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

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

Animation: Buck
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

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

Animation: Buck
the stellar disc
the stellar disc

the peanut bulge
the stellar disc

the peanut bulge

dwarf galaxy population
How did the Milky Way form?

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

- The stellar disc
- The peanut bulge
- The early stellar disc
- Dwarf galaxy population
How did the Milky Way form?

- the stellar disc
- the peanut bulge
- The early stellar disc
- dwarf galaxy population
How did the Milky Way form?

- the stellar disc
- the peanut bulge
- The early stellar disc
- dwarf galaxy population
How did the Milky Way form?

- the stellar disc
- the peanut bulge
- The early stellar disc
- dwarf galaxy population
How did the Milky Way form?

- The early stellar disc
- The peanut bulge
- Dwarf galaxy population

NIHAO
Galaxy Simulations
How did the Milky Way form?

The early stellar disc

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

The peanut bulge

dwarf galaxy population
How did the Milky Way form?

The early 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.)

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

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)

NIHAO I: Wang+15
(82 galaxies in this plots)

image: Buck

Wadsley+2017
The NIHAO Simulation suite

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

SPH - Gasoline2 (Wadsley+2017)

NIHAO I: Wang+15
(82 galaxies in this plots)

$M_{\text{star}}$ vs $M_{200}$

$z=0$ Kravtsov+ (2014)
$\mu = 0.16$
$n > 400$ khost

image: Buck g8.26e11
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

4. early stellar feedback
   and SN feedback
   (energy + metals)
   Stinson+2013

star formation regions

Tobias Buck
CLUES 2018 - Tenerife
27.07.18
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

4. early stellar feedback
   and SN feedback (energy + metals)
   Stinson+2013

Tobias Buck

CLUES 2018 - Tenerife

27.07.18
High-resolution hydro simulations of MW mass galaxies
Why fully cosmological, high-resolution, hydro simulations?

A: dwarf galaxy population
B: stellar disc structure

image: Buck
Stellar light

face-on

edge-on

animation: Buck
face-on

edge-on

Stellar light

50x50 kpc

400x400 kpc

animation: Buck
Gravitational softening and particle masses:
• dark matter: 400 pc, $1.5 \times 10^5 M_\odot$
• gas: 180 pc, $2.8 \times 10^4 M_\odot$
• stars: 180 pc, 9300 $M_\odot$

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

similar zoom-in projects: Aumer+2013, Latte-project (Wetzel+2016), Apostle (Sawala+2016), Auriga (Grand+2017)
How did the Milky Way form?

- high-redshift clumpy galaxies
- structure in position and abundance space
- thin and thick disc
- spatial distribution
- environmental effects

- morphology, kinematics
- formation

The early stellar disc

dwarf galaxy population
High-resolution hydro simulations of MW mass galaxies: Can we reproduce the Local Group dwarf galaxy population?
The missing satellites problem

cumulative number counts $N(>V_{\text{circ}})$

factor of 10 discrepancy

increasing mass

$V_{\text{circ}}$ (km/s)

$\Lambda$CDM satellites

DMO

Local Group dwarfs

Kravtsov+2004

increasing mass
Satellite stellar mass function

- **N(\text{\textless} M_{\text{star}})**
- **M_{\text{star}} [M_{\odot}]**

- MW
- M31

- Cumulative number counts

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

Tobias Buck

CLUES 2018 - Tenerife

27.07.18
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,

Buck+2018b subm.

Tobias Buck

CLUES 2018 - Tenerife
Line-of-sight velocity velocity dispersions of simulations and observations agree

\[ \sigma_{v, 1D} \text{ [km/s]} \]

\[ M_{\text{star}} \text{ [M}_\odot\text{]} \]

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

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
Can we identify backsplash galaxies
Backsplash galaxies lost mass during the close encounter with MW

present day galacto-centric distance $R/R_{200}(z = 0)$

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

see also: Teyssier+ 2012
Can we identify backsplash galaxies

see also: Teyssier+ 2012
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?

