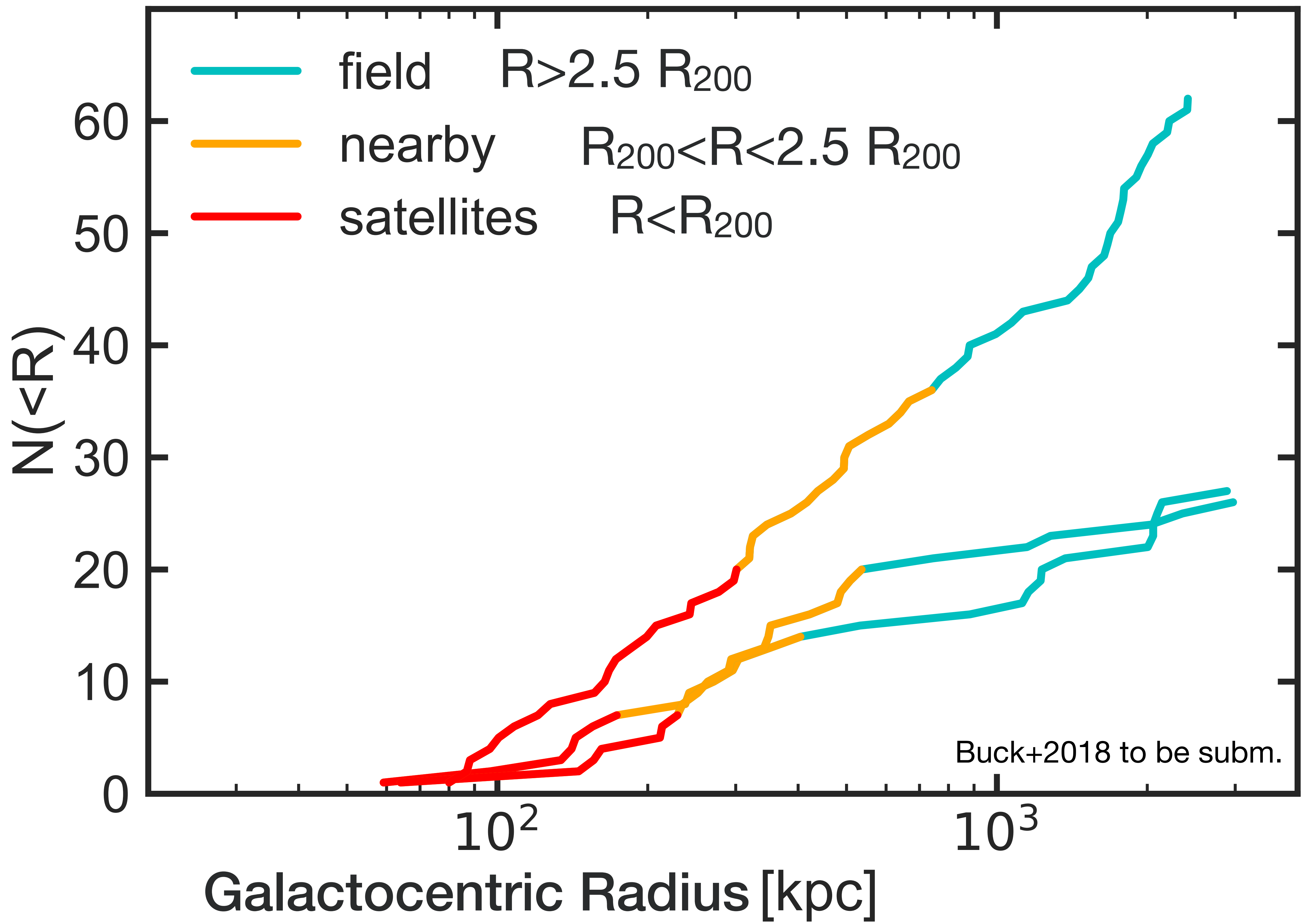


Mass-metallicity relation of dwarf galaxies:

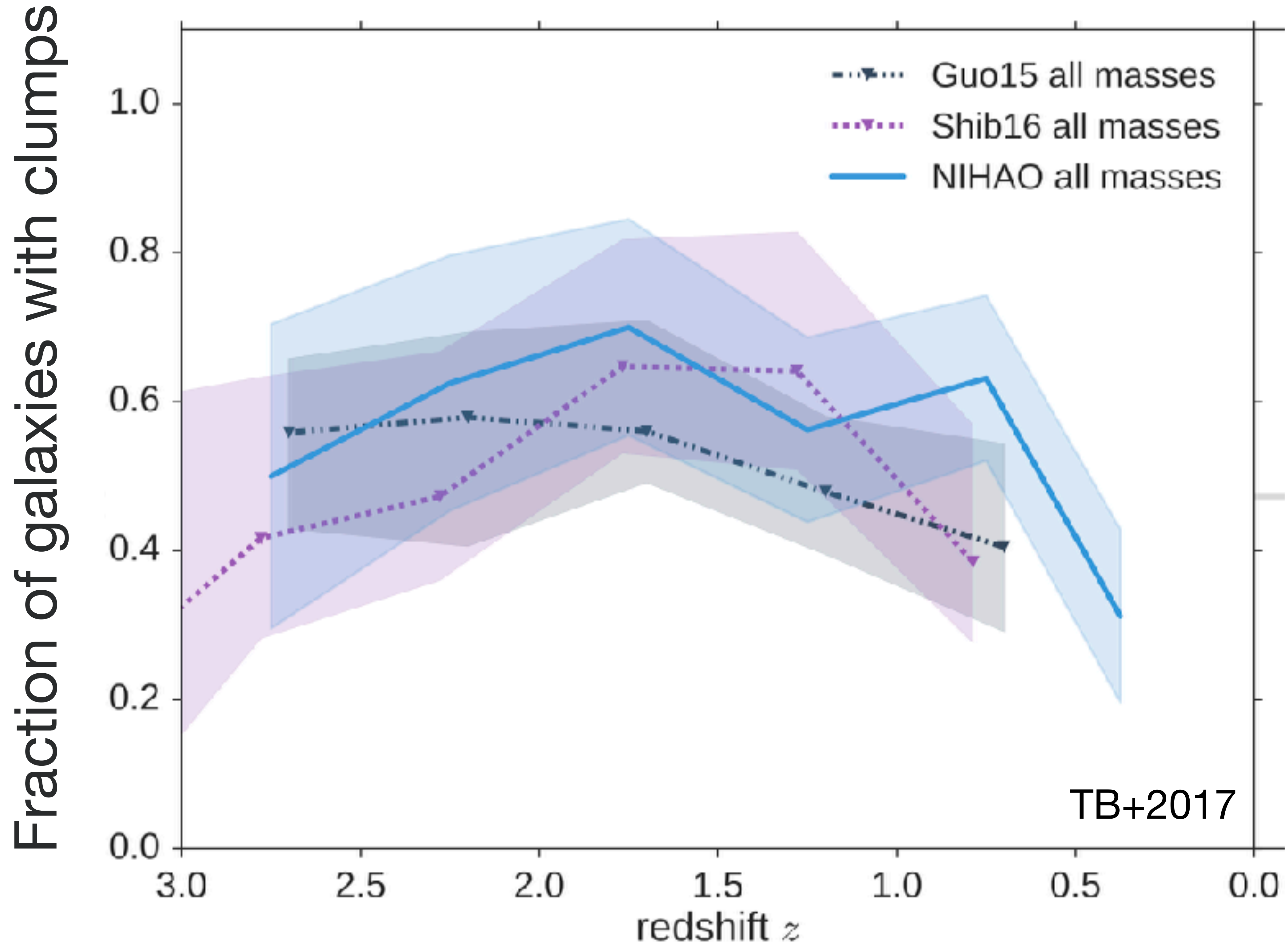


Need to update the chemical enrichment implementation

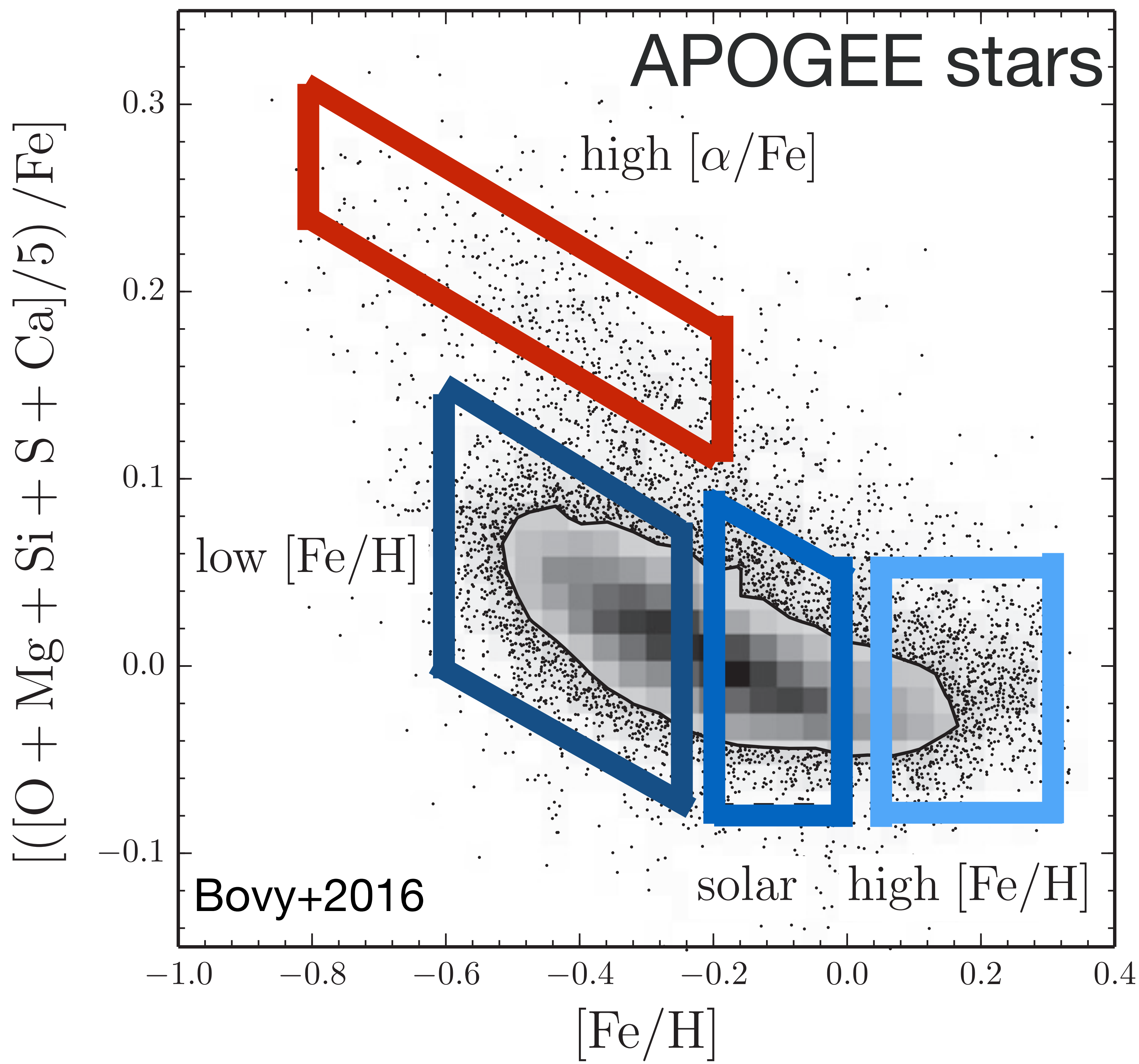
Defining 3 dwarf galaxy population:



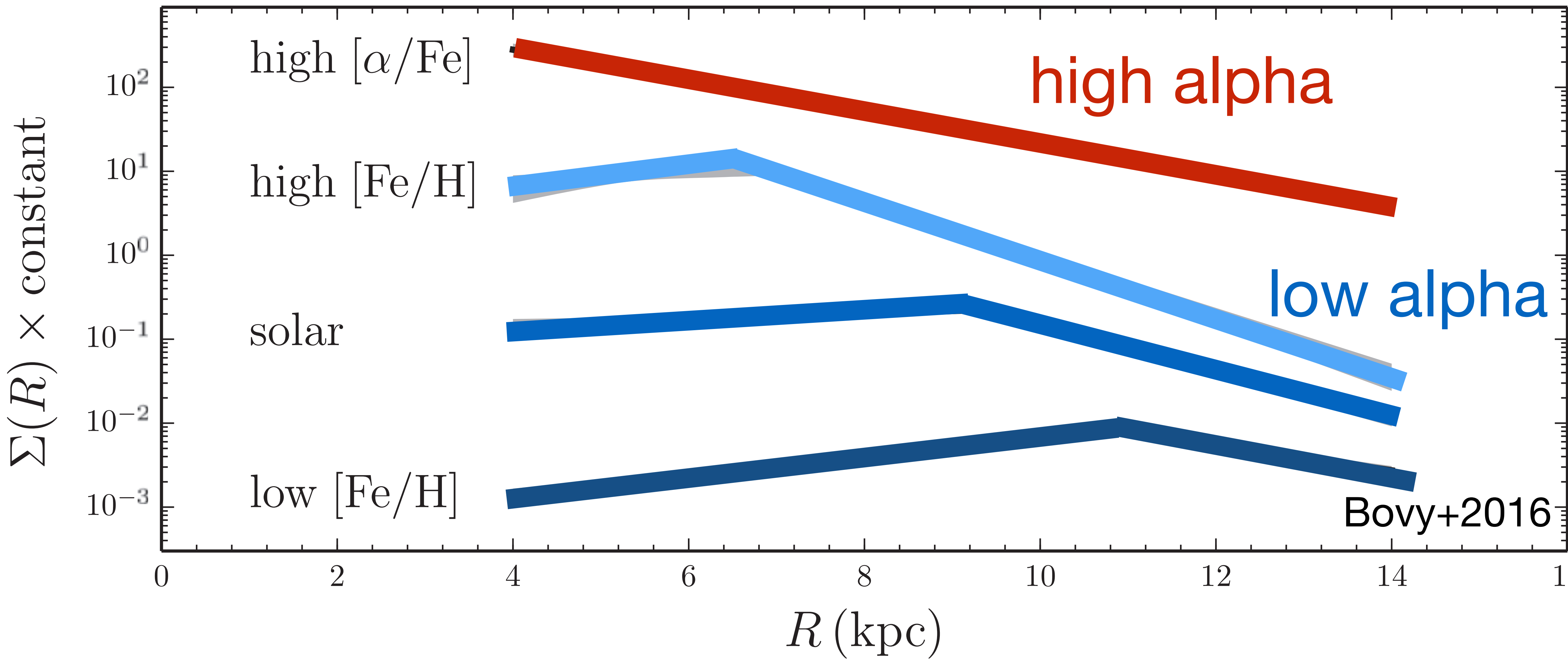
The „observed“ clumpy fraction of NIHAO



MW's Stellar Disc Structure

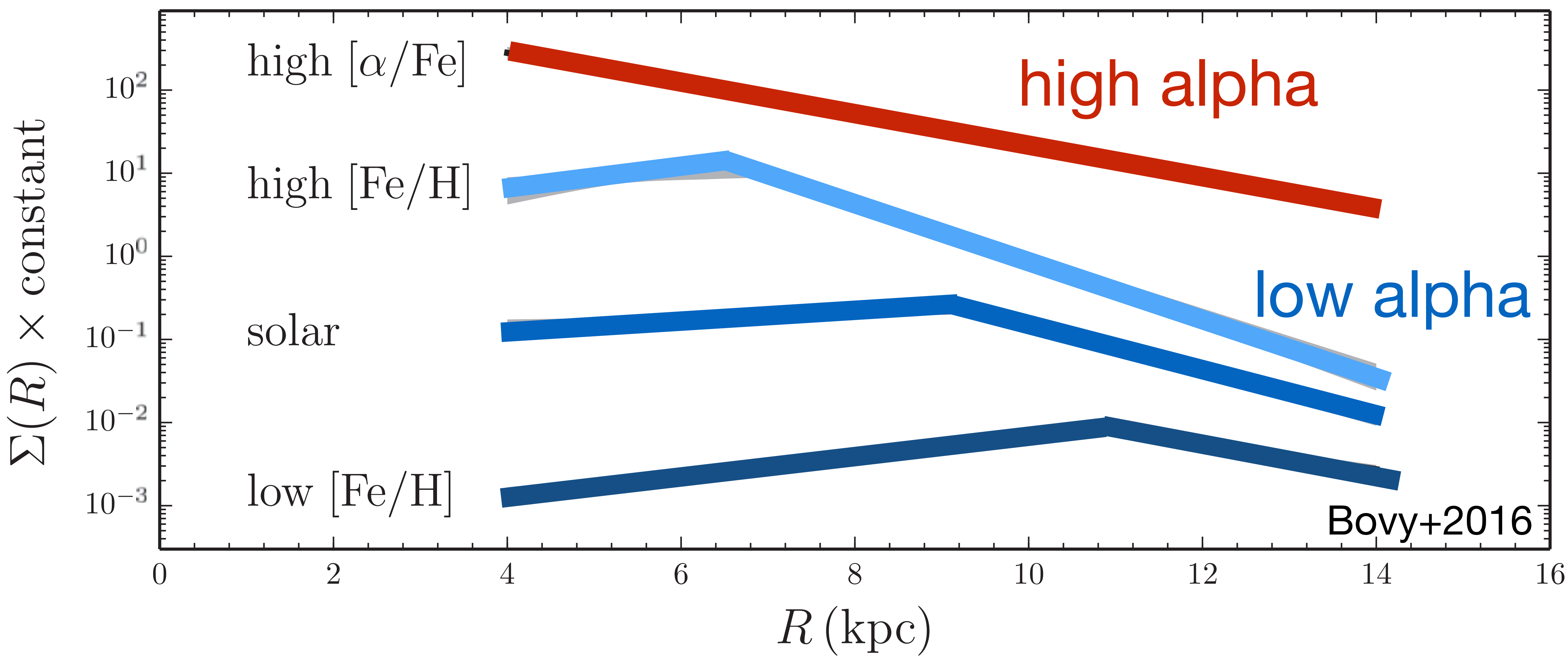


Today's Stellar Disc Structure



