Resolved Massive Cluster Formation at Low and High Redshift

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(Liverpool JMU)

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Stellar Clusters

Type	Age	Mass	Found
Open	0 - (3-10) Gyr	100 - 10^4 M_o	where star-formation is happening
Young Massive Clusters (YMCs)	<100 Myr or 0 - (1-10) Gyr	> 10^4 M_o	where star-formation is happening
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GCs and YMCs

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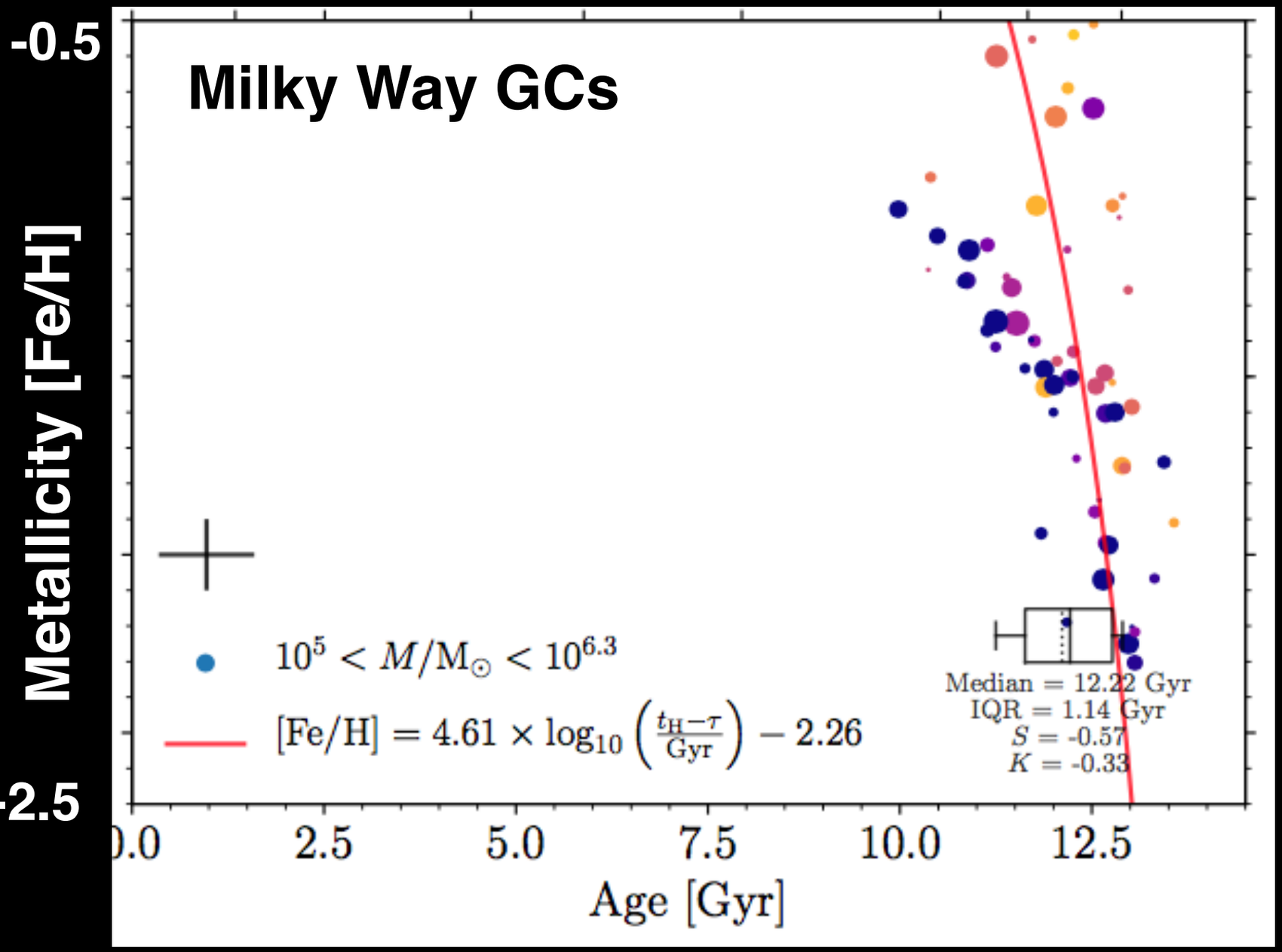

Kruijssen+ 2019b

Forbes & Bridges 2010
Muratov & Gnedin 2010
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Kruijssen+ 2019a,b,2020
Pfeffer+2020

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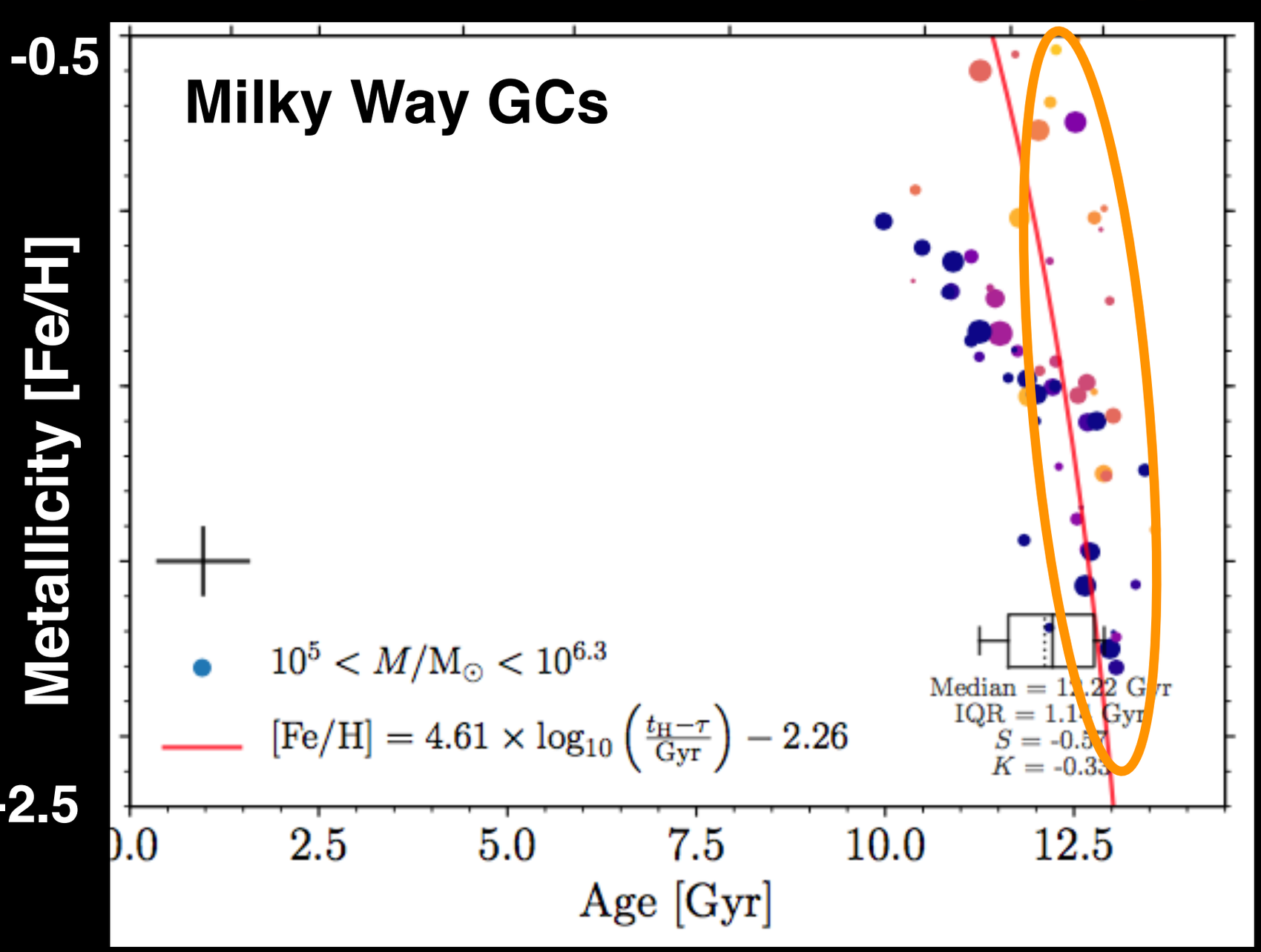

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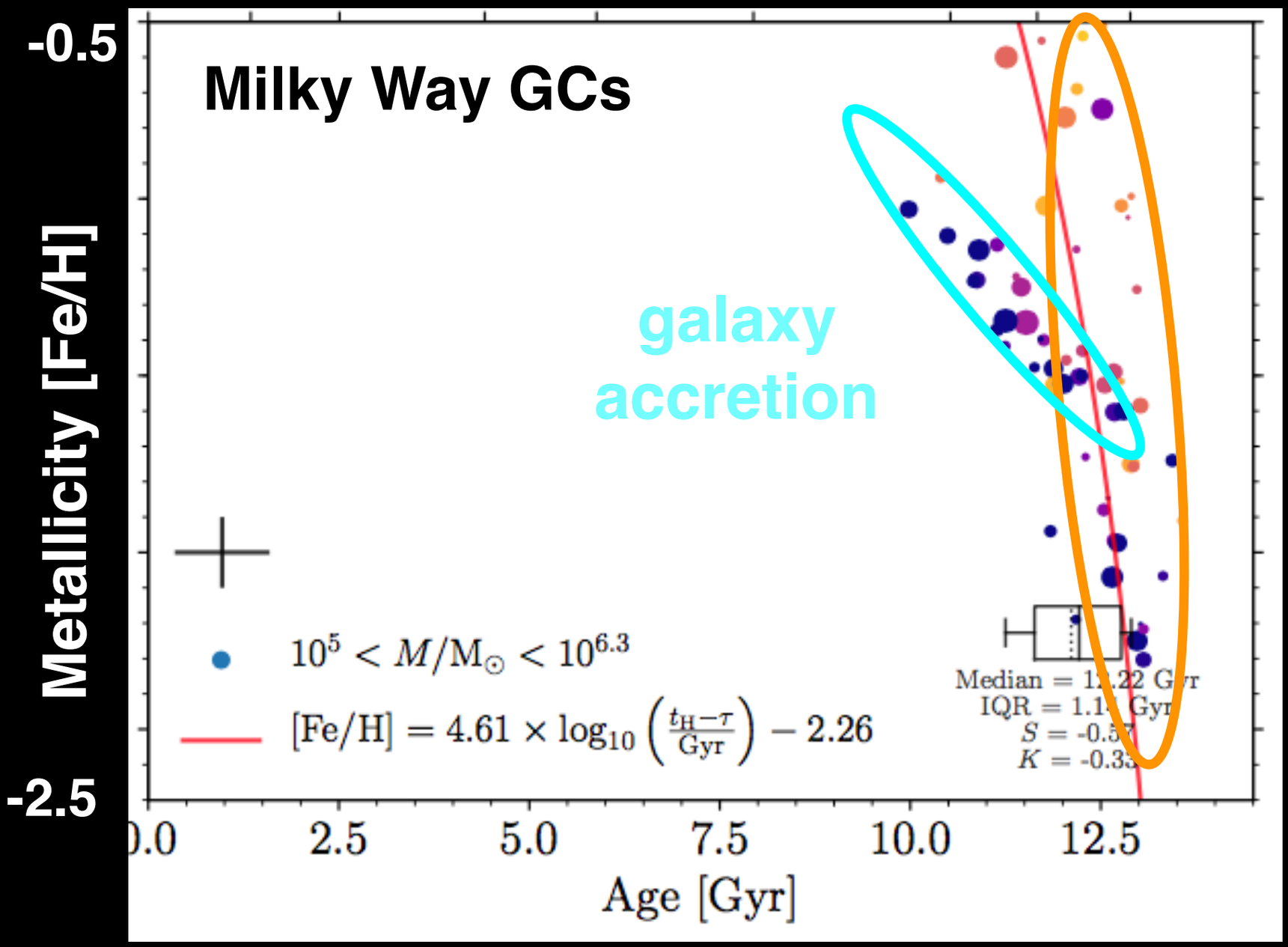