• high-redshift clumpy galaxies

The early stellar disc

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

• spatial distribution
• environmental effects

NIHAO

Galaxy Simulations

the peanut bulge

• morphology, kinematics
• formation

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!
The peanut-shaped bulge is caused by the bar seen edge-on!
The peanut-shaped bulge is caused by the bar seen edge-on!
The peanut-shaped bulge is caused by the bar seen edge-on!
The formation scenario of the peanut bulge!
Kinematic Decomposition

$\log(M) = 11.20, \log(J_z) = 3.21$

all stars

decomposition: Obreja+ (incl. Buck) 2018
Kinematic Decomposition

decomposition: Obreja+(incl. Buck) 2018
Kinematic Decomposition

decomposition: Obreja+(incl. Buck) 2018

Buck+2018c to be subm.
Different properties for peanut and spherical component

- **Spherical Bulge - All**
  - $117556, 26628$

- **Peanut Bulge - All**
  - $74113, 18251$

- **Bulge Comps - All**
  - $191751, 44936$

For different inclinations and distances:
- $\langle v_r \rangle$ [km/s]
- $\sigma_{v_r}$ [km/s]
- $l$ [°]
- $|b| = 5$
- $|b| = 10$
- $MW b = -5$
- $MW b = -10$

**Graphs and Data**

- Two graphs showing velocity against longitude for different inclinations and distances.
- Data points and trend lines indicate variations in velocity with longitude.
- Specific velocities and ranges are marked for each category.

**Notes**

- Data sourced from Buck+2017 and Buck+2018c.
- CLUES 2018 - Tenerife.
Different properties for peanut and spherical component

- Spherical bulge - all: 117556, 26628
- Peanut bulge - all: 74113, 18251
- Bulge comps - all: 191751, 44936

MW $b = -5$, $MW b = -10$, $|b| = 5$, $|b| = 10$

Buck+2018c to be subm.
Birth properties of peanut and spherical bulge stars are different

**birth position**

**birth angular momentum**

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
How did the Milky Way form?

- the stellar disc
- the peanut bulge
- The early stellar disc
- dwarf galaxy population

NIHAO Galaxy Simulations
How did the Milky Way form?

- Correct number, mass and structure of dwarf galaxies (Buck+2018b subm.)
How did the Milky Way form?

- The early 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.)

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 $\rightarrow$ 5+1D phase space coordinates (25th of April 2018)

APOGEE2 + 4MOST + Galah $\rightarrow$ chemical abundances

KEPLER + APOGEE (Cannon) $\rightarrow$ ages

image credit: Ivan Minchev

movie: T. Buck, G. Stinson
The structure of the whole MW stellar disc will be measured

Gaia $\rightarrow$ 5+1D phase space coordinates (25th of April 2018)

APOGEE2 + 4MOST + Galah $\rightarrow$ chemical abundances

KEPLER + APOGEE (Cannon) $\rightarrow$ ages

image credit: Ivan Minchev

movie: T. Buck, G. Stinson
The structure of the whole MW stellar disc will be measured

Gaia $\rightarrow$ 5+1D phase space coordinates (25th of April 2018)

APOGEE2 + 4MOST + Galah $\rightarrow$ chemical abundances

KEPLER + APOGEE (Cannon) $\rightarrow$ ages

image credit: Ivan Minchev

CLUES 2018 - Tenerife
Tobias Buck
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 early stellar disc

The peanut bulge

dwarf galaxy population

NIHAO
Galaxy Simulations
How did the Milky Way form?

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

the peanut bulge

the stellar disc

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

- Correct number, mass, and structure of dwarf galaxies (Buck+2018b subm.)
- First cosmo sim reproducing MW bulge (Buck+2018a, Buck+2018c to be subm.)
- 2 kinematically distinct bulge comps.

The early stellar disc

Dwarf galaxy population

The stellar disc

The peanut bulge
How did the Milky Way form?