- high alpha population has constant scale height
- low alpha population flares

MW's Stellar Disc Structure



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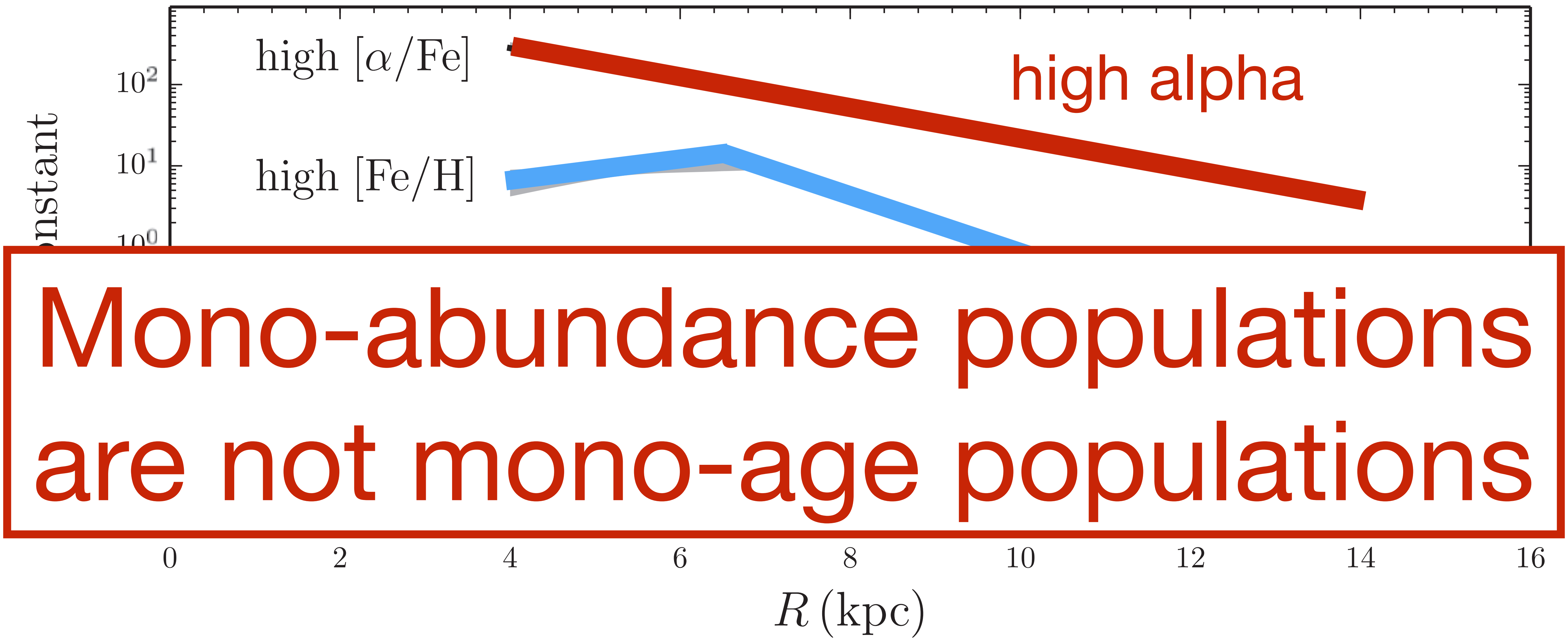


