The E-MOSAICS project: simulating the formation and evolution of galaxies and their globular cluster systems

Marta Reina-Campos (Heidelberg)
Diederik Kruijssen (Heidelberg), Joel Pfeffer (LJMU), Rob Crain (LJMU), Nate Bastian (LJMU)
The E-MOSAICS project: simulating the formation and evolution of galaxies and their globular cluster systems

Marta Reina-Campos (Heidelberg)
Diederik Kruijssen (Heidelberg), Joel Pfeffer (LJMU), Rob Crain (LJMU), Nate Bastian (LJMU)
The E-MOSAICS project: simulating the formation and evolution of galaxies and their globular cluster systems

Marta Reina-Campos (Heidelberg)
Diederik Kruijssen (Heidelberg), Joel Pfeffer (LJMU),
Rob Crain (LJMU), Nate Bastian (LJMU)
Open questions on theoretical studies of GC formation:

- What are the important physical mechanisms that shape the GC population that we see at $z=0$?
- What do GCs reveal about the formation and assembly history of its host galaxy?

Can only be answered in the context of a hypothesis for GC formation and evolution
Constraining GC formation:
- We see GC-like clusters forming where gas pressure and SFR are high
- Both peaked near GC formation redshift

First question(s) must be:
- Could the products of regular cluster formation at high redshift have survived until the present day?
- Are these relics consistent with the properties of local GC populations?
Constraining GC formation:
• We see GC-like clusters forming where gas pressure and SFR are high
• Both peaked near GC formation redshift

First question(s) must be:
• Could the products of regular cluster formation at high redshift have survived until the present day?
• Are these relics consistent with the properties of local GC populations?

Paraphrasing: are GCs old YMCs that have survived?
Constraining GC formation:
- We see GC-like clusters forming where gas pressure and SFR are high
- Both peaked near GC formation redshift

First question(s) must be:
- Could the products of regular cluster formation at high redshift have survived until the present day?
- Are these relics consistent with the properties of local GC populations?

Paraphrasing: are GCs old YMCs that have survived?

We require an end-to-end model for GC formation and evolution.
Analytical end-to-end model:

(Kruijssen 2015)
Analytical end-to-end model:

- **YMC formation**
- **Cluster migration**
- **GC populations**

**Time**

- \( t_{\text{form}} \)  
- \( t_{\text{merge}} \)  
- \( t_{\text{now}} \)

**Disc:** gas-rich  
**Halo:** gas-poor

- \( t_{\text{disc}} \)  
  - Rapid disruption by tidal shocks
- \( t_{\text{halo}} \)  
  - Slow disruption by evaporation

(Kruijssen 2015)
Analytical end-to-end model:
Analytical end-to-end model:
Analytical end-to-end model:
Analytical end-to-end model:

(Kruijssen 2015)
This model reproduces a large variety of observables describing GCs.

**BUT** the environmental dependence implies that *cosmic variance is important*.

Need **more** than analytical model: *fully self-consistent galaxy formation simulations* in order to account for space/time variation of cluster formation, migration & disruption.
What do we need to model star clusters over a Hubble time?
What do we need to model star clusters over a Hubble time?

EAGLE
What do we need to model star clusters over a Hubble time?

**EAGLE**

**MOSAICS**
The **EAGLE** project: **E**volution and **A**ssembly of **G**alaxies and their **E**nvironments

Cosmological, hydrodynamical galaxy formation simulations

*(Schaye + 2015; Crain + 2015)*

Largest run: 6.8 billion particles, 100 Mpc box, containing >10,000 galaxies Milky Way or bigger.

Resolution $10^6 \, M\odot$, 0.7 kpc

(high-res: $2 \times 10^5 \, M\odot$, 0.35 kpc)
MOSAICS:
MOdelling Star cluster population Assembly In Cosmological Simulations

Sub-grid model for cluster formation and evolution

- On-the-fly modelling
- Form cluster population within each star particle in simulation
- Cluster mass-loss model consistent with direct N-body simulations of clusters in a tidal field (Baumgardt & Makino 2003)
- Disruption by tidal shocks and evaporation using the evolving local tidal field of each ‘cluster particle’

(Kruijssen et al. 2011, 2012; Pfeffer et al. 2017, subm.)
MOSAICS: MOdelling Star cluster population Assembly In Cosmological Simulations