**The early 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.

**Dwarf galaxy population**
- correct number, mass and structure of dwarf galaxies (Buck+2018b subm.)
State of the art simulations: realistic!
Use them with up-coming Galactic surveys!
Extra Material
Stellar mass-halo mass relation: the signature of stripping

Stellar mass $M_{\text{star}}$ vs. halo mass $M_{\text{halo}}$ with different stellar types: field, sats, nearby, and backsplash. The plot shows data points and a trend line from Moster+ 2013 with additional data from Buck+2018b subm. at KoCo - MPIA.
Mass-metallicity relation of dwarf galaxies:

Buck+2018 to be subm.

\[ \text{Buck+2018 to be subm.} \]
The peanut/X-shaped morphology shows strong age dependence.

\[ t_{\text{star}}/\text{Gyr} < 2.5 \]
\[ 2.5 < t_{\text{star}}/\text{Gyr} < 6.0 \]
\[ t_{\text{star}}/\text{Gyr} > 10.0 \]

Buck+2018a
Mass-metallicity relation of dwarf galaxies:

Buck+2018 to be subm.

Need to update the chemical enrichment implementation
Defining 3 dwarf galaxy population:

- Field: $R > 2.5 \ R_{200}$
- Nearby: $R_{200} < R < 2.5 \ R_{200}$
- Satellites: $R < R_{200}$

The plot shows the number of dwarf galaxies ($N(<R)$) as a function of galactocentric radius ($[kpc]$). The data is from Buck et al. 2018 and will be submitted soon.
The „observed“ clumpy fraction of NIHAO

Fraction of galaxies with clumps

- Guo15 all masses
- Shib16 all masses
- NIHAO all masses

redshift $z$

TB+2017

NIHAO
MW’s Stellar Disc Structure

(APOGEE stars)

low [Fe/H]

high [α/Fe]

solar high [Fe/H]

Bovy+2016
Today’s Stellar Disc Structure

- **high alpha population** has constant scale height
- **low alpha population** flares
MW’s Stellar Disc Structure

The radial dependence of surface density and vertical profiles can be considered a broken exponential, with an almost universal shape between very small and very large peaks. The behavior found for the majority of MAPs has well-constrained profiles. For all MAPs along the high-[Fe/H] sequences for clarity, but the behavior of other high-[α/Fe] sequences is displayed in Figure 27.07.18. The radial dependence of individual high-[α/Fe] profiles is increasing, while the high-[Fe/H] profiles are exponentially with the same scale length. In all cases, that high-[α/Fe] profiles without this constraint are exponentially with the same scale length. In all of the low-[Fe/H] profiles separately, but both were measured using the alternative model of Equation 5.2. That is, we fit the behavior found for the high-[α/Fe] profiles as a broken exponential, while the high-[Fe/H] profiles are constrained, as the low-[α/Fe] profiles are relative to the density at an arbitrary offset in the vertical direction has been applied to separate the four profiles. The behavior seen in Figure 12 indicates that high-[α/Fe] profiles without this constraint are exponentially with the same scale length. In all cases, that high-[α/Fe] profiles without this constraint are exponentially with the same scale length. In all of the low-[Fe/H] profiles separately, but both were measured using the alternative model of Equation 5.2. That is, we fit the behavior found for the high-[α/Fe] profiles as a broken exponential, while the high-[Fe/H] profiles are constrained, as the low-[α/Fe] profiles are relative to the density at an arbitrary offset in the vertical direction has been applied to separate the four profiles.

The behavior seen in Figure 12 indicates that high-[α/Fe] profiles without this constraint are exponentially with the same scale length. In all cases, that high-[α/Fe] profiles without this constraint are exponentially with the same scale length. In all of the low-[Fe/H] profiles separately, but both were measured using the alternative model of Equation 5.2. That is, we fit the behavior found for the high-[α/Fe] profiles as a broken exponential, while the high-[Fe/H] profiles are constrained, as the low-[α/Fe] profiles are relative to the density at an arbitrary offset in the vertical direction has been applied to separate the four profiles.

The behavior seen in Figure 12 indicates that high-[α/Fe] profiles without this constraint are exponentially with the same scale length. In all cases, that high-[α/Fe] profiles without this constraint are exponentially with the same scale length. In all of the low-[Fe/H] profiles separately, but both were measured using the alternative model of Equation 5.2. That is, we fit the behavior found for the high-[α/Fe] profiles as a broken exponential, while the high-[Fe/H] profiles are constrained, as the low-[α/Fe] profiles are relative to the density at an arbitrary offset in the vertical direction has been applied to separate the four profiles.