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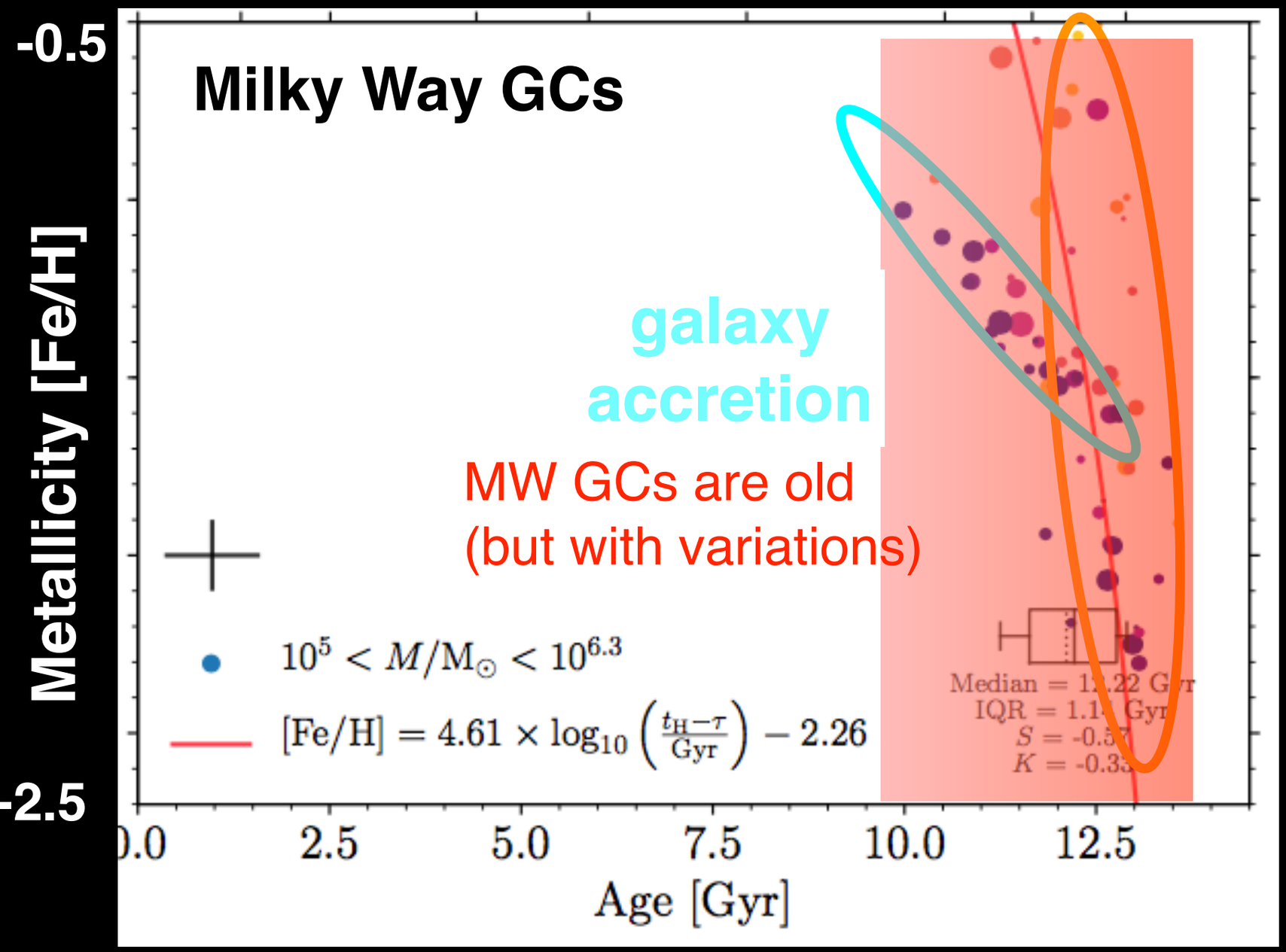

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Age Distributions:
The Milky Way

At fixed metallicity, accreted GCs are younger

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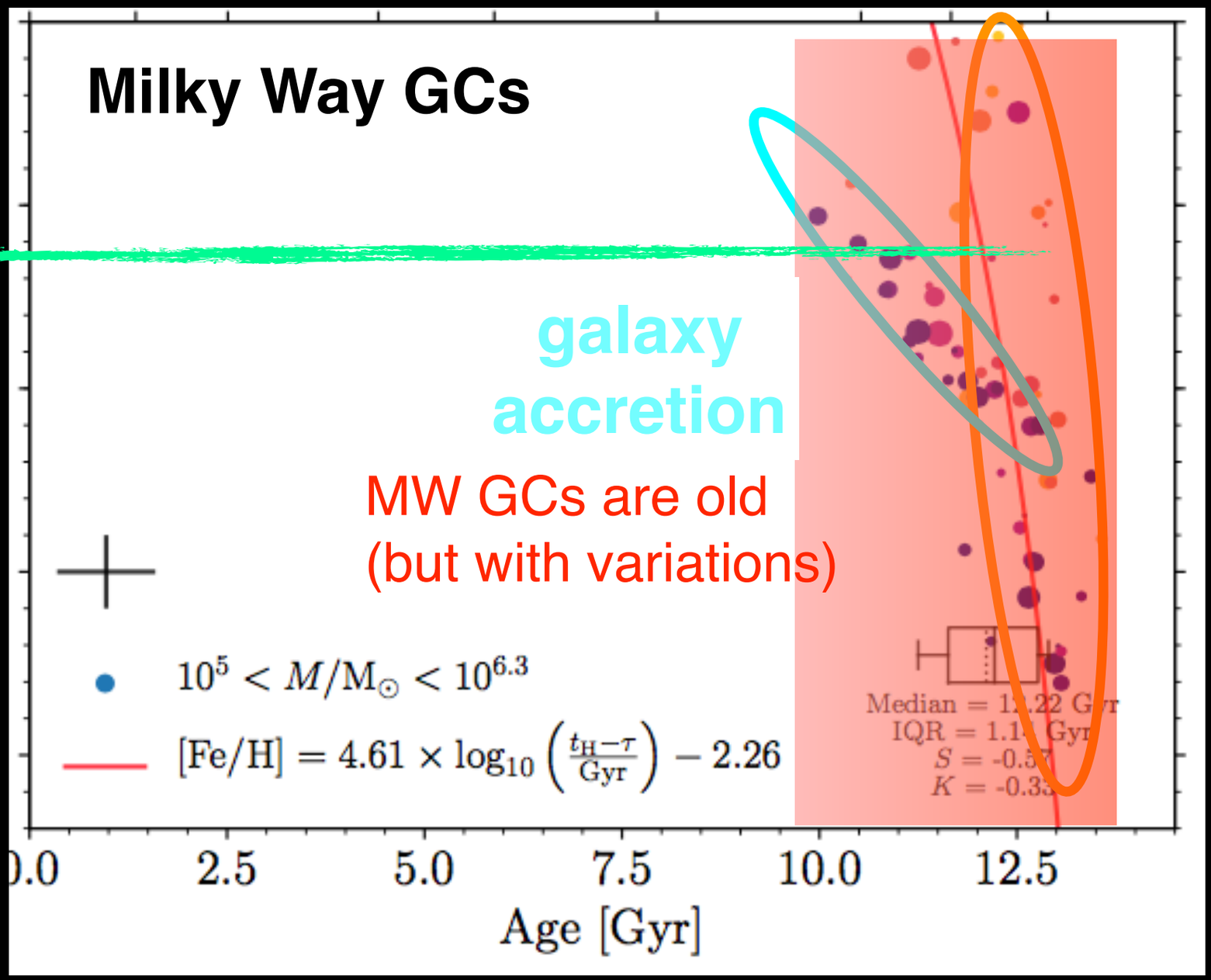
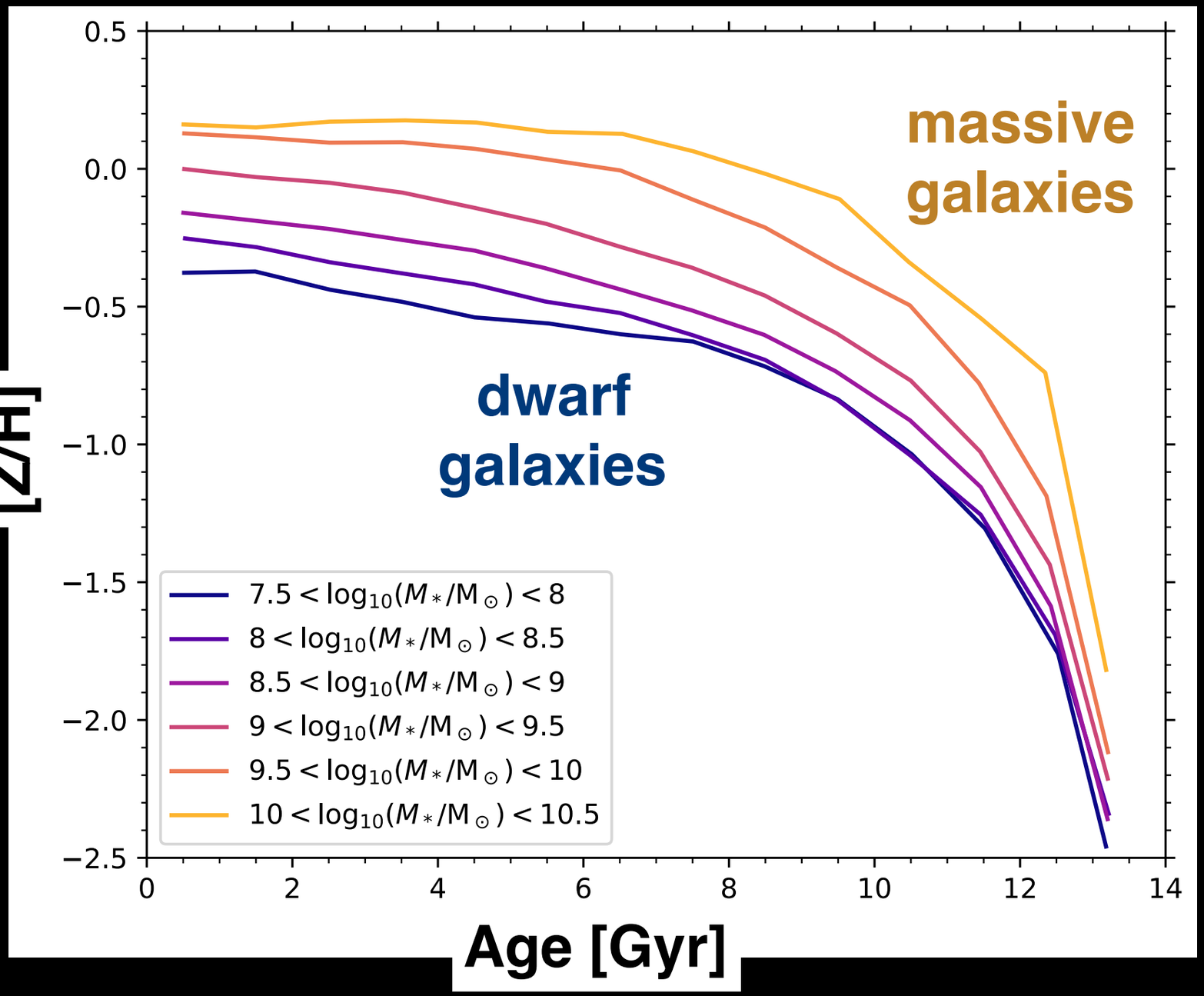


