The Star Cluster Factory

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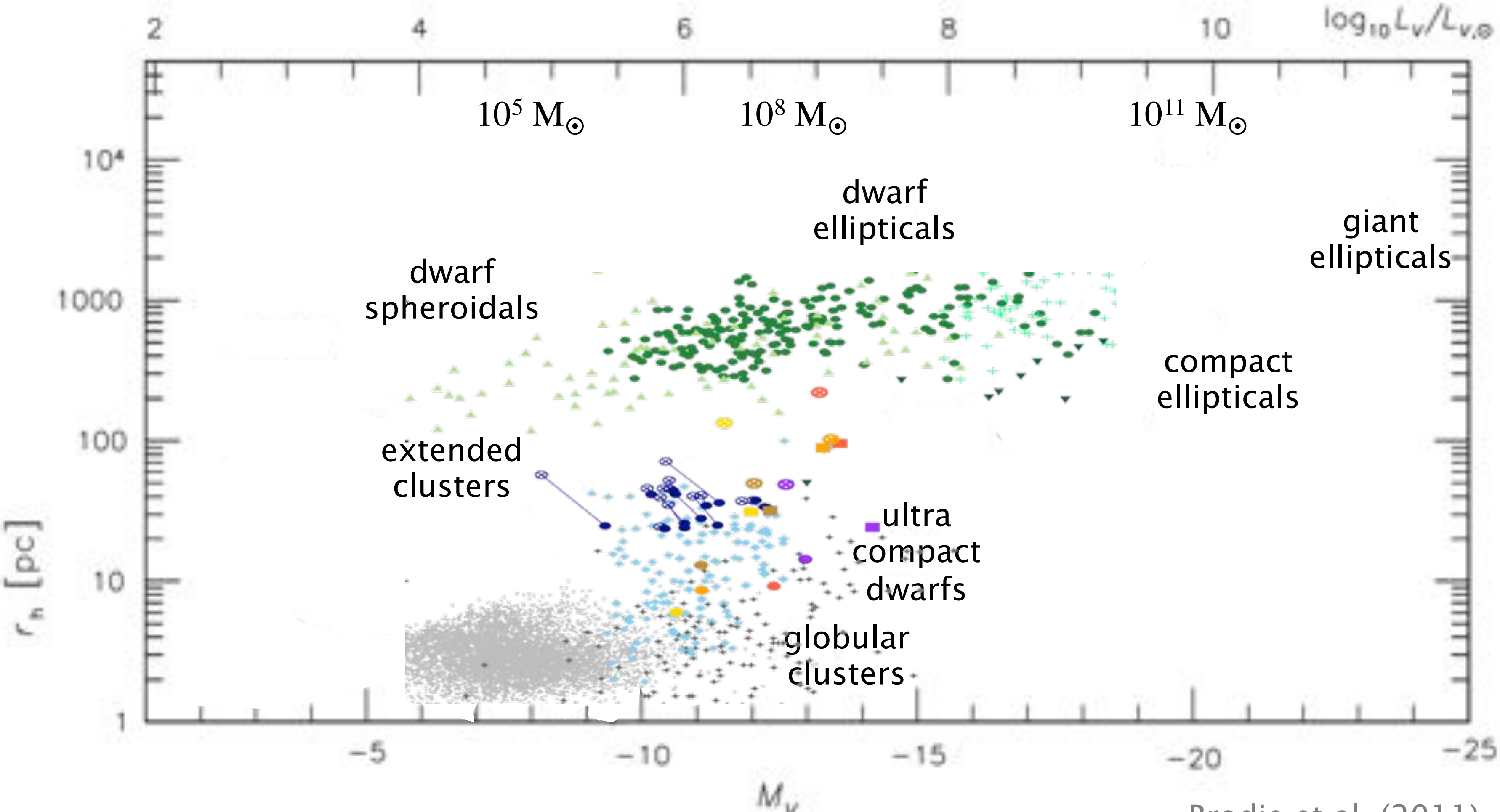
A zoo of stellar objects

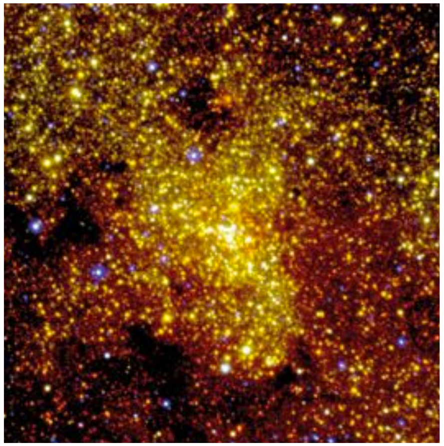


Brodie et al. (2011)
Voggel et al. (2016)