Mono-abundance populations are not mono-age populations

- high alpha population has constant scale height
- low alpha population flares

Simulations: Gòmez+2016,

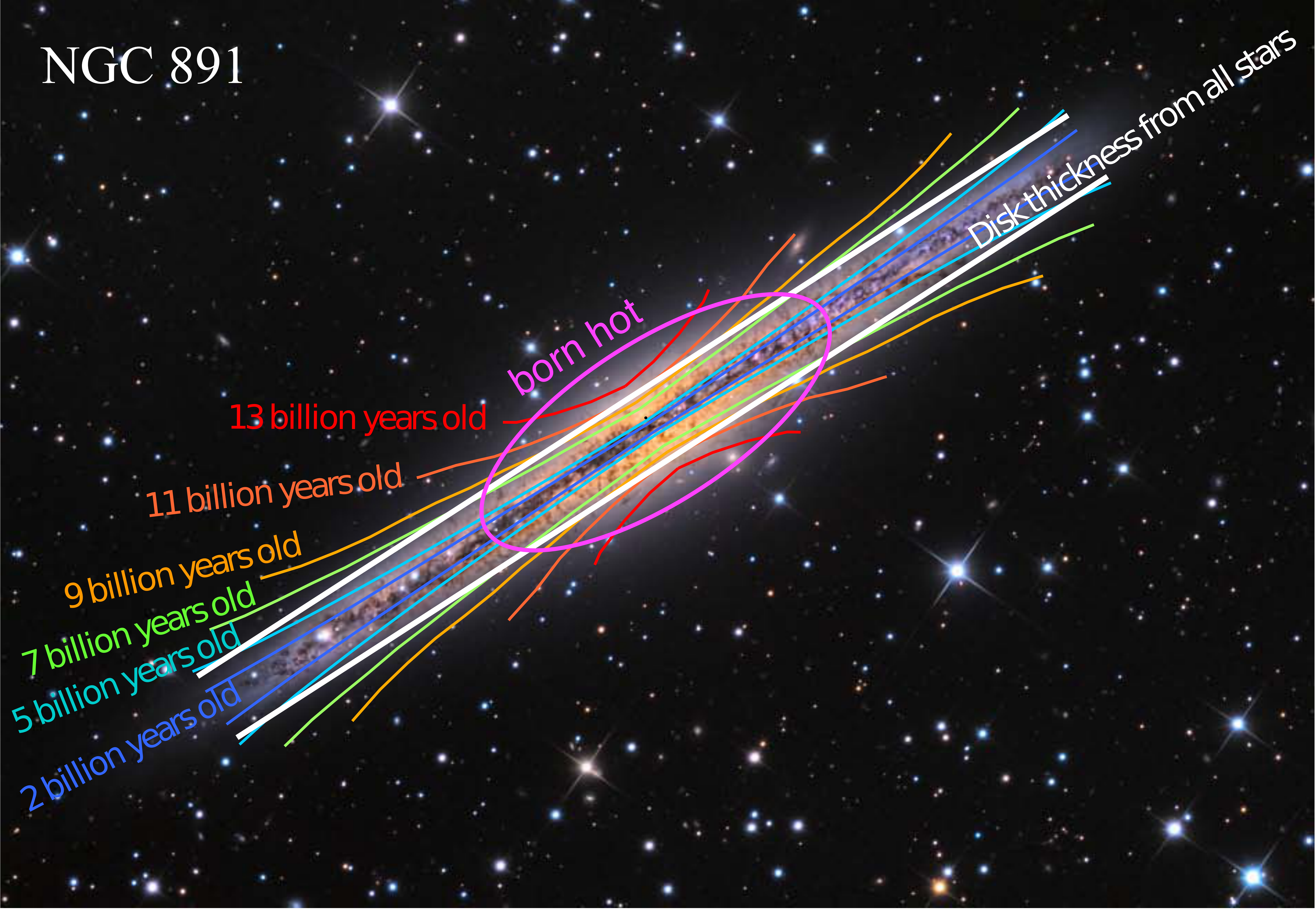
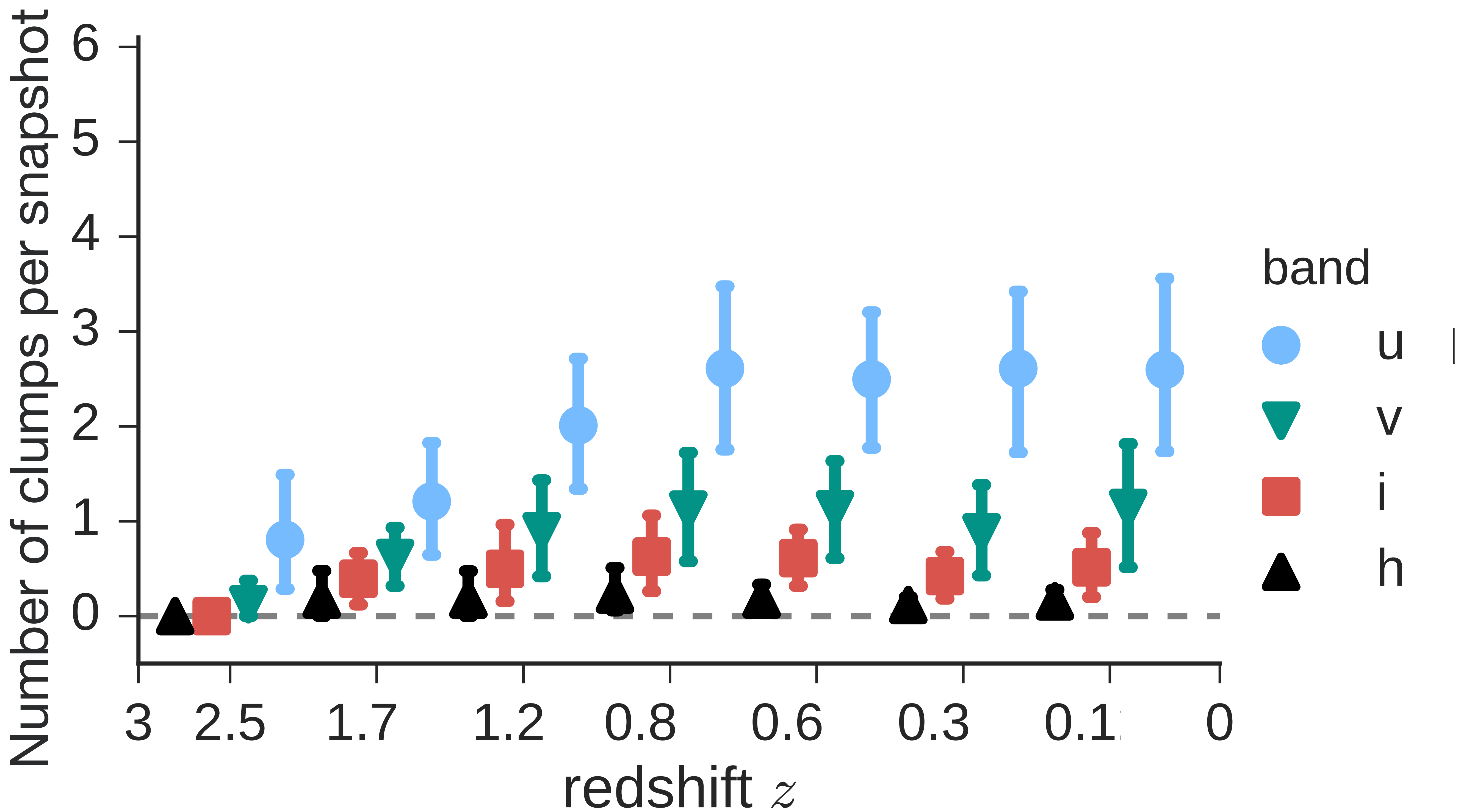