Kruijssen+ 2019b

Age Distributions:
Expectations

If GCs trace star-formation, we expect different age distributions



courtesy of Joel Pfeffer (from the EAGLE simulations)

R136
~2 Myr

NGC 1850
~100 Myr

NGC 1856
~300 Myr

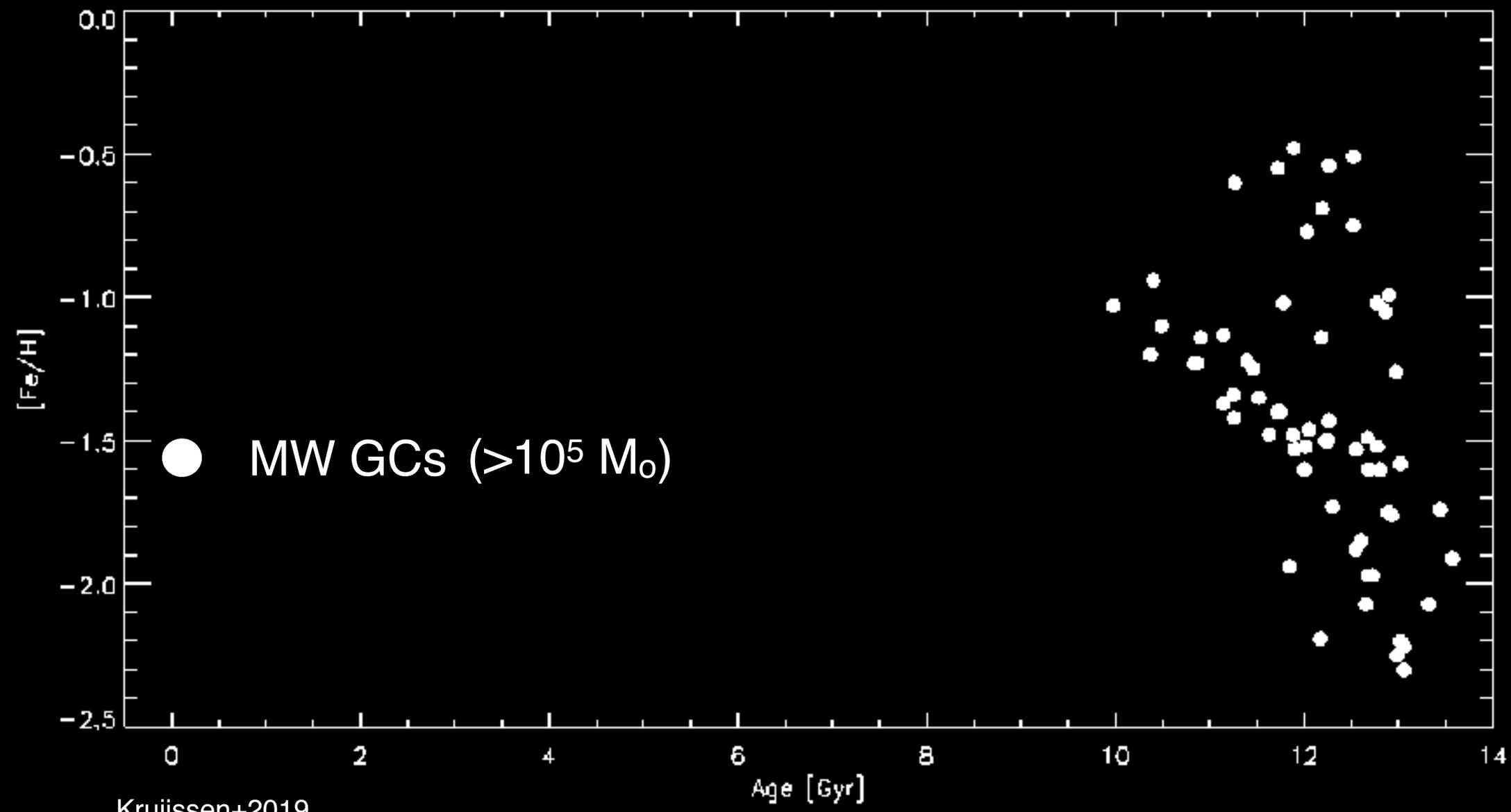
NGC 419
~1.5 Gyr

NGC 416
~6 Gyr

NGC 121
~11 Gyr

all ~few * 10^5 $M_\odot$

Age Distributions:
Our closest neighbours



● MW GCs (>10^5 M_o)

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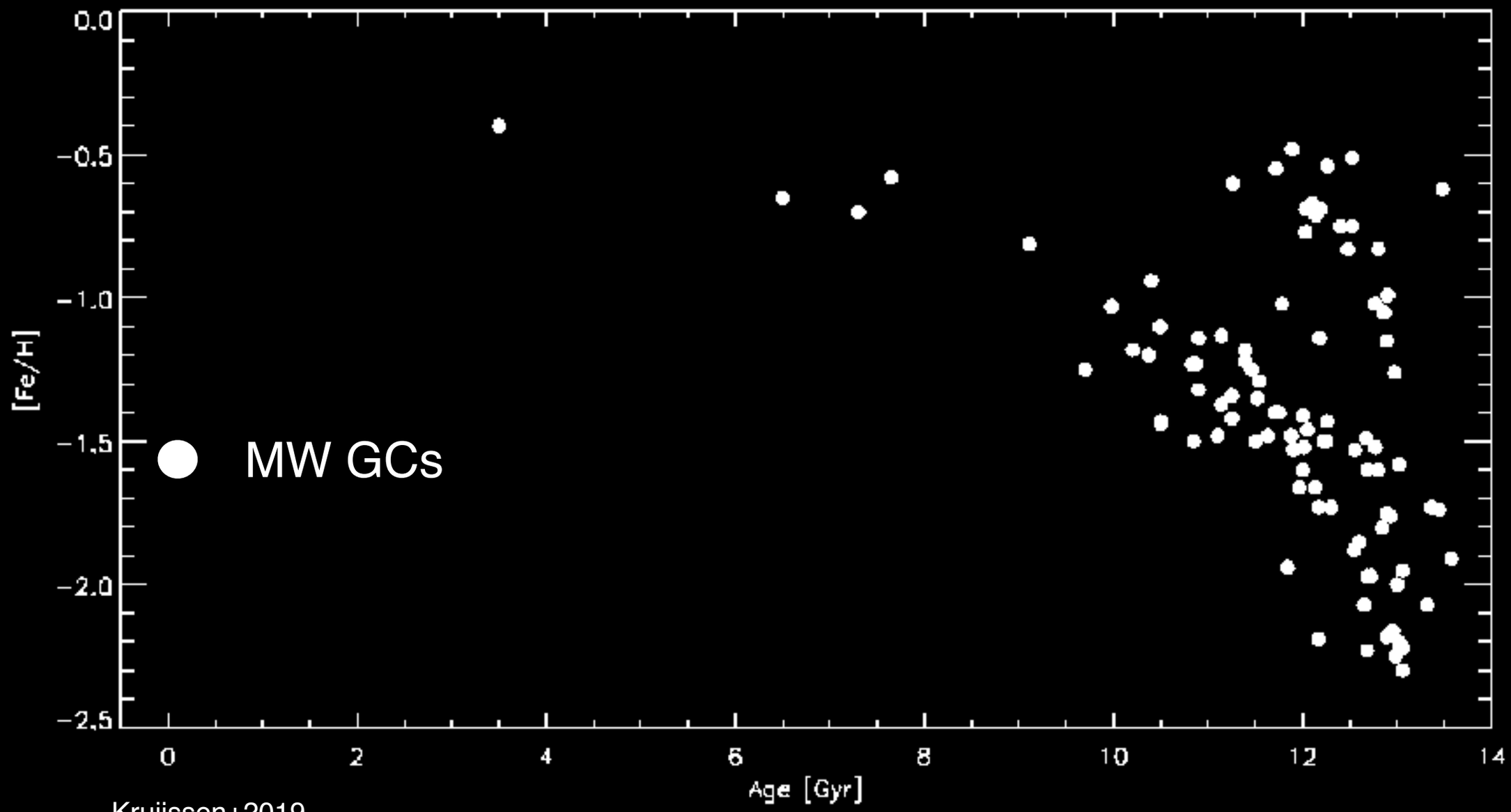

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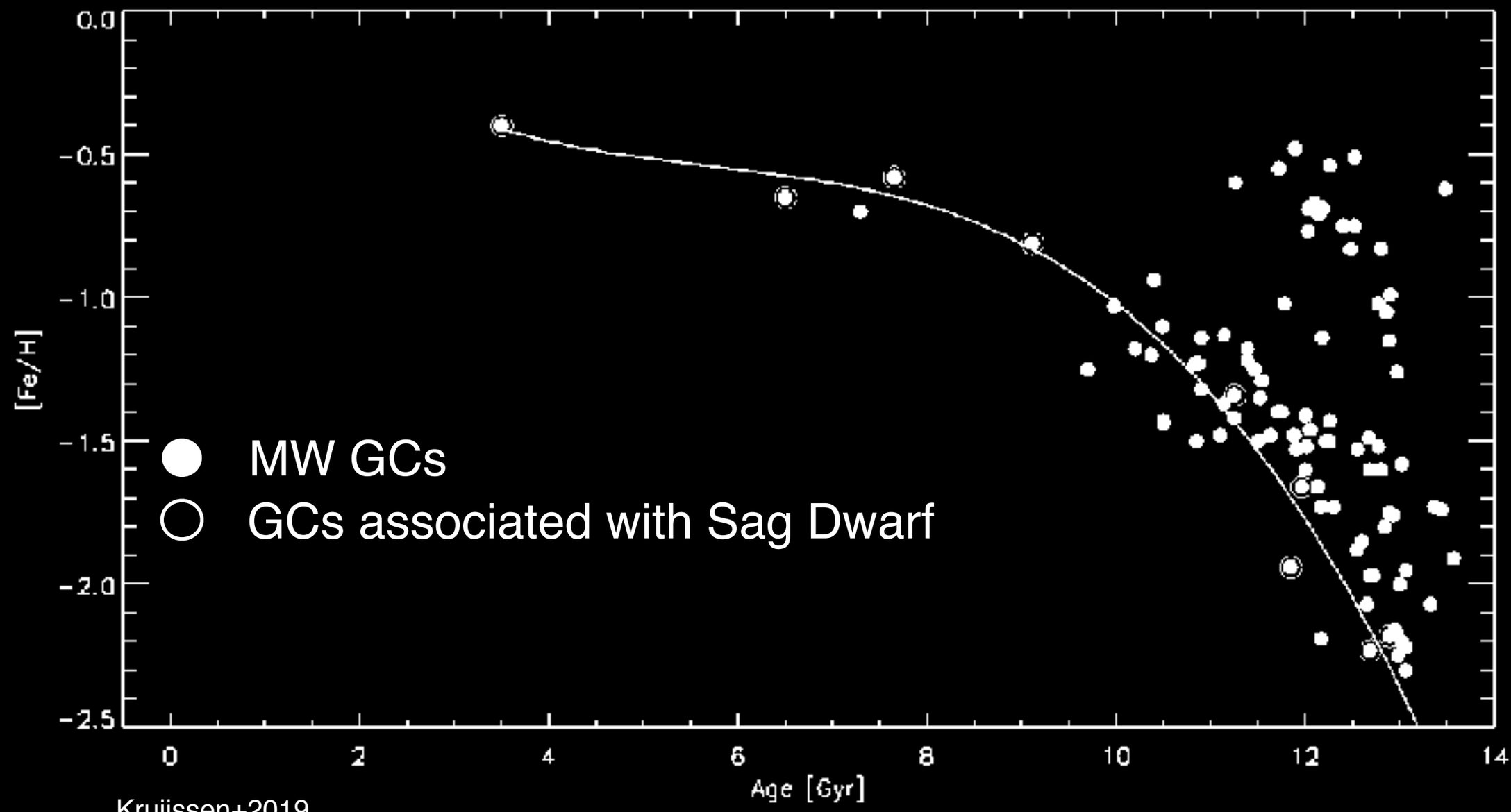