Star clusters probe their environment

- Interstellar medium (embedded clusters, < 10 Myr)
- Extreme environments (young massive clusters, > 10^6 $M_\odot$)
- Galactic dynamics (nuclear clusters)
- Early Universe (globular clusters, ~10 Gyr)

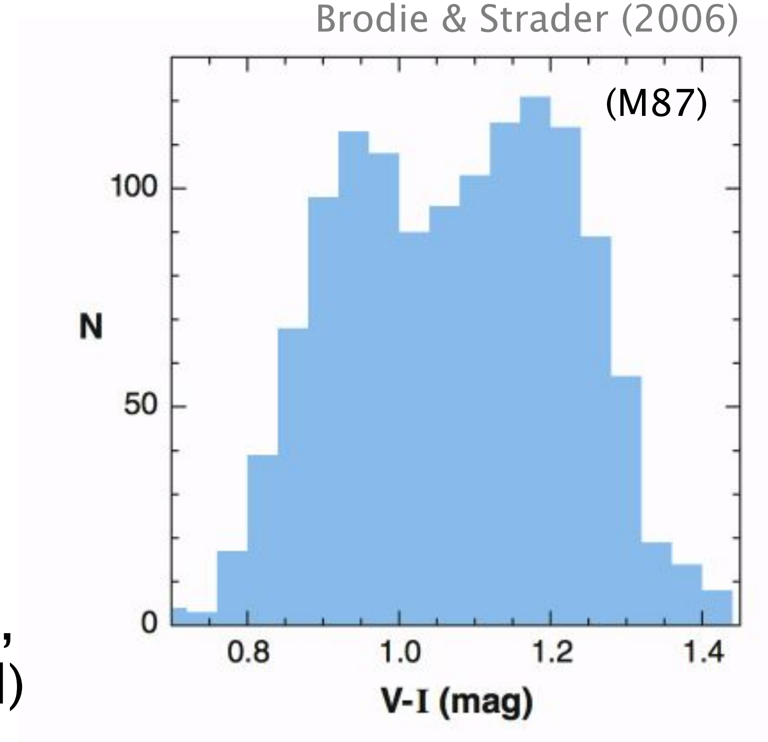





Bimodality in globular clusters

Harris (2001, 2006)
Larsen et al. (2001)
Brodie & Strader (2006)

- Blue ("halo clusters")
  metal-poor ([Fe/H] ~ -1.5)
  no rotation
  spatially extended
- Red ("disk, bulge clusters")
  metal-rich ([Fe/H] ~ -0.5)
  rotation
  spatially concentrated



- Formed in progenitors (blue), then in gas-rich mergers (red)
  Ashman & Zepf (1992)
- Multiphase collapse
  Forbes, Brodie & Grillmair (1997)
- Accreted (blue) and in-situ (red)
  Coté et al. (1998)

A multi-scale and multi-physics problem

Large scales

- Galaxy formation
- Galaxy interactions
- Structure formation (disk, bar, spiral)

Small scales

- Star cluster formation
- Stellar evolution, feedback
- 2-body relaxation, internal evolution

Combining the two

this talk

Just a tiny fraction of theoretical star cluster-centered studies:

Peebles & Dicke (1968)
Krauss & Chaboyer (2003)
Rieder et al. (2013)
Renaud & Gieles (2015c)
Kimm et al. (2016)

Renaud & Gieles (2013)
Miholics et al. (2014, 2015)
Bianchini, Renaud et al. (2015)
Renaud et al. (2016)
Fensch, Renaud et al. (submitted)

Gnedin & Ostriker (1997)
Gieles et al. (2007)
Rossi & Hurley (2015)
Renaud et al. (2015d)

Fall & Rees (1985)
Schweizer (1987)
Ashman & Zepf (1992)
Fellhauer et al. (2002)
Kravstov & Gnedin (2005)
Renaud et al. (2014, 2015a)
Maji et al. (2016)
Guillard et al. (2016)
Li et al. (2016)