Sub-grid model for cluster formation and evolution

- On-the-fly modelling
- Form cluster population within each star particle in simulation
- Cluster mass-loss model consistent with direct N-body simulations of clusters in a tidal field (Baumgardt & Makino 2003)
- Disruption by tidal shocks and evaporation using the evolving local tidal field of each ‘cluster particle’

(Kruijssen et al. 2011, 2012; Pfeffer et al. 2017, subm.)
MOSAICS: sub-grid model for cluster formation and evolution

Physical ingredients:

- Cluster formation efficiency (CFE) model $\Gamma(P)$ (Kruijssen 2012)
- Schechter cluster mass function $N \propto M^{-2} \exp(-M/M_c, *)$
- Local maximum cluster mass $(M_c, *)$ (Reina-Campos & Kruijssen 2017)
- Cluster mass-loss by stellar evolution, tidal shocks and evaporation using the evolving local tidal field of each ‘cluster particle’
- Dynamical friction in post-processing

(Kruijssen et al. 2011, 2012; Pfeffer et al. 2017, subm.)
**MOSAICS**: sub-grid model for cluster formation and evolution

Physical ingredients:

- Cluster formation efficiency (CFE) model $\Gamma(P)$ (*Kruijssen 2012*)
- Schechter cluster mass function $N \propto M^{-2} \exp(-M/M_{c,*})$
- Local maximum cluster mass $(M_{c,*})$ (*Reina-Campos & Kruijssen 2017*)
- Cluster mass-loss by stellar evolution, tidal shocks and evaporation using the evolving local tidal field of each ‘cluster particle’
- Dynamical friction in post-processing

*(Kruijssen et al. 2011, 2012; Pfeffer et al. 2017, subm.)*
**MOSAICS**: sub-grid model for cluster formation and evolution

Physical ingredients:

- Cluster formation efficiency (CFE) model $\Gamma(P)$ (*Kruijssen 2012*)
- Schechter cluster mass function $N \propto M^{-2} \exp(-M/M_{c,*})$
- Local maximum cluster mass ($M_{c,*}$) (*Reina-Campos & Kruijssen 2017*)
- Cluster mass-loss by stellar evolution, tidal shocks and evaporation using the evolving local tidal field of each ‘cluster particle’
- Dynamical friction in post-processing

See Michael’s Grudić talk tomorrow @ 14:55
**MOSAICS**: sub-grid model for cluster formation and evolution

Physical ingredients:

- Cluster formation efficiency (CFE) model $\Gamma(P)$ (Kruijssen 2012)
- Schechter cluster mass function $N \propto M^{-2} \exp(-M/M_c,\ast)$
- Local maximum cluster mass $(M_c,\ast)$ (Reina-Campos & Kruijssen 2017)
- Cluster mass-loss by stellar evolution, tidal shocks and evaporation using the evolving local tidal field of each ‘cluster particle’
- Dynamical friction in post-processing

(Kruijssen et al. 2011, 2012; Pfeffer et al. 2017, subm.)
**MOSAICS**: sub-grid model for cluster formation and evolution

Physical ingredients:

- Cluster formation efficiency (CFE) model $\Gamma(P)$ (*Kruijssen 2012*)
- Schechter cluster mass function $N \propto M^{-2} \exp(-M/M_{c,*})$
- Local maximum cluster mass $(M_{c,*})$ (*Reina-Campos & Kruijssen 2017*)
- Cluster mass-loss by stellar evolution, tidal shocks and evaporation using the evolving local tidal field of each ‘cluster particle’
- Dynamical friction in post-processing

(*Kruijssen et al. 2011, 2012; Pfeffer et al. 2017, subm.*)
**MOSAICS**: sub-grid model for cluster formation and evolution

Physical ingredients:

- Cluster formation efficiency (CFE) model $\Gamma(P)$ \cite{Kruijssen2012}
- Schechter cluster mass function $N \propto M^{-2} \exp(-M/M_{c,*})$
- Local maximum cluster mass $M_{c,*}$ \cite{Reina-Campos2017}
- Cluster mass-loss by stellar evolution, tidal shocks and evaporation using the evolving local tidal field of each ‘cluster particle’
- Dynamical friction in post-processing

\cite{Kruijssen2011,2012; Pfeffer2017, subm.}
**MOSAICS**: sub-grid model for cluster formation and evolution

Physical ingredients:

- Cluster formation efficiency (CFE) model $\Gamma(P)$ (*Kruijssen 2012*)
- Schechter cluster mass function $N \propto M^{-2} \exp(-M/M_{c,*})$
- Local maximum cluster mass $(M_{c,*})$ (*Reina-Campos & Kruijssen 2017*)
- Cluster mass-loss by stellar evolution, tidal shocks and evaporation using the evolving local tidal field of each ‘cluster particle’
- Dynamical friction in post-processing

(*Kruijssen et al. 2011, 2012; Pfeffer et al. 2017, subm.*)
**MOSAICS**: sub-grid model for cluster formation and evolution

Physical ingredients:

- Cluster formation efficiency (CFE) model $\Gamma(P)$ (*Kruijssen 2012*)
- Schechter cluster mass function $N \propto M^{-2} \exp(-M/M_{c,*})$
- Local maximum cluster mass $(M_{c,*})$ (*Reina-Campos & Kruijssen 2017*)
- Cluster mass-loss by stellar evolution, tidal shocks and evaporation using the evolving local tidal field of each ‘cluster particle’
- Dynamical friction in post-processing

Both cluster formation and disruption are more intense and efficient in high pressure and dense environments

(*Kruijssen et al. 2011, 2012; Pfeffer et al. 2017, subm.*)
The **E-MOSAICS** project: co-formation of galaxies and GCs

**MOdelling** Star cluster population **Assembly** In **Cosmological** **Simulations** in the context of **EAGLE**

Using EAGLE Recal (high-res) model

10 cosmological zoom-ins of Milky Way-mass galaxies (over 100 simulations in total including subgrid model testing)

Many ‘bonus’ galaxies, including an elliptical galaxy ($M_{\text{vir}} \approx 10^{13} \, M_{\odot}$)

(Pfeffer et al. 2017, subm., Kruijssen et al. in prep.)
The **E-MOSAICS** project: co-formation of galaxies and GCs

First time that the formation and evolution of the entire cluster population is modelled self-consistently across cosmic history

*(Pfeffer et al. 2017, subm., Kruijssen et al. in prep.)*
The **E-MOSAICS** project: co-formation of galaxies and GCs

First time that the formation and evolution of the entire cluster population is modelled **self-consistently** across cosmic history.

*(Pfeffer et al. 2017, subm., Kruijssen et al. in prep.)*
Modelling GCs as surviving YMC analogues
E-MOSAICS - Cluster formation efficiency (CFE)

Higher pressure environments at high redshift

(Pfeffer et al. 2017, subm.)
E-MOSAICS - Truncation mass ($M_{c,*}$)

Higher pressure environments at high redshift

(Pfeffer et al. 2017, subm.)
E-MOSAICS - Tidal field strength

Disruption by tidal shocks is more efficient at high redshift.

(Pfeffer et al. 2017, subm.)
Disruption by tidal shocks is more efficient at high redshift.

(Pfeffer et al. 2017, subm.)
Clusters formed in high pressure/density environments have peaked MF
Too many low-mass clusters survive at low birth pressures
But not resolving real cluster formation densities (need cold ISM!)

(Kruijssen 2015)
**E-MOSAICS - Blue tilt**

Bailin & Harris (2009) suggest self-enrichment of GCs to explain the deficit of massive clusters at low metallicities.

BUT, the blue tilt comes as a natural consequence of cluster formation due to our maximum mass model (Reina-Campos & Kruijssen 2017)

---

**Usher et al. (in prep.)**
Bailin & Harris (2009) suggest self-enrichment of GCs to explain the deficit of massive clusters at low metallicities. BUT, the blue tilt comes as a natural consequence of cluster formation due to our maximum mass model (Reina-Campos & Kruijssen 2017).
Tracing galaxy formation with GCs
We reproduce the age-metallicity plane of the Milky Way.