image credit: Ivan Minchev

The „intrinsic“ clumps of NIHAO



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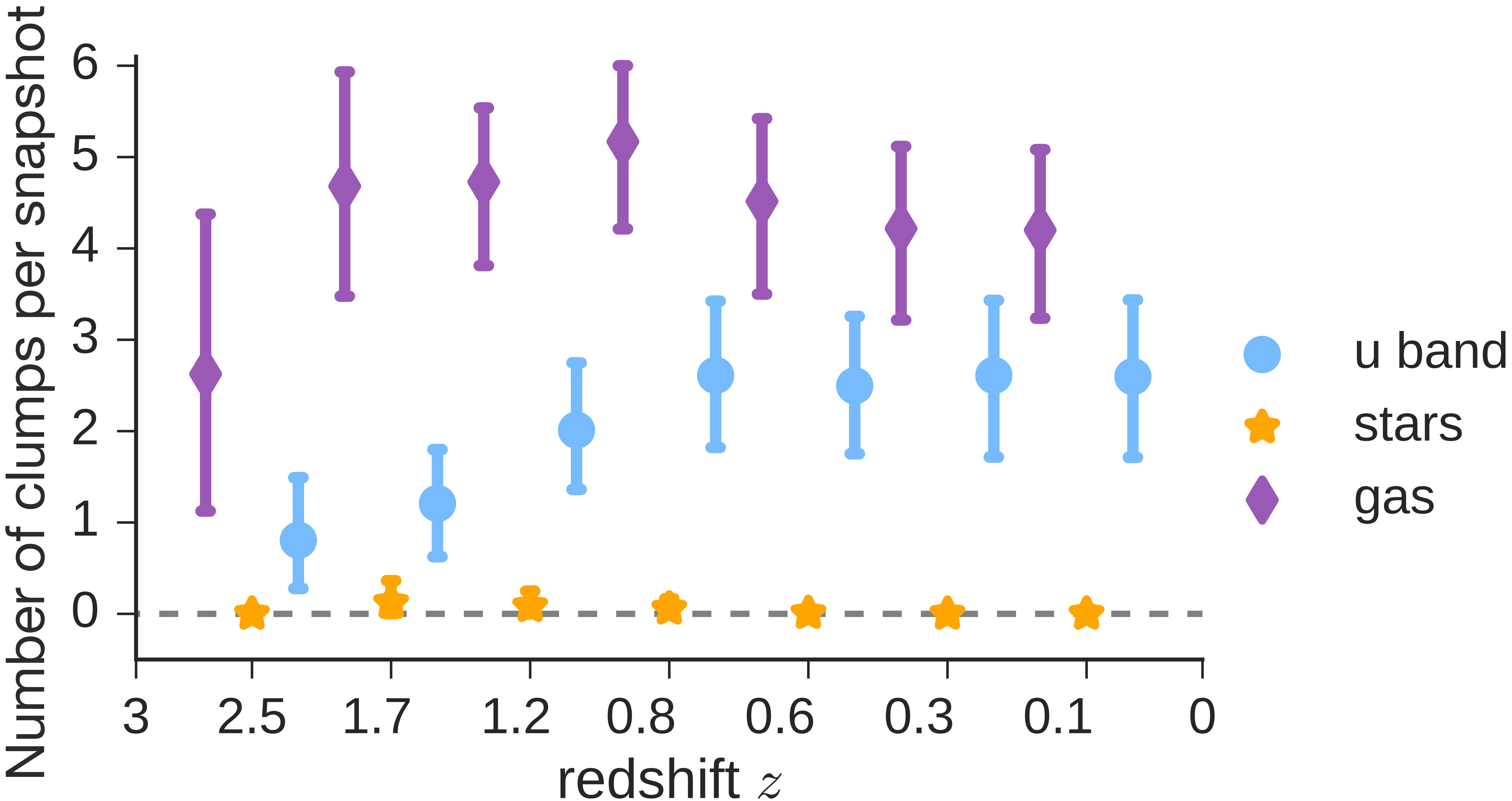

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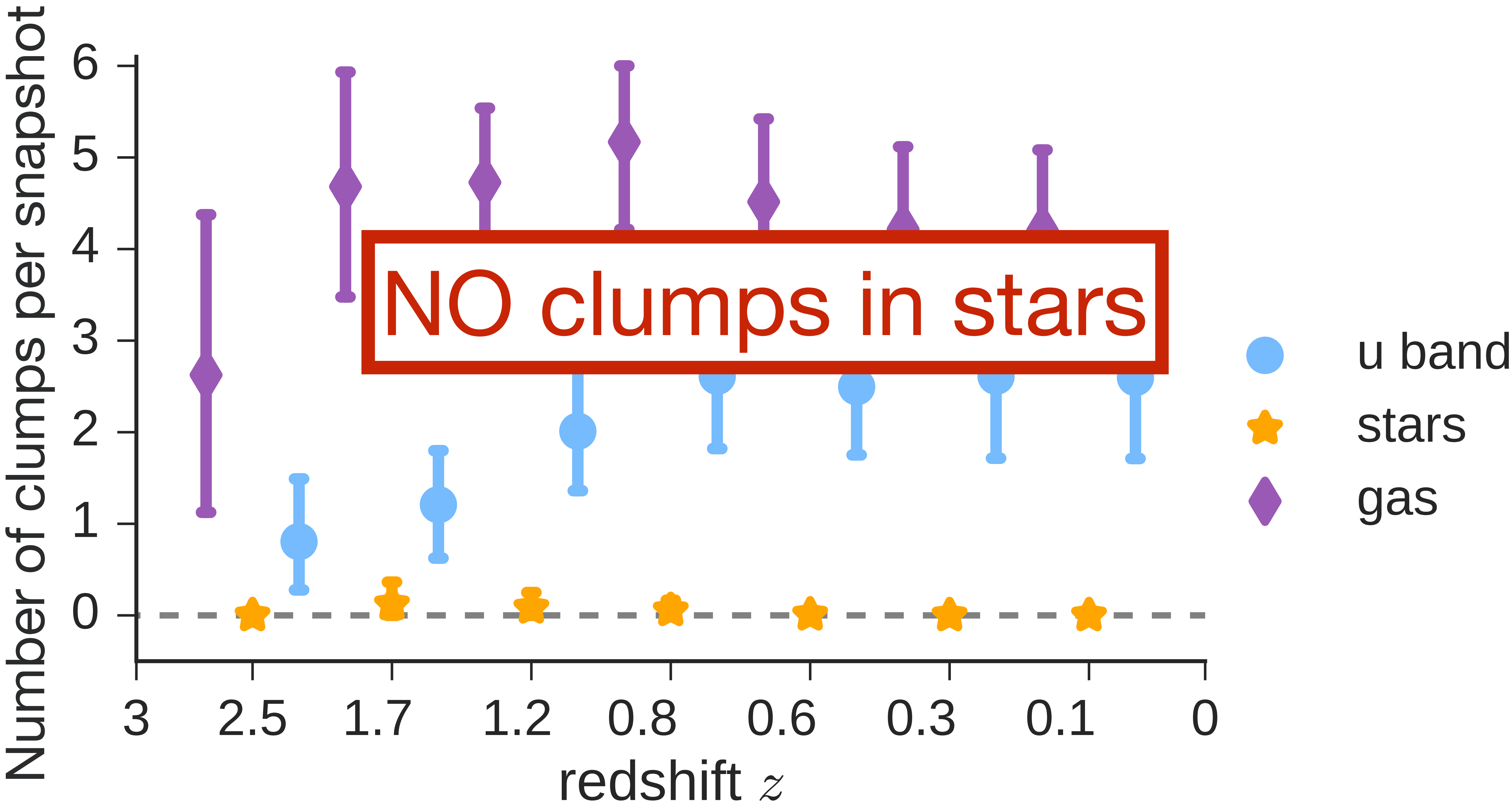


High-resolution hydro simulations:

Future plans: How much evolutionary memory is encoded in the structure of the stellar disc?