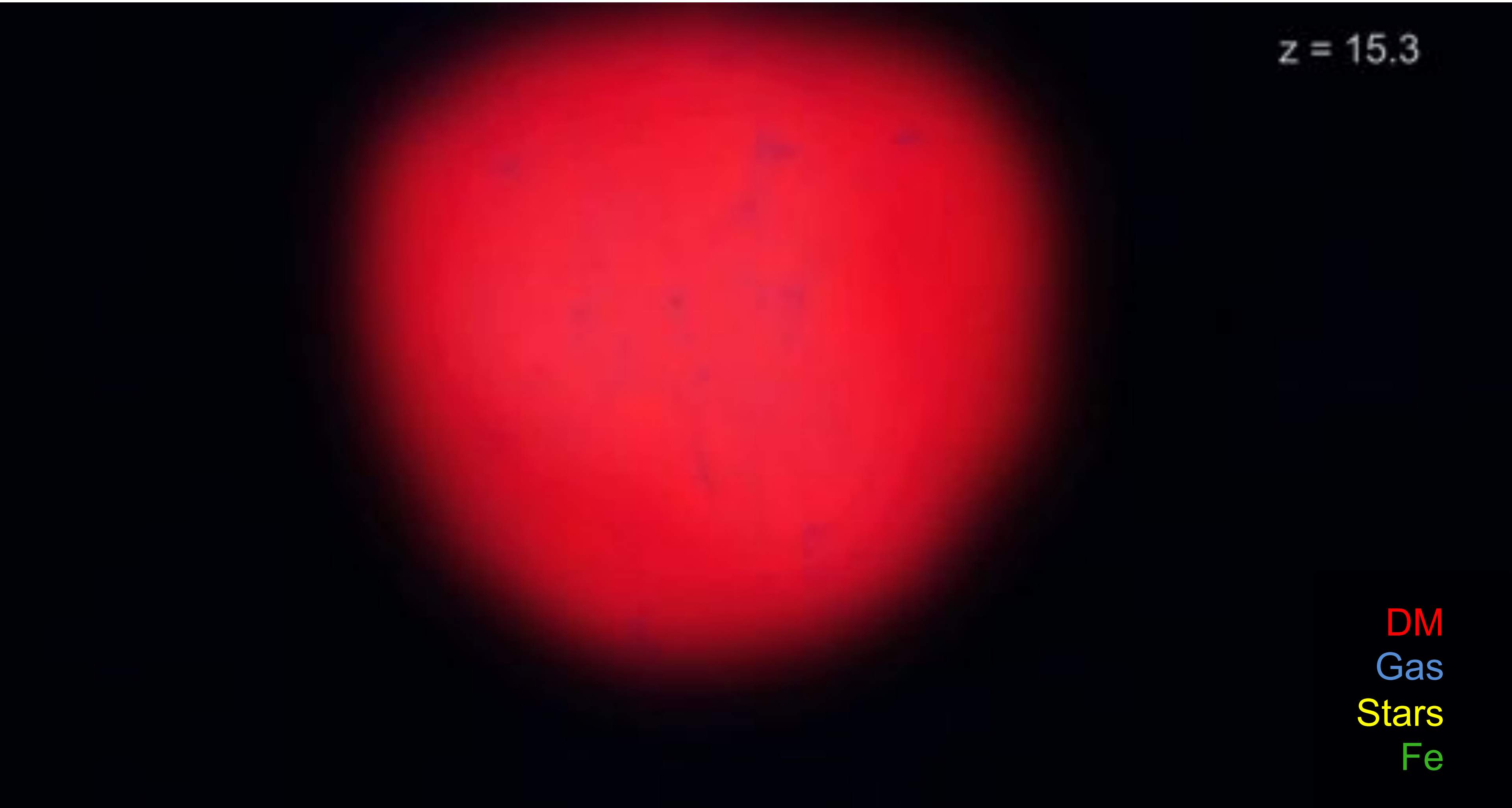
Hurley et al. (2002)
Boily & Kroupa (2003a,b)
Fellhauer & Kroupa (2005)
Smith et al. (2011)
Guillard, Renaud et al. (in prep)

Hénon (1961, 1965)
Vesperini (1998)
Fukushige & Heggie (2000)
Baumgardt & Makino (2003)
Heggie & Hut (2003)
Gieles et al. (2006)
Kuepper et al. (2010)
Elmegreen (2010)
Renaud et al. (2011)
Hurley & Shara (2012)
Madrid et al. (2012)
Berentzen & Athanassoula (2012)
Vesperini et al. (2014)
Webb et al. (2014, 2015)
Gieles & Renaud (2016)

Formation of the Milky Way

Renaud et al. (submitted)