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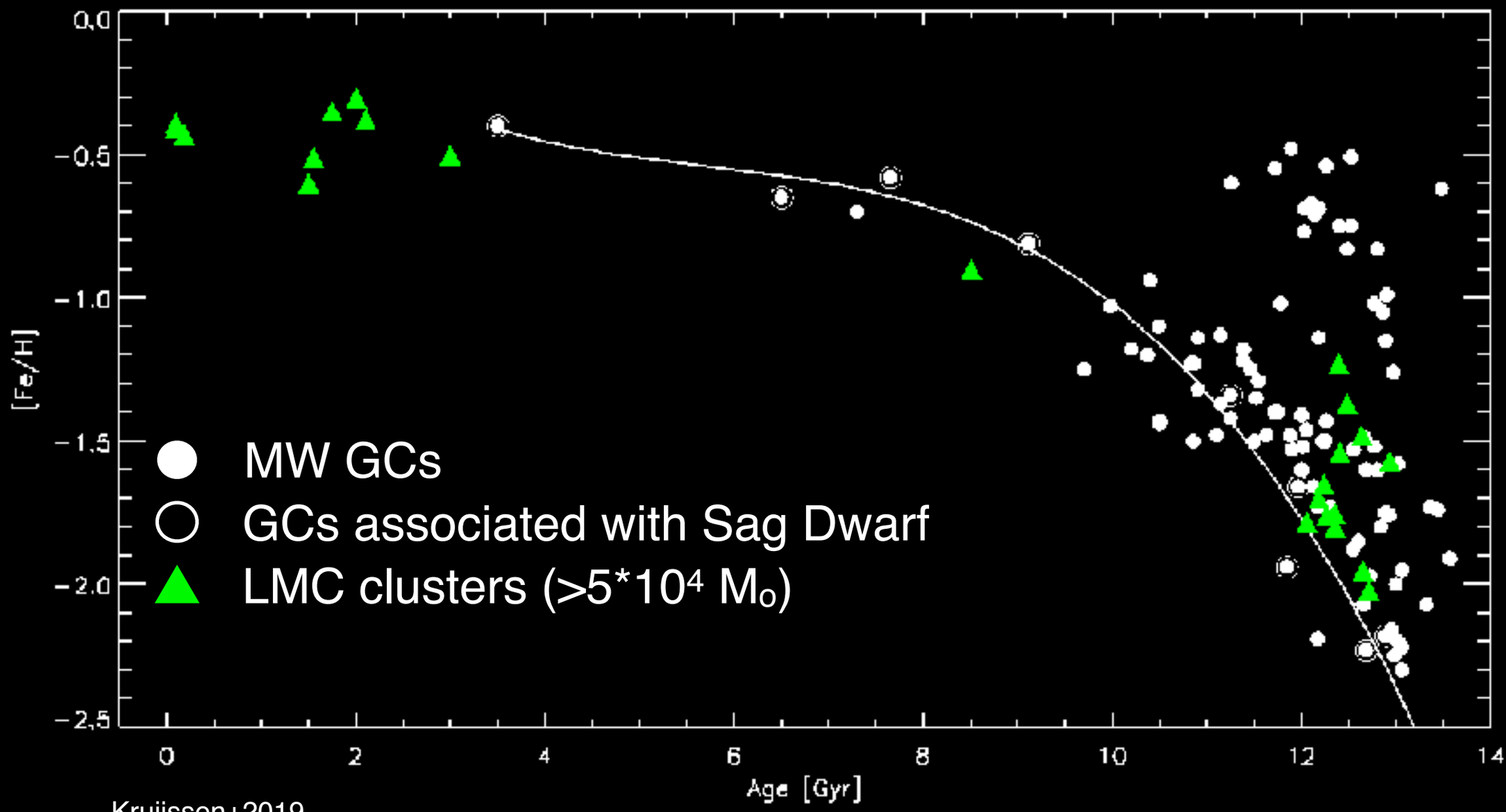

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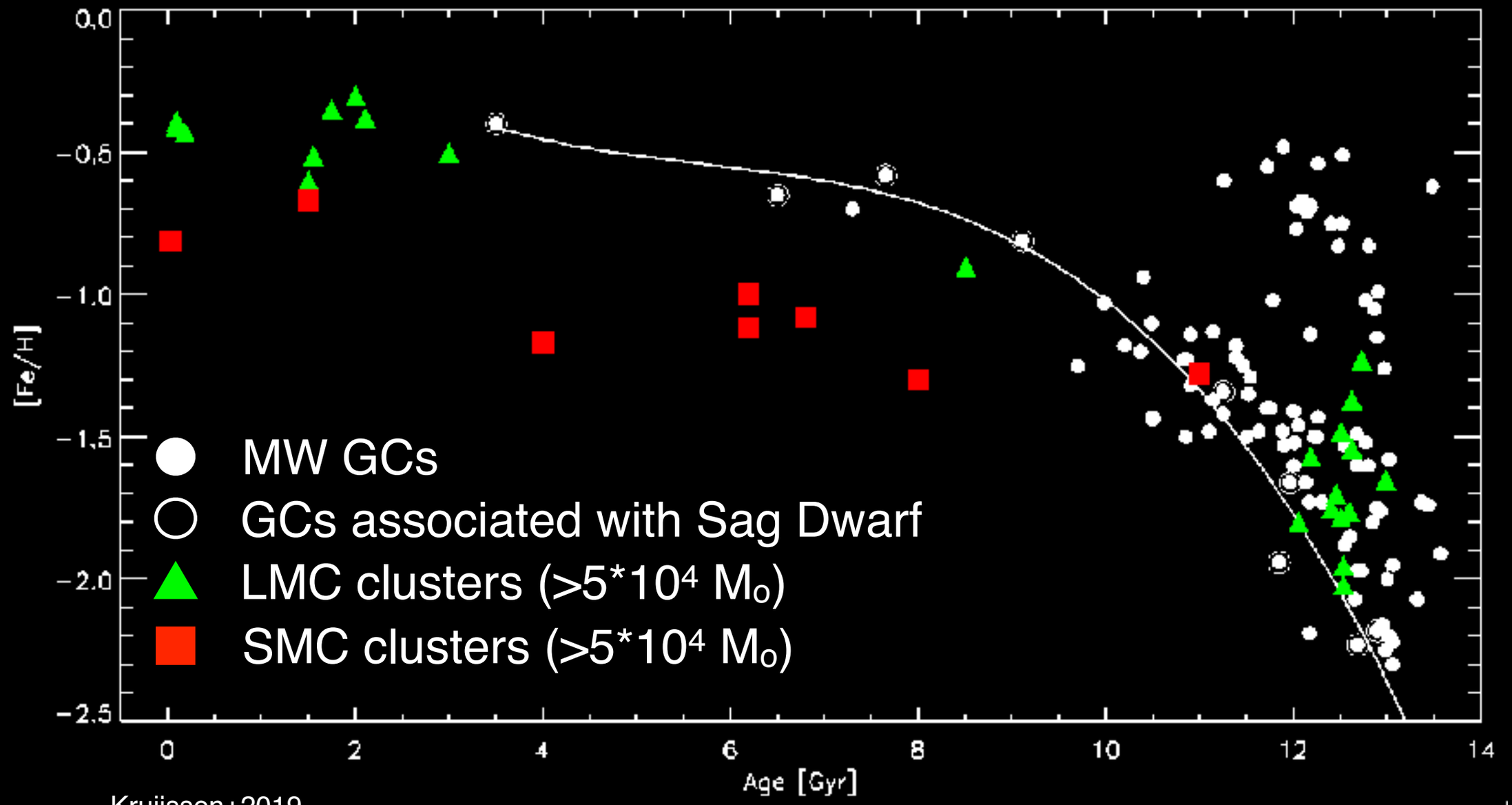

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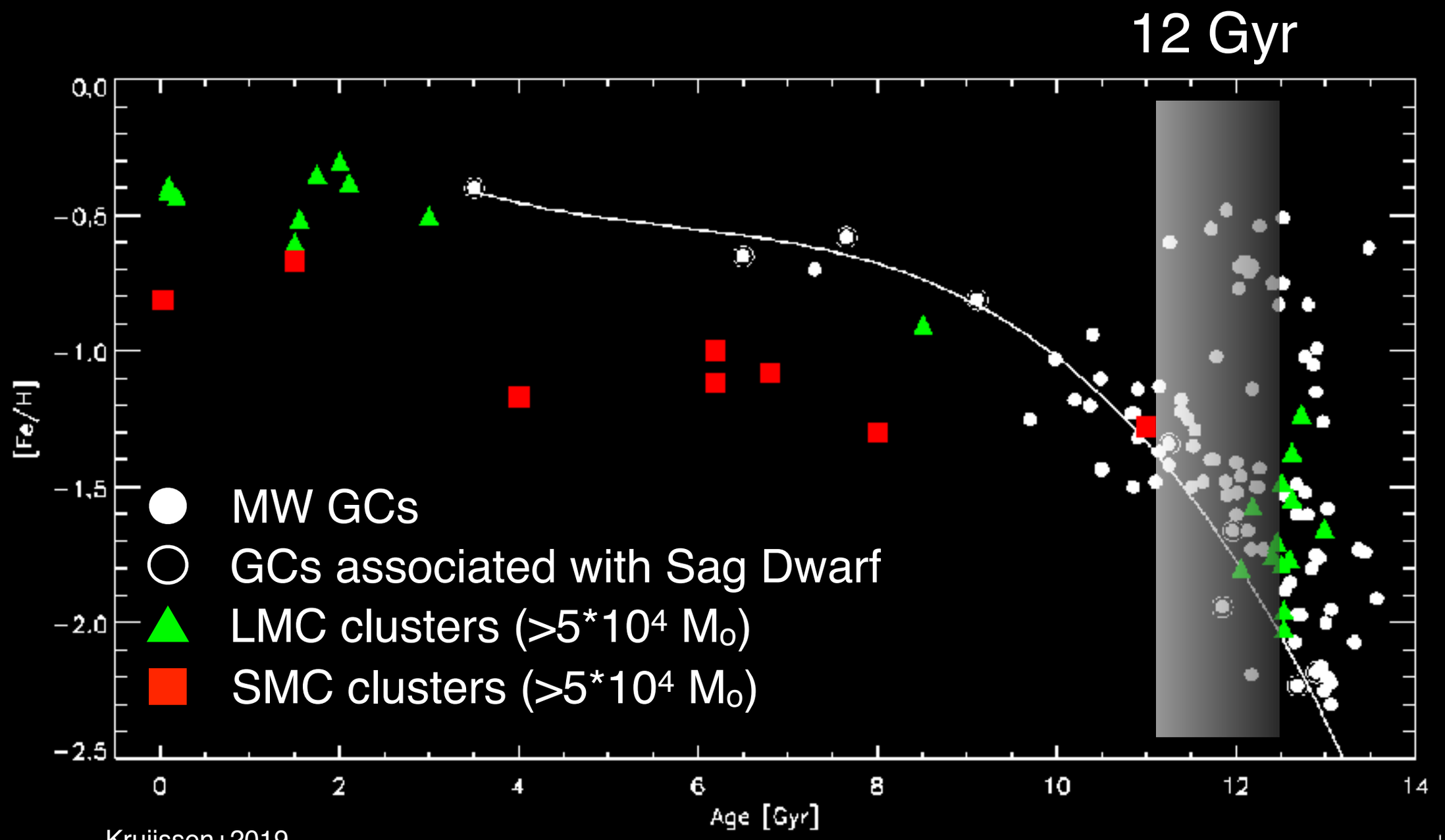