Kinematic decomposition of stellar discs

dissect the stellar disc in `classical´ 6D phase space using

Galactic Structure Finder (GSF)

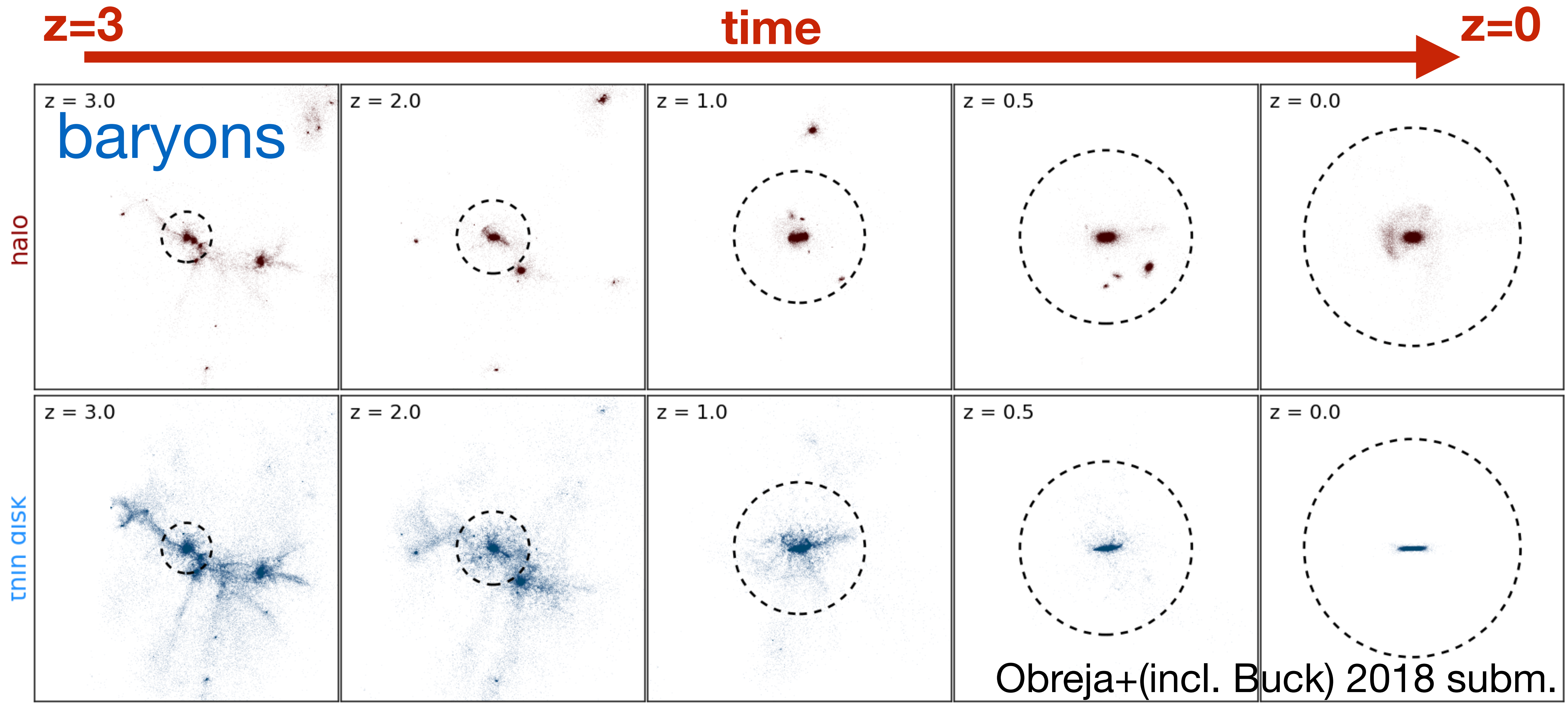
Obreja+(incl. Buck) 2018 subm.

parameter set (j_z /j_c , j_p /j_c , e)

- What is the chemo-kinematical structure of the disc?
- What are the differences between morphologically, chemically and kinematically defined disc components?
- Do the kinematics of (disc) stars encode information about the formation of the MW?

kinematic decomposition also possible for external galaxies: Zhu+2017

The Build-up of different kinematic components in simulations



see also: Amorisco2017 (stellar haloes), Teklu+2015 (ang. mom.), Burkert+2016 (observed ang. mom.) Monachesi+2016 (metallicity profile of stellar haloes)

High-resolution hydro simulations:

Future plans: The information content of the orbital action space

What are orbital actions?