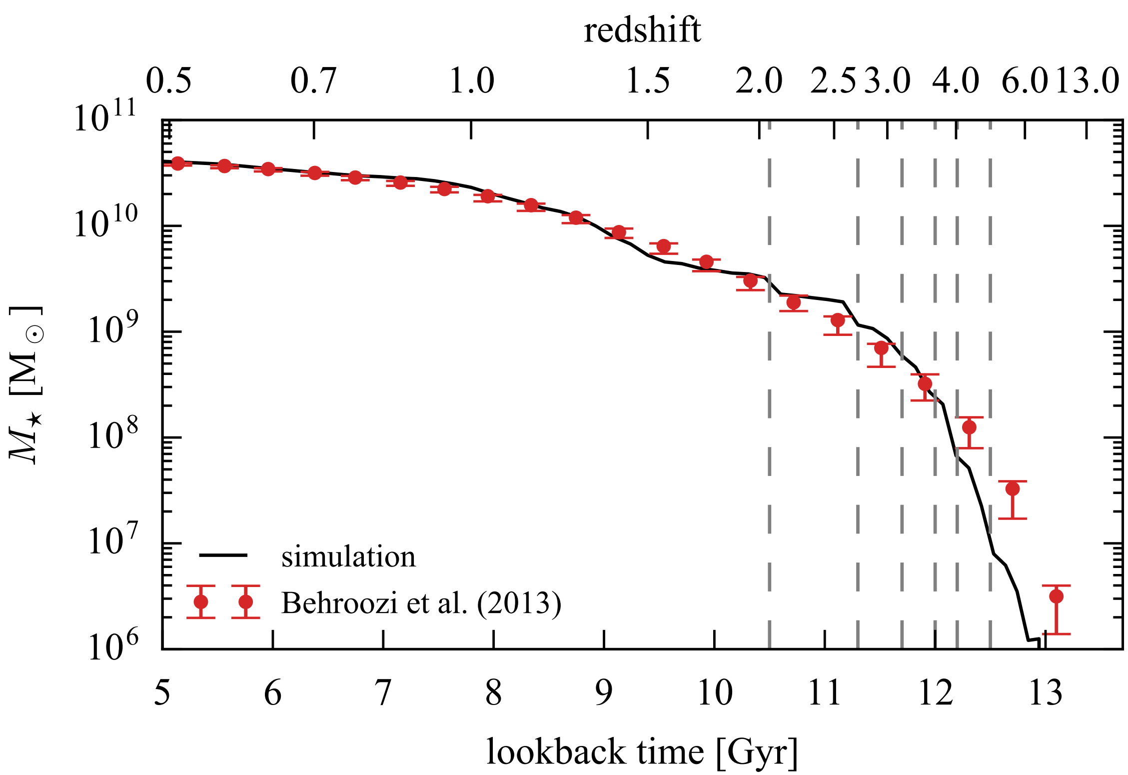
- Zoom-in (identical to Weztel et al. 2016)
- Ramses (Teyssier 2002)
- SF, winds, radiation pressure, SNII, SNIa (Agertz et al. 2013, 2015, 2016)