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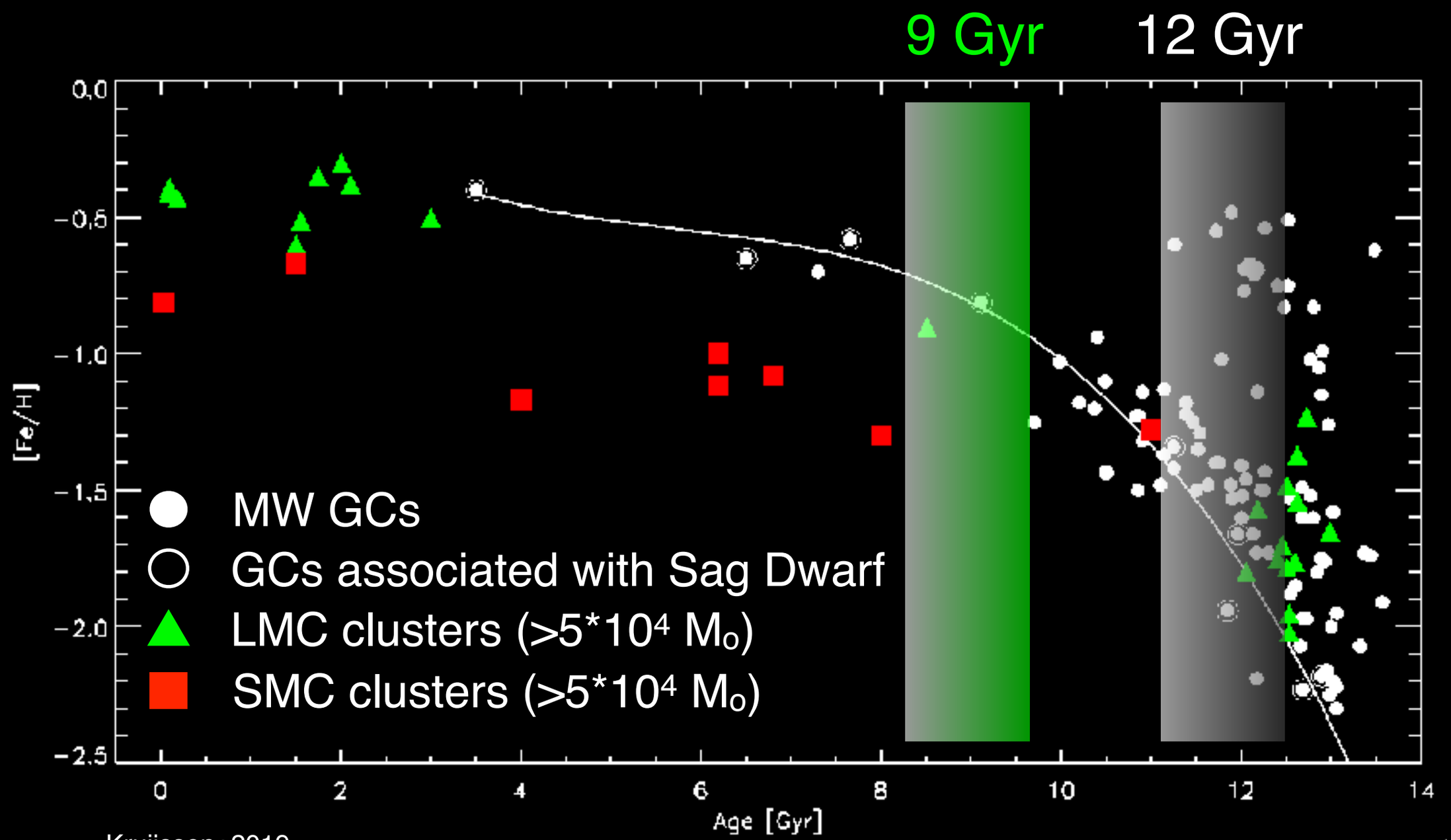

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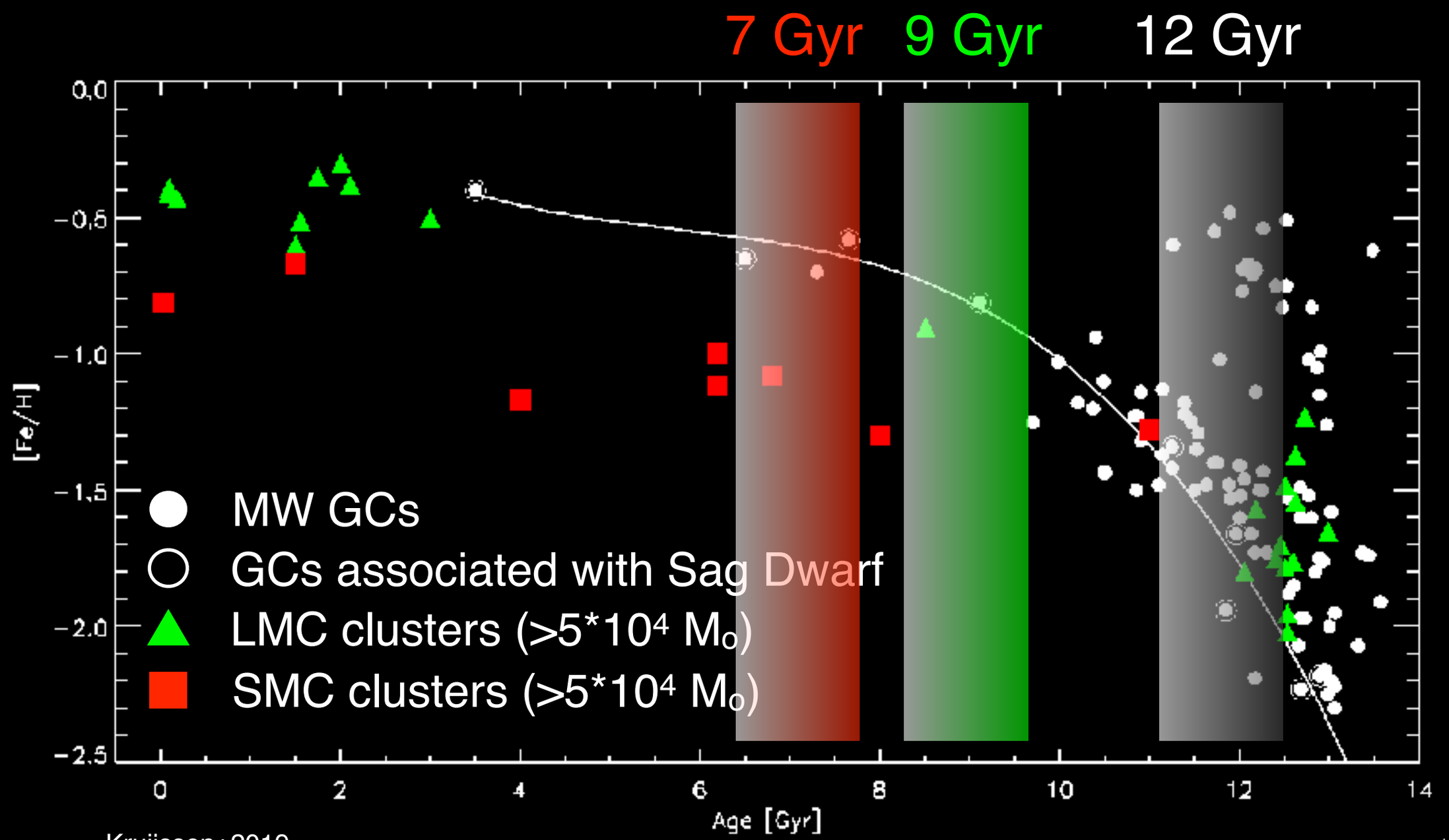

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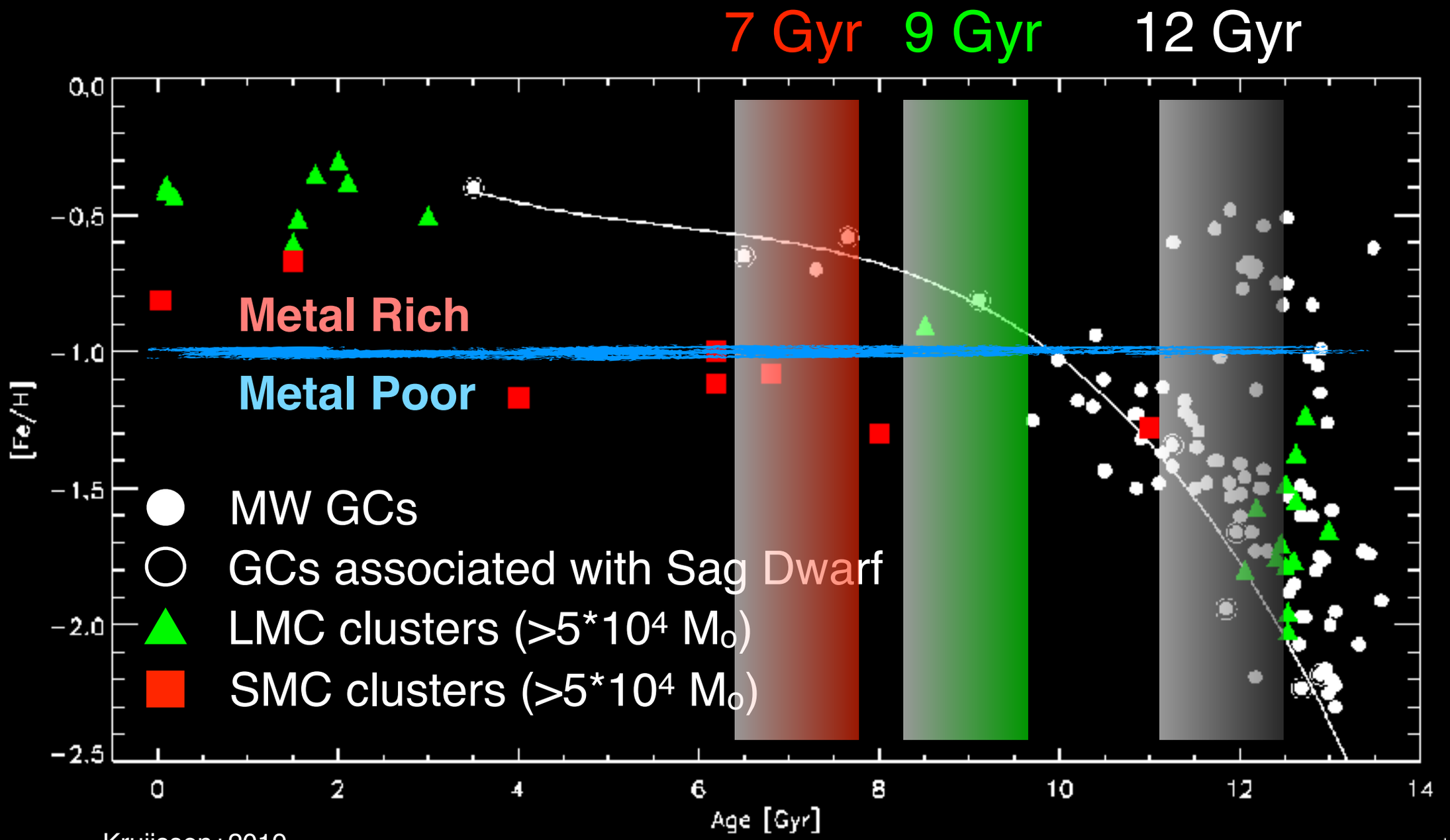

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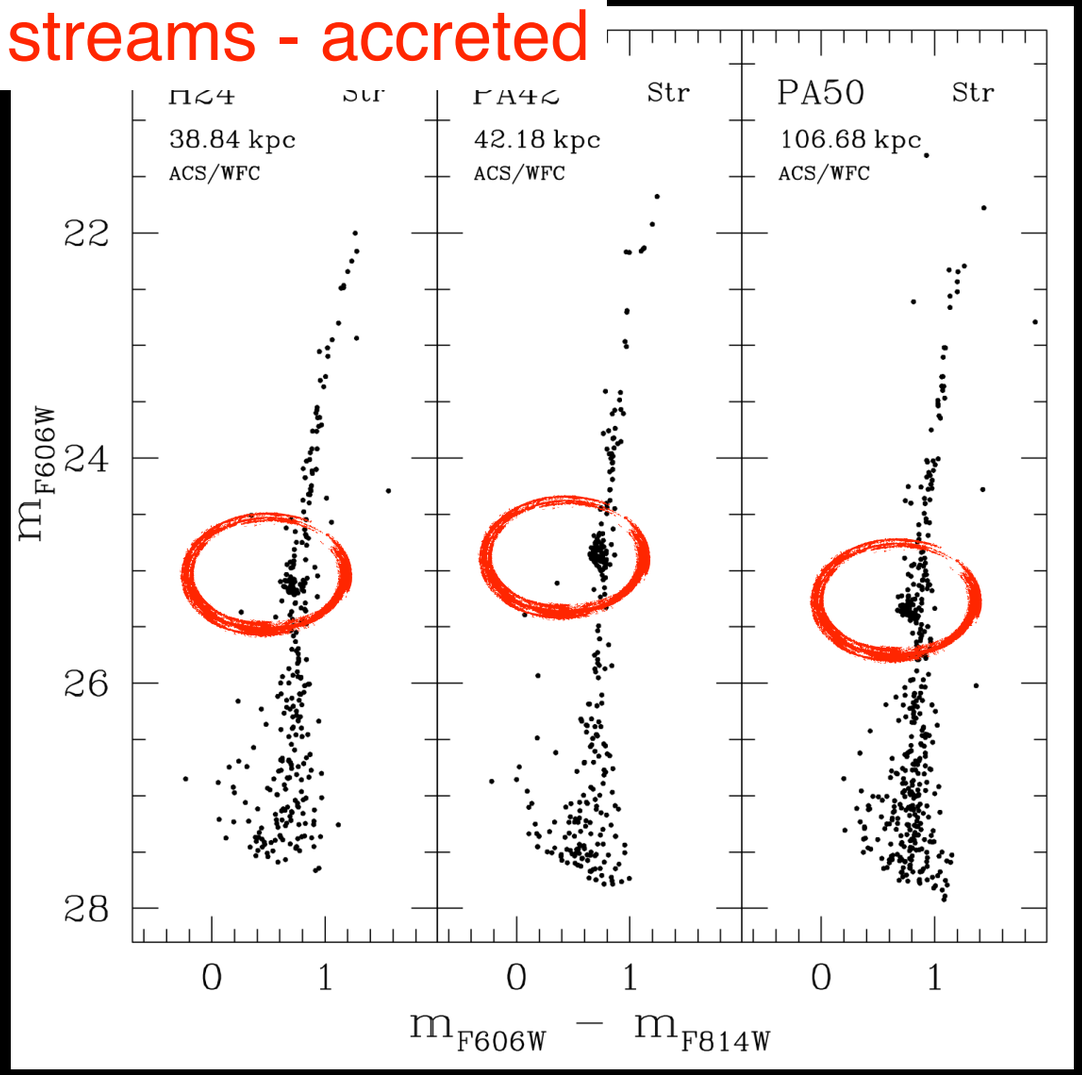
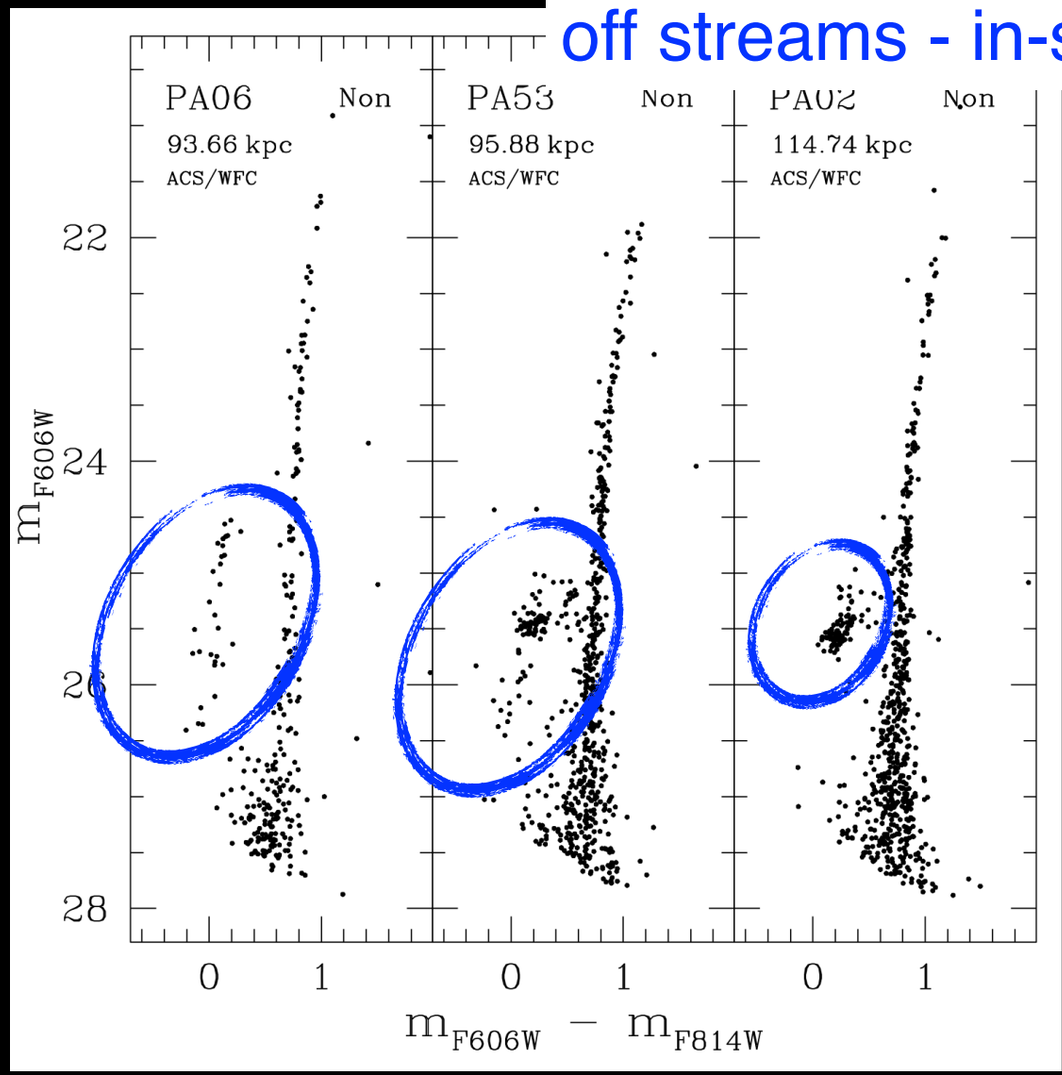
Age Distributions:
M31

- all are ‘metal poor’
- red HBs >2-4 Gyr younger than blue HBs (at fixed [Fe/H])
- Direct evidence of substantial age spread in GC population of M31

on streams - accreted

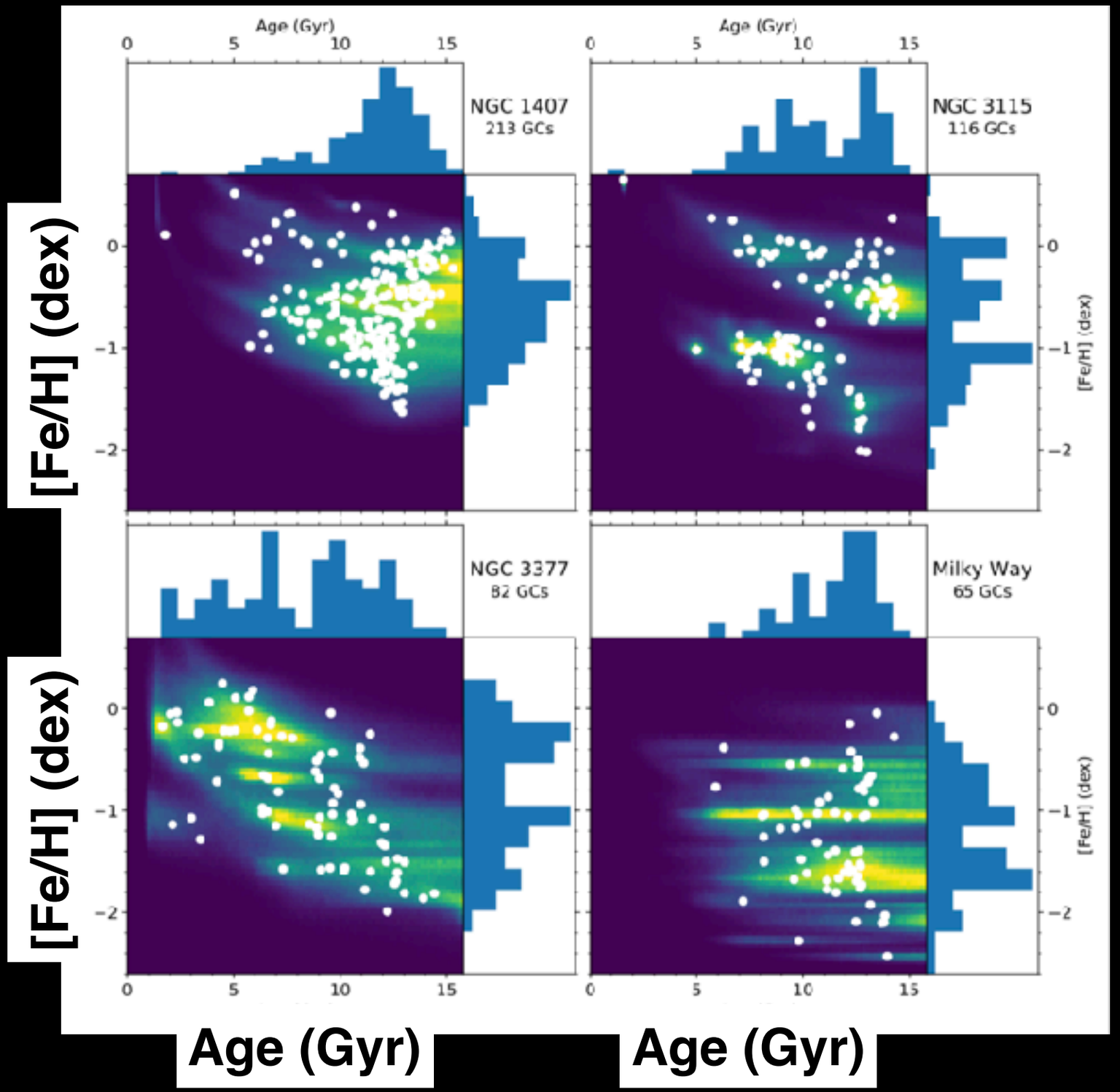


off streams - in-situ



Mackey et al. 2019; in prep.; courtesy of Annette Ferguson

Age Distributions:
Outside the Local Group



Usher+ 2019 (SLUGGS)
Puzia+2005
Chies-Santos+2012

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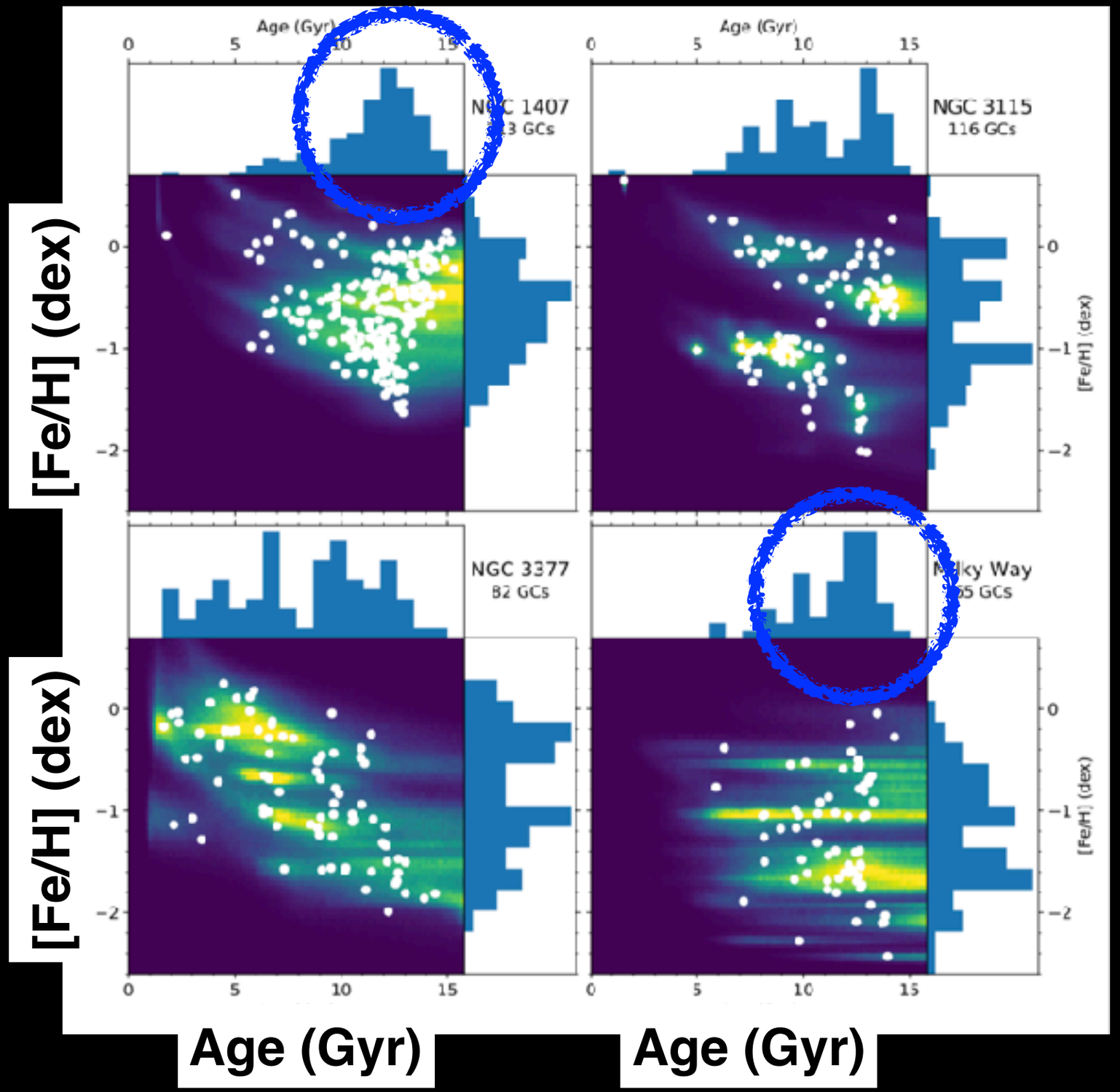

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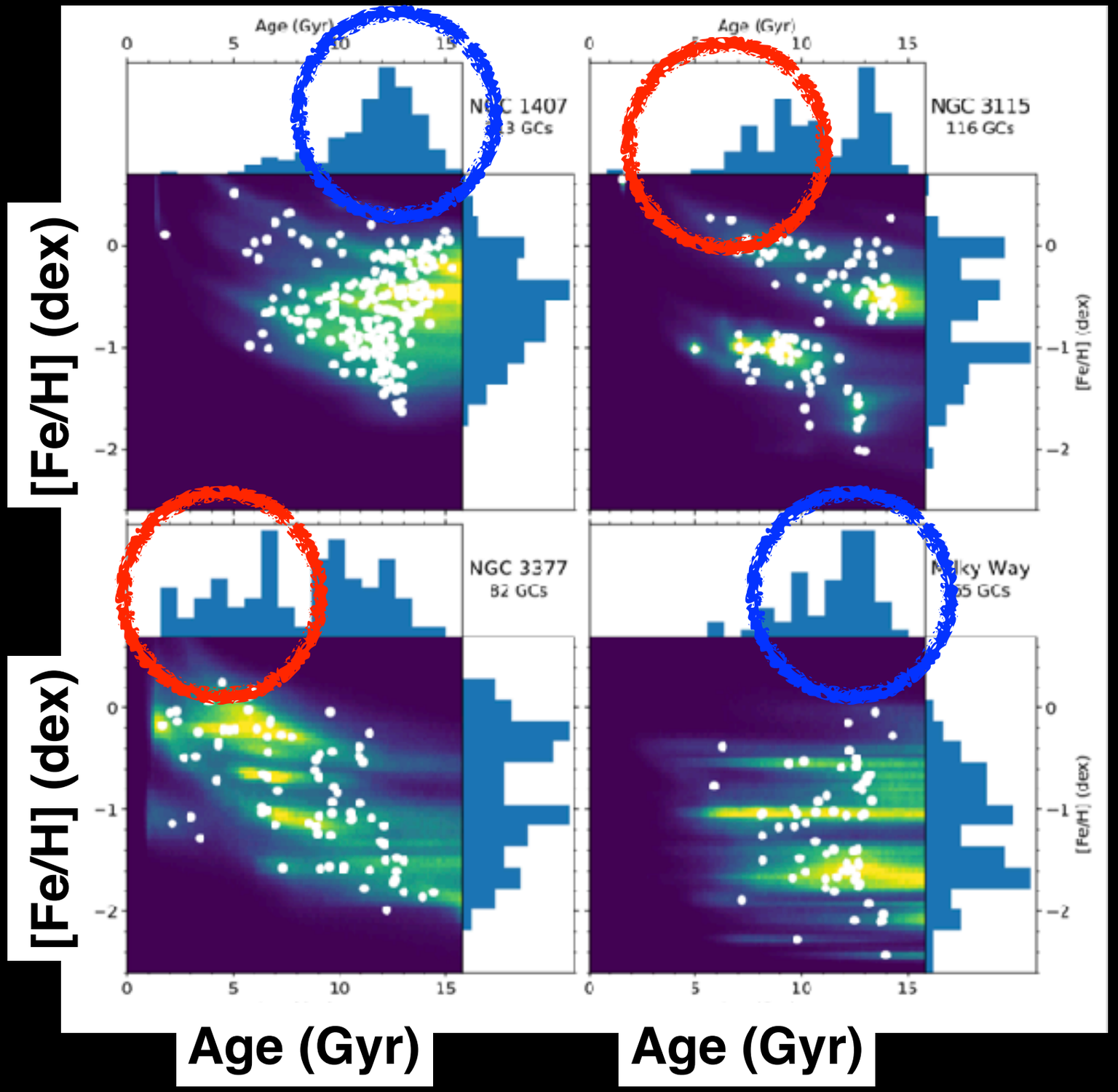

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Age Distributions:
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Clear differences in the age distributions

Agrees with other (galaxy) age indicators

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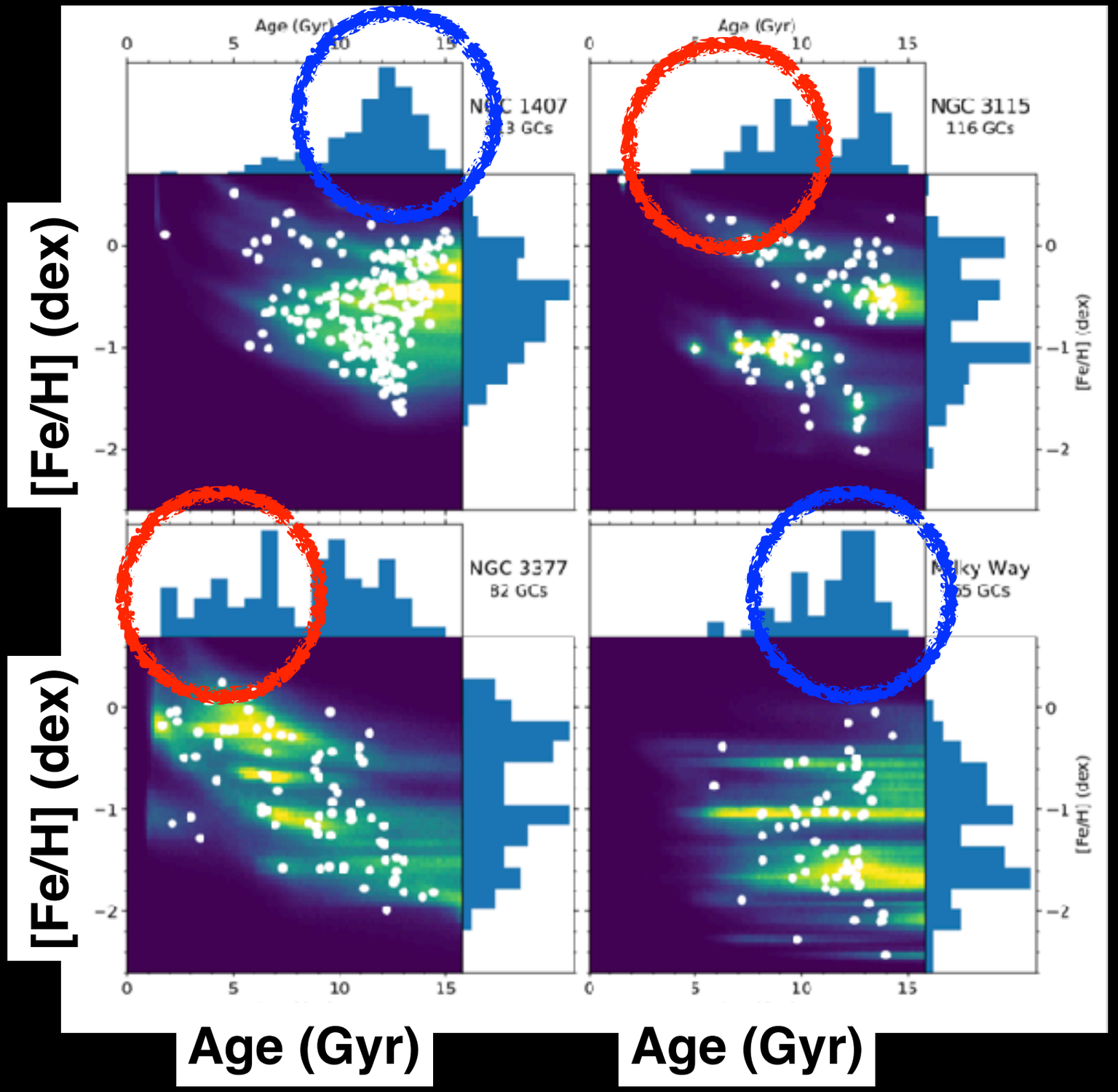

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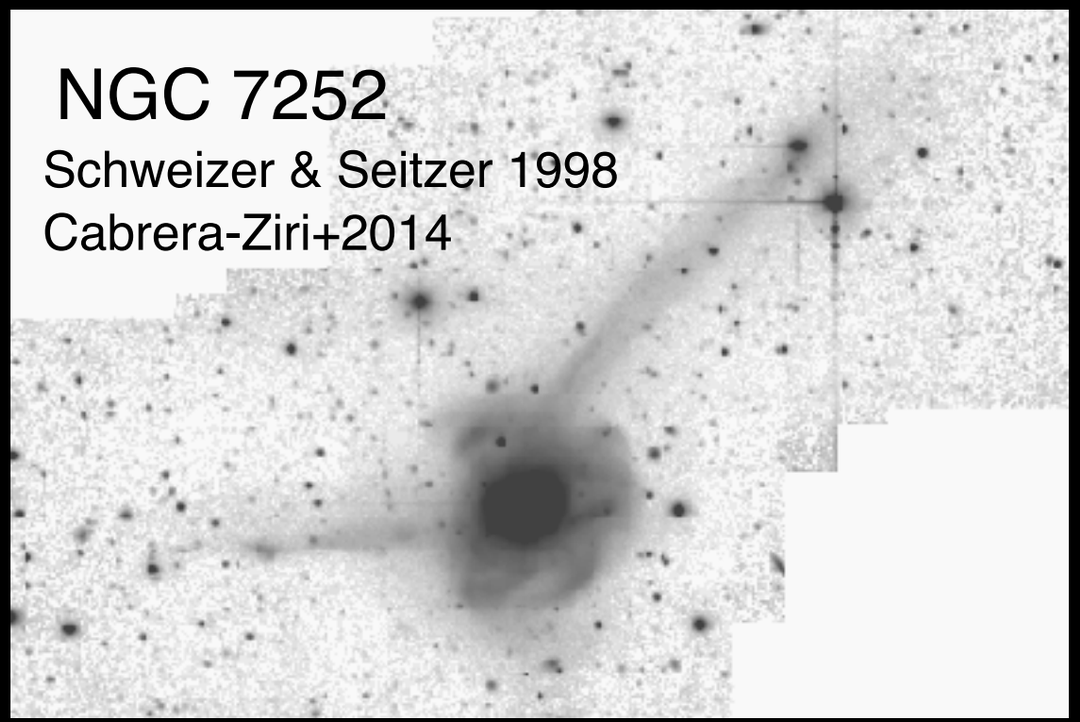

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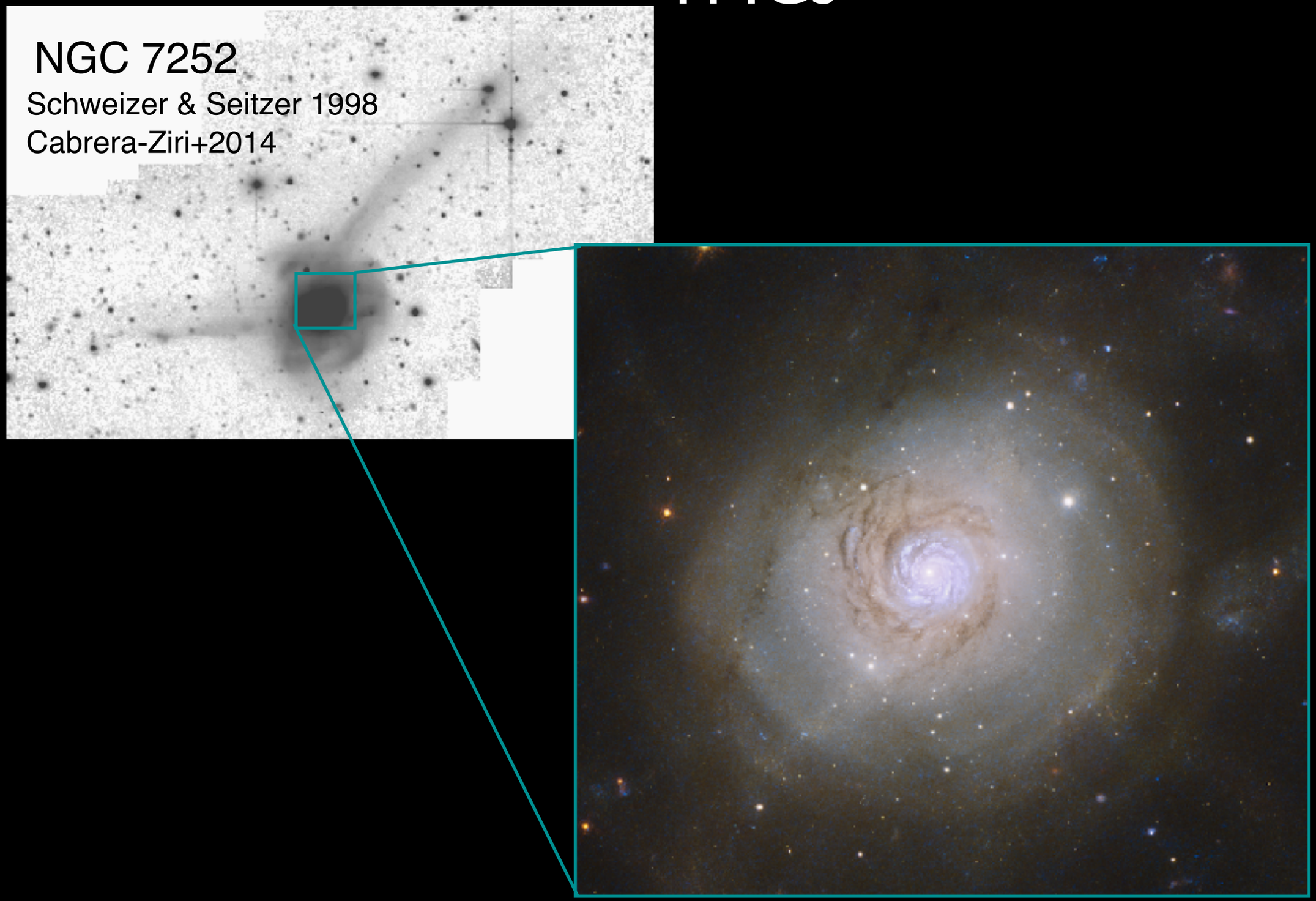

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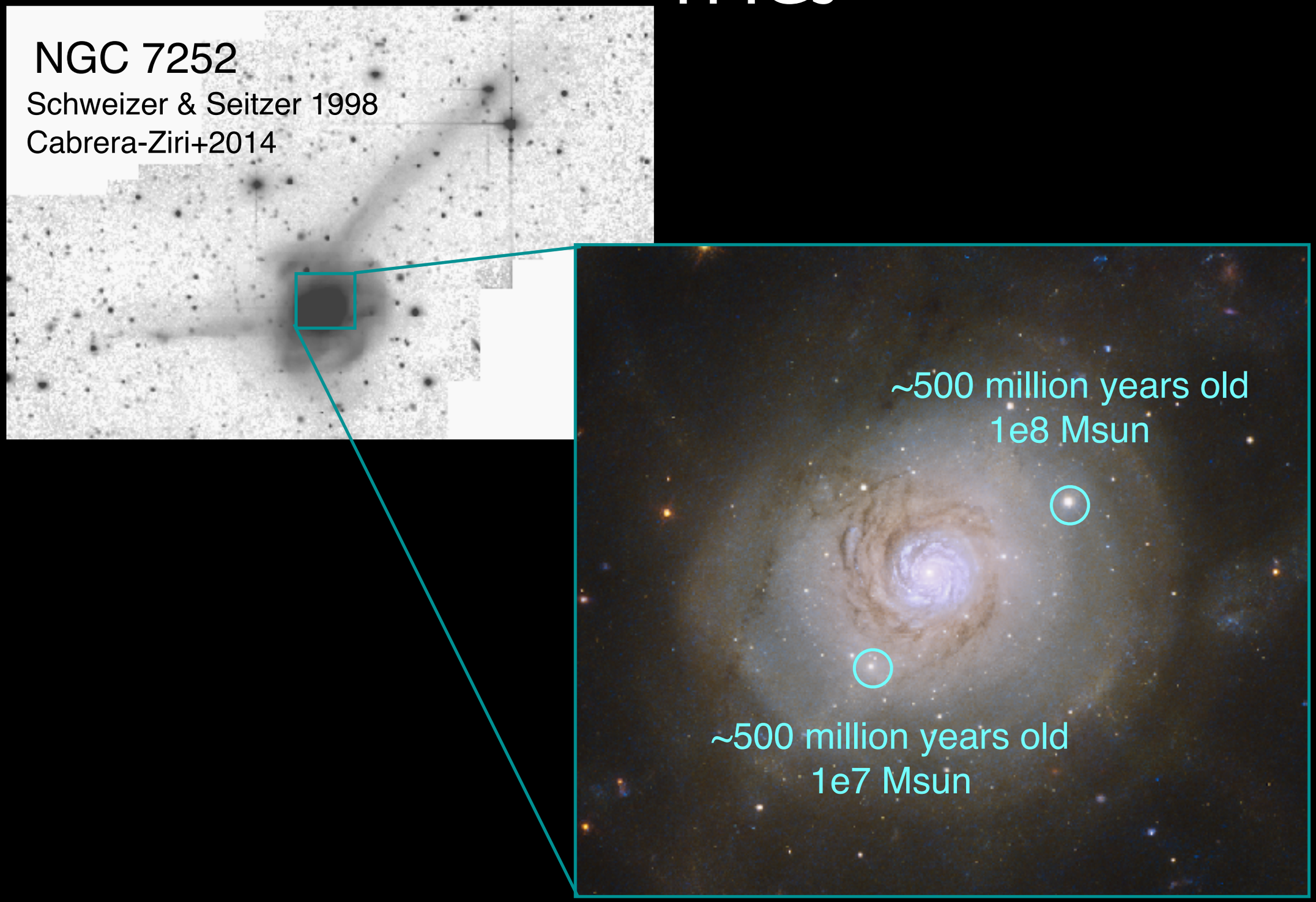

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