orbital actions are integrals of motion

steady state, axisymmetric case: orbital actions are conserved

orbital actions will be determined by Wilma Trick from Gaia data

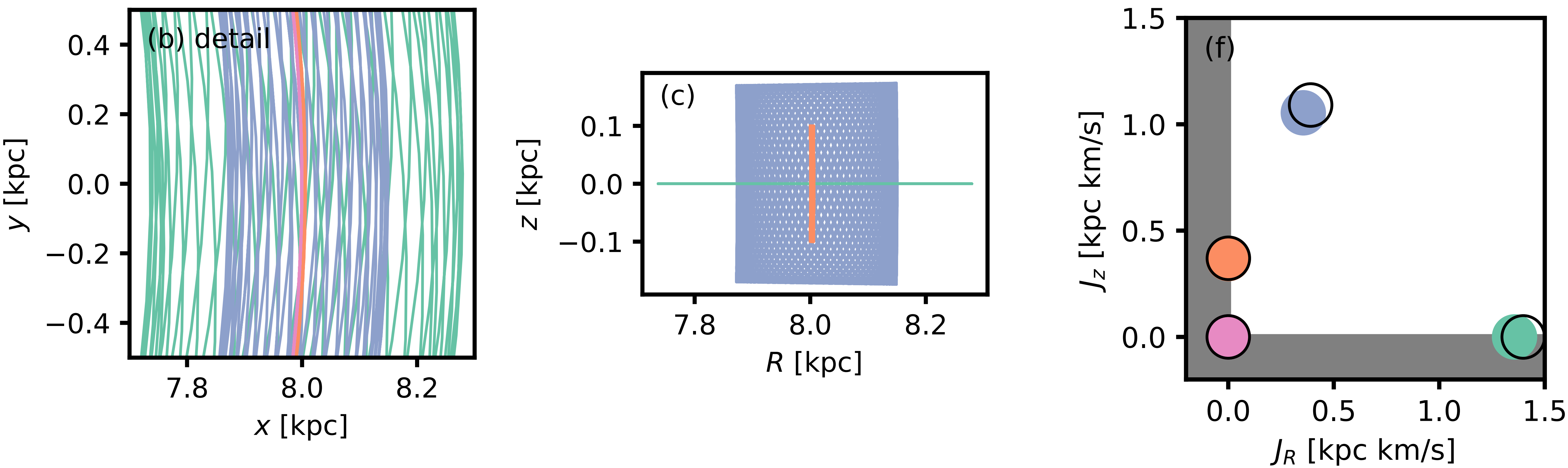


image credit: PhD thesis Wilma Trick

What can we learn from orbital actions about the formation of the MW?

- How much evolutionary memory is encoded in the orbit-age-abundance distribution?
- What aspects of this distribution are generic to disk-dominated galaxies?
- What aspects reflect the particular growth-history?
- Can we identify special stars via their orbital actions?

see also: Maffione+2015, McMillan+2008

How much evolutionary memory is encoded in the structure of the stellar disc?

I propose

- to study the structure of simulated stellar discs of MW analogues
  - kinematic decomposition
  - orbital action space

How did the Milky Way form?

How did the Milky Way form?

- clumps (Buck+2017)
  - are ONLY in stellar light
  - are NOT in stellar mass

mock observations

dwarf galaxy population

- correct number, mass and structure of dwarf galaxies
- backsplash galaxies are common (Buck+2018 to be subm.)

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structure of the MW

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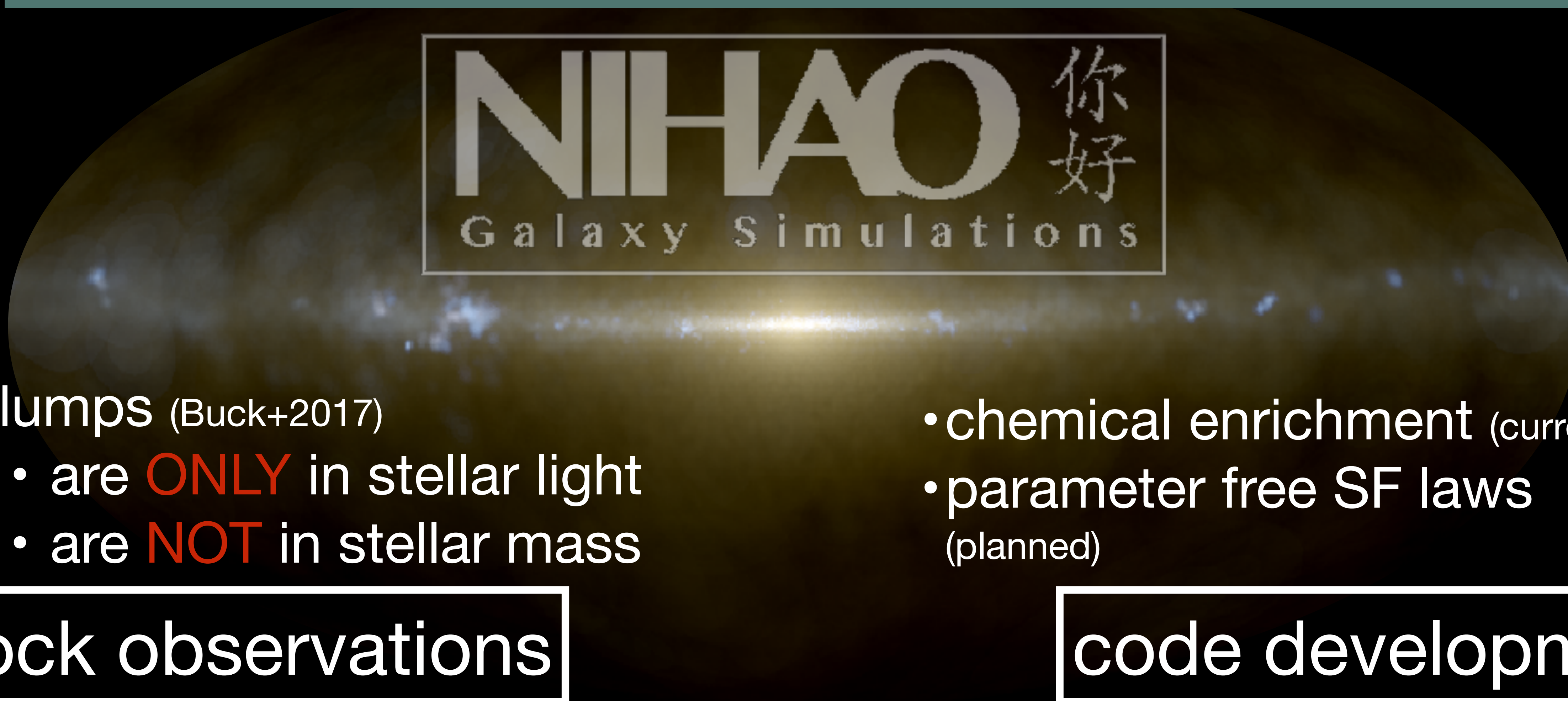

mock observations

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code development

- chemical enrichment (currently)
- parameter free SF laws (planned)