Formation of the Milky Way

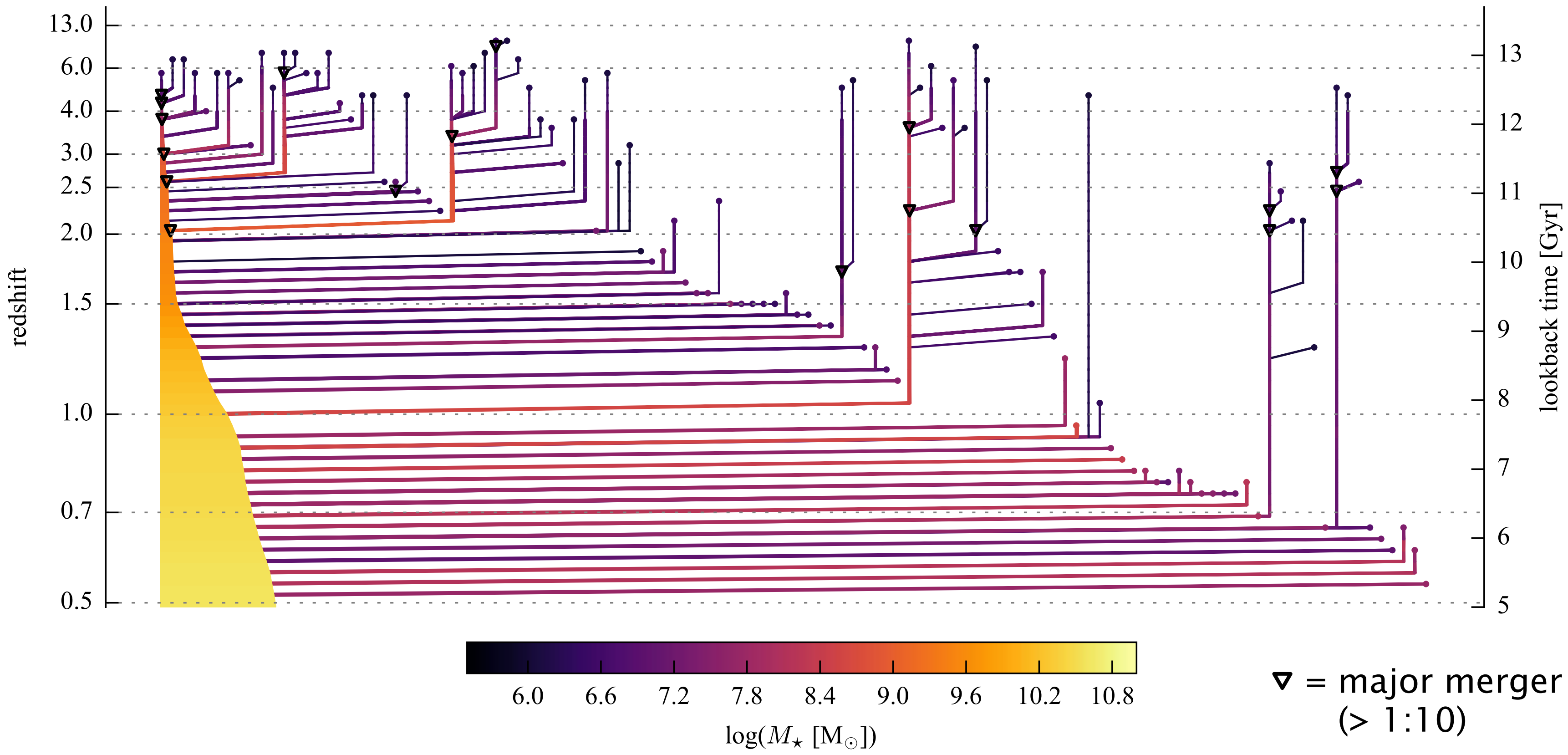
Renaud et al. (submitted)

- Early growth via major mergers ($z > 2$)
- Steady increase via slow SF (~ 1-10 $M_{\odot}$/yr)



Merger tree

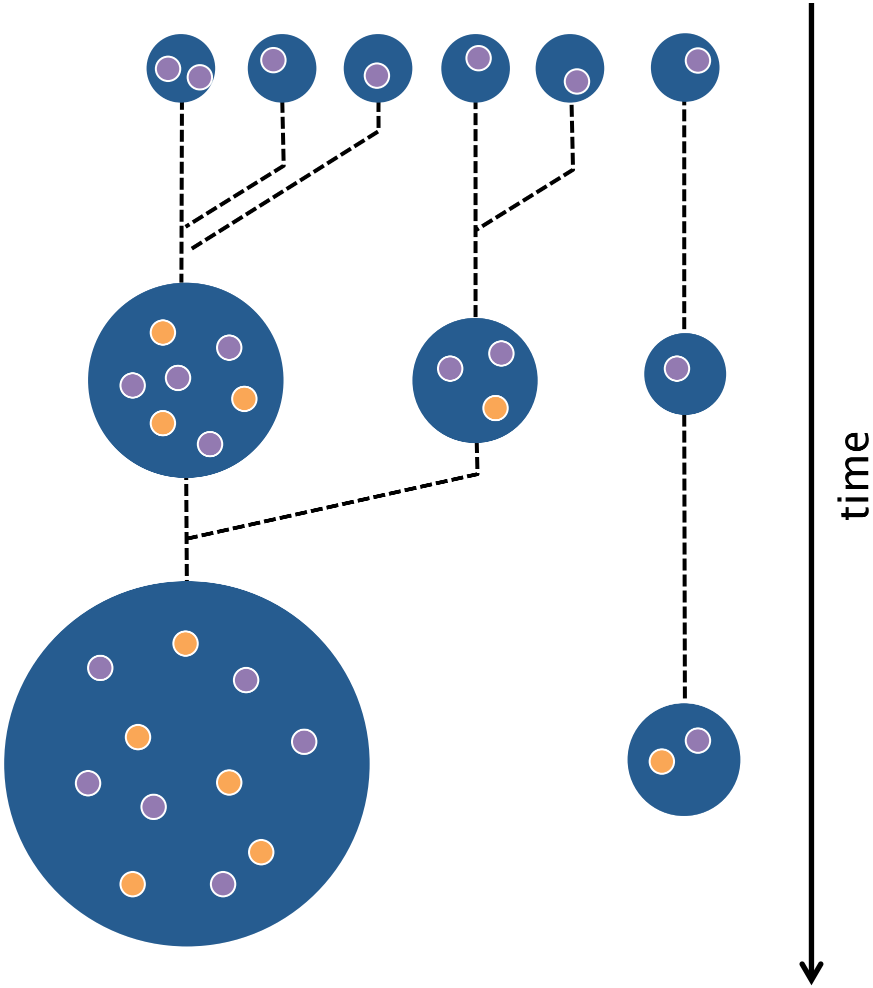
Renaud et al. (submitted)