The behavior seen in Figure 12 indicates that high-[α/Fe] profiles without this constraint are exponentially with the same scale length. In all cases, that high-[α/Fe] profiles without this constraint are exponentially with the same scale length. In all of the low-[Fe/H] profiles separately, but both were measured using the alternative model of Equation 5.2. That is, we fit the behavior found for the high-[α/Fe] profiles as a broken exponential, while the high-[Fe/H] profiles are constrained, as the low-[α/Fe] profiles are relative to the density at an arbitrary offset in the vertical direction has been applied to separate the four profiles.

The behavior seen in Figure 12 indicates that high-[α/Fe] profiles without this constraint are exponentially with the same scale length. In all cases, that high-[α/Fe] profiles without this constraint are exponentially with the same scale length. In all of the low-[Fe/H] profiles separately, but both were measured using the alternative model of Equation 5.2. That is, we fit the behavior found for the high-[α/Fe] profiles as a broken exponential, while the high-[Fe/H] profiles are constrained, as the low-[α/Fe] profiles are relative to the density at an arbitrary offset in the vertical direction has been applied to separate the four profiles.

The behavior seen in Figure 12 indicates that high-[α/Fe] profiles without this constraint are exponentially with the same scale length. In all cases, that high-[α/Fe] profiles without this constraint are exponentially with the same scale length. In all of the low-[Fe/H] profiles separately, but both were measured using the alternative model of Equation 5.2. That is, we fit the behavior found for the high-[α/Fe] profiles as a broken exponential, while the high-[Fe/H] profiles are constrained, as the low-[α/Fe] profiles are relative to the density at an arbitrary offset in the vertical direction has been applied to separate the four profiles.

The behavior seen in Figure 12 indicates that high-[α/Fe] profiles without this constraint are exponentially with the same scale length. In all cases, that high-[α/Fe] profiles without this constraint are exponentially with the same scale length. In all of the low-[Fe/H] profiles separately, but both were measured using the alternative model of Equation 5.2. That is, we fit the behavior found for the high-[α/Fe] profiles as a broken exponential, while the high-[Fe/H] profiles are constrained, as the low-[α/Fe] profiles are relative to the density at an arbitrary offset in the vertical direction has been applied to separate the four profiles.

The behavior seen in Figure 12 indicates that high-[α/Fe] profiles without this constraint are exponentially with the same scale length. In all cases, that high-[α/Fe] profiles without this constraint are exponentially with the same scale length. In all of the low-[Fe/H] profiles separately, but both were measured using the alternative model of Equation 5.2. That is, we fit the behavior found for the high-[α/Fe] profiles as a broken exponential, while the high-[Fe/H] profiles are constrained, as the low-[α/Fe] profiles are relative to the density at an arbitrary offset in the vertical direction has been applied to separate the four profiles.
Mono-abundance populations are not mono-age populations

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

Simulations: Gòmez+2016,
NGC 891

Disk thickness from all stars

13 billion years old
11 billion years old
9 billion years old
7 billion years old
5 billion years old
2 billion years old

born hot

image credit: Ivan Minchev
The „intrinsic“ clumps of NIHAO

Number of clumps per snapshot vs. redshift $z$.
The "intrinsic" clumps of NIHAO

Number of clumps per snapshot vs. redshift $\zeta$
The „intrinsic“ clumps of NIHAO

Number of clumps per snapshot

NO clumps in stars

redshift $\sim$

u band
stars
gas
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
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
dwarf galaxy population
• correct number, mass and structure of dwarf galaxies
• backsplash galaxies are common (Buck+2018 to be subm.)

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.)

structure of the MW

• How much evolutionary information is contained in the structure of MW’s stellar disc? (planned)

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.)

structure of the MW

- How much evolutionary information is contained in the structure of MW’s stellar disc? (planned)

How did the Milky Way form?

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

mock observations
code development

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