(Kruijssen et al. in prep.)
E-MOSAICS - Age - metallicity plane

We reproduce the age-metallicity plane of the Milky Way

(Dotter et al. 2011)

(Kruijssen et al. in prep.)
E-MOSAICS - Age - metallicity plane

(Kruijssen et al. in prep.)
E-MOSAICS - Age - metallicity plane

(Kruijssen et al. in prep.)
E-MOSAICS - Age - metallicity plane

(Kruijssen et al. in prep.)
E-MOSAICS - Age - metallicity plane

Using the age-metallicity space we can reconstruct the merger tree of the host galaxy

(Kruijssen et al. in prep.)
E-MOSAICS - Cosmic formation histories

Madau & Dickinson (2014)

Reina-Campos et al. (in prep.)
E-MOSAICS - Cosmic formation histories

Each population forms at a different time

Madau & Dickinson (2014)

Reina-Campos et al. (in prep.)
E-MOSAICS - Cosmic formation histories

Reina-Campos et al. (in prep.)
E-MOSAICS - Cosmic formation histories

If no formation physics is included, surviving GCs are the **youngest** objects.
If all formation physics is included, surviving GCs are the **oldest** objects.

\[ \Delta t \approx 2 \text{ Gyr} \]
\[ \Delta z \approx 0.8 \]
Planned future work

- Age-metallicity relations *(Kruijssen et al., in prep.)*
- Cluster formation histories *(Reina-Campos et al., in prep.)*
- Metallicity and spatial distributions
- Blue tilt *(Usher et al., in prep.)*
- GCs and streams
- Specific frequency
- GC system dynamics
- Size evolution
- Nuclear clusters
- High redshift predictions *(Bastian et al., in prep.)*
- Galaxy groups and clusters *(Pfeffer et al., Kruijssen et al. in prep.)*

Longer timescale

- Periodic box
- Couple with other cosmological simulations
  (e.g. AREPO and EAGLE-2)
Let’s go back…

- What are the important physical mechanisms that shape the GC population that we see at $z=0$?

- What do GCs reveal about the formation and assembly history of its host galaxy?
Let’s go back...

- What are the important physical mechanisms that shape the GC population that we see at \( z=0 \)?

  *cluster formation efficiency, maximum mass, shock-driven disruption, migration, evaporation*

- What do GCs reveal about the formation and assembly history of its host galaxy?
Let’s go back…

- What are the important physical mechanisms that shape the GC population that we see at z=0?

  *cluster formation efficiency, maximum mass, shock-driven disruption, migration, evaporation*

  **Caution**: avoid particle tagging, include the necessary physics

- What do GCs reveal about the formation and assembly history of its host galaxy?
Let’s go back...

- What are the important physical mechanisms that shape the GC population that we see at z=0?

  cluster formation efficiency, maximum mass, shock-driven disruption, migration, evaporation

**Caution:** avoid particle tagging, include the necessary physics

- What do GCs reveal about the formation and assembly history of its host galaxy?

  distribution of GCs in age-metallicity-mass space is sensitive to host galaxy formation and assembly
Let’s go back…

- What are the important physical mechanisms that shape the GC population that we see at z=0?

  cluster formation efficiency, maximum mass, shock-driven disruption, migration, evaporation

**Caution**: avoid particle tagging, include the necessary physics

- What do GCs reveal about the formation and assembly history of its host galaxy?

  distribution of GCs in age-metallicity-mass space is sensitive to host galaxy formation and assembly

**Exciting**: this seems to be deterministic
Let’s go back…

• What are the important physical mechanisms that shape the GC population that we see at z=0?

  cluster formation efficiency, maximum mass, shock-driven disruption, migration, evaporation

  **Caution**: avoid particle tagging, include the necessary physics

• What do GCs reveal about the formation and assembly history of its host galaxy?

  distribution of GCs in age-metallicity-mass space is sensitive to host galaxy formation and assembly

  **Exciting**: this seems to be deterministic

  **Caution**: requires running large galaxy samples
Summary

Modelling GC formation has remained a major problem in astrophysics.

E-MOSAICS: first simulations to self-consistently model formation and evolution of galaxies and star clusters over full cosmic history.

Sub-grid methods only way to study GCs over cosmological volumes and time.

GCs natural outcome of high-redshift star cluster formation, making a wide range of quantitative, observationally testable predictions.

Tidal shock-driven disruption greatly outweighs evaporation over cosmic history; disruption peaks at high redshift.
Summary

Modelling GC formation has remained a major problem in astrophysics

E-MOSAICS: first simulations to self-consistently model formation and evolution of galaxies and star clusters over full cosmic history

Sub-grid methods only way to study GCs over cosmological volumes and time

GCs natural outcome of high-redshift star cluster formation, making a wide range of quantitative, observationally testable predictions

Tidal shock-driven disruption greatly outweighs evaporation over cosmic history; disruption peaks at high redshift