- Last major merger at z=2

A recipe for metallicity bimodality

- Massive *enough* galaxy
  = high SFR
  high v_{escape}
  = self-enrichment
  - Formation in low-mass galaxy
    → metal-poor
  - Formation in massive galaxy
    → metal-rich
- Growth + merger history
  = bimodality

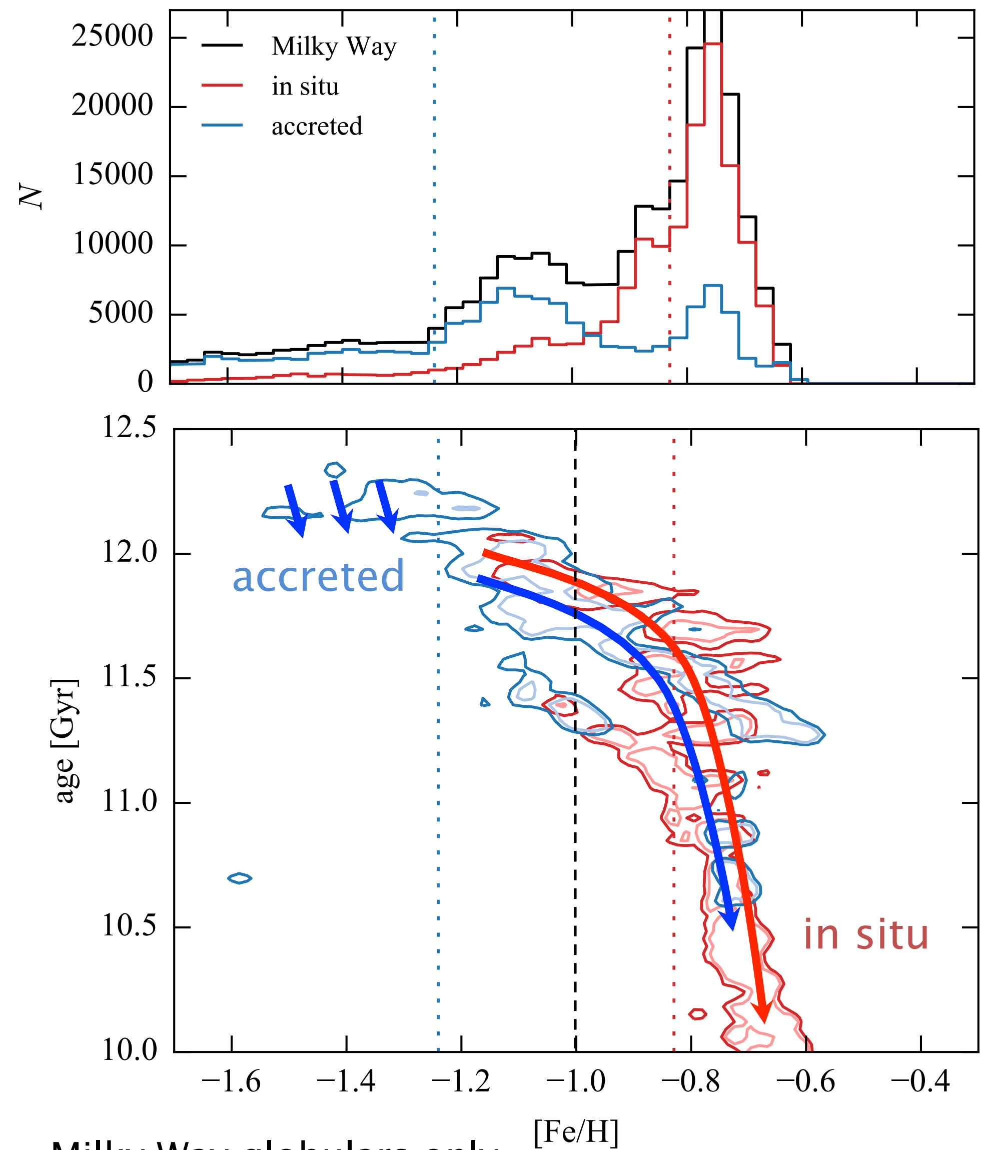


Metallicity traces clusters' origins

Renaud et al. (submitted)

- Metal-rich =
  in situ formation
  (+ massive galaxy accretion)

- Metal-poor =
  low-mass galaxy accretion
  (+ early in situ formation)

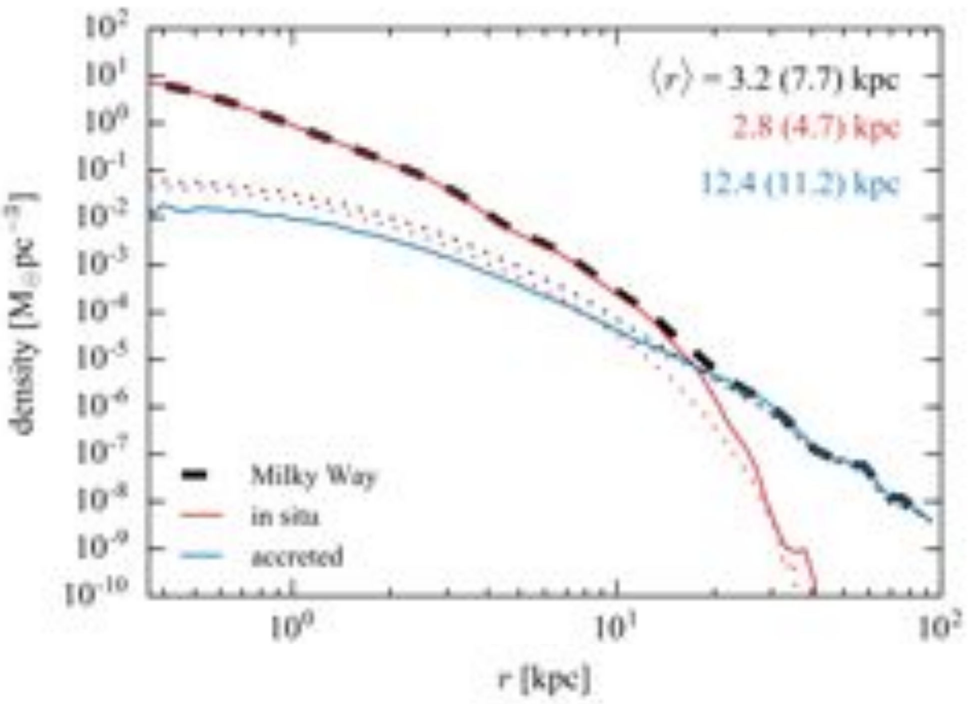


Milky Way globulars only

Notable differences between in situ and accreted clusters

- Accreted
  - metal-poor ([Fe/H] ~ -1.3)
  - no rotation
  - spatially extended
- Just like blue clusters
- In situ
  - metal-rich ([Fe/H] ~ -0.8)
  - rotation
  - spatially concentrated
- Just like red clusters

Renaud et al. (submitted)



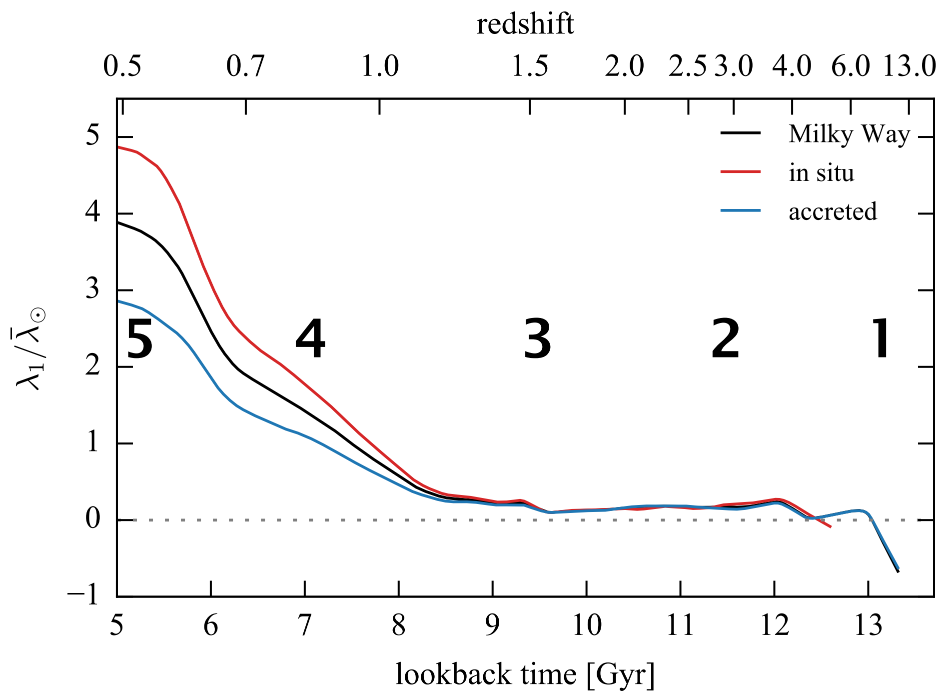
- Coté et al. (1998) scenario + a twist (accreted metal-rich)

Monitoring tides

Renaud et al. (submitted)

5 phases:

1. $z > 5$
   early compression



$$\lambda = \frac{2GM(< r)}{r^3}$$

completly wrong, but ... whatever

Compressive tides

- Cores in potential
- In overlaps of extended profiles
  e.g. interactions
- But also at high redshift
  Renaud et al. (in prep)
- Stop destroying clouds
- Favor/trigger SF
  (via compressive turbulence)
  Renaud et al. (2014)
- Young massive clusters
  Renaud et al. (2015)

Simulation: Agertz et al. (in prep)
Renaud et al. (2008)

red ≃ compressive tides

Monitoring tides

Renaud et al. (submitted)

5 phases:

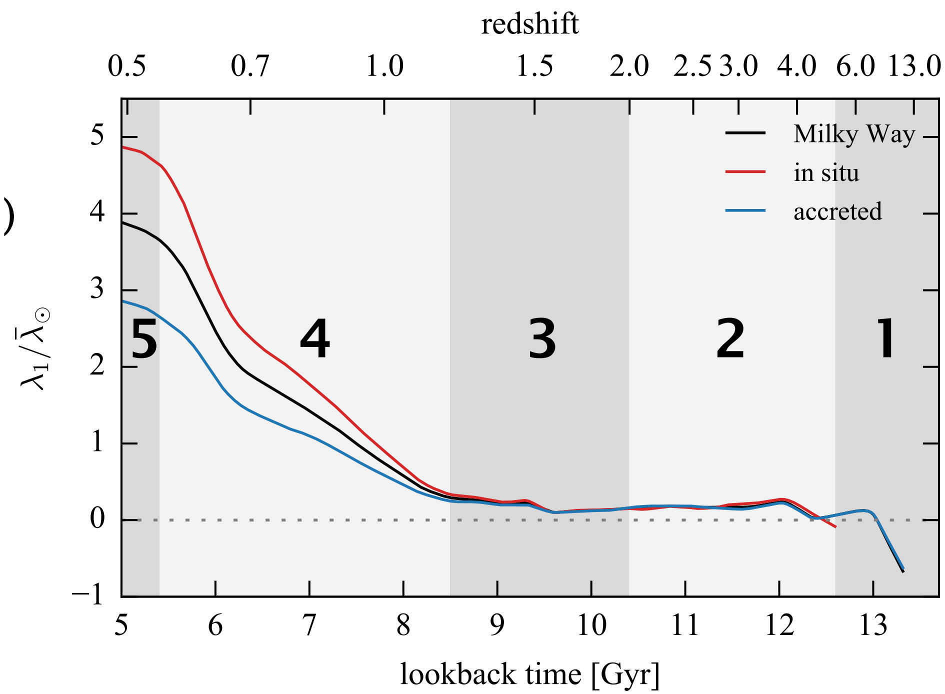
1. $z > 5$
   early compression
   (similar physics as in mergers)

2. $2 < z < 5$
   major mergers
   (increasing M and r)

3. $1.2 < z < 2$
   in situ SF
   (~constant M, decreasing r)

4. $0.6 < z < 1.2$
   (same as before but increasing M. Disk formation)

5. $z < 0.6$
   slower growth via weak SF
   (~constant M and r)



$$\lambda = \frac{2GM(<r)}{r^3}$$

completly wrong, but ... whatever

Summary

Star clusters co-evolve with their hosts
(and can tell us how)

- Observed red/blue groups retrieved in simulated in situ / accreted populations
- Bimodalities regulated by merger history
- Globular = aged young massive cluster?
    - Maybe same trigger (compressive tides)
    - But different metallicities
    - And different evolution
- Tidal histories follow galaxy build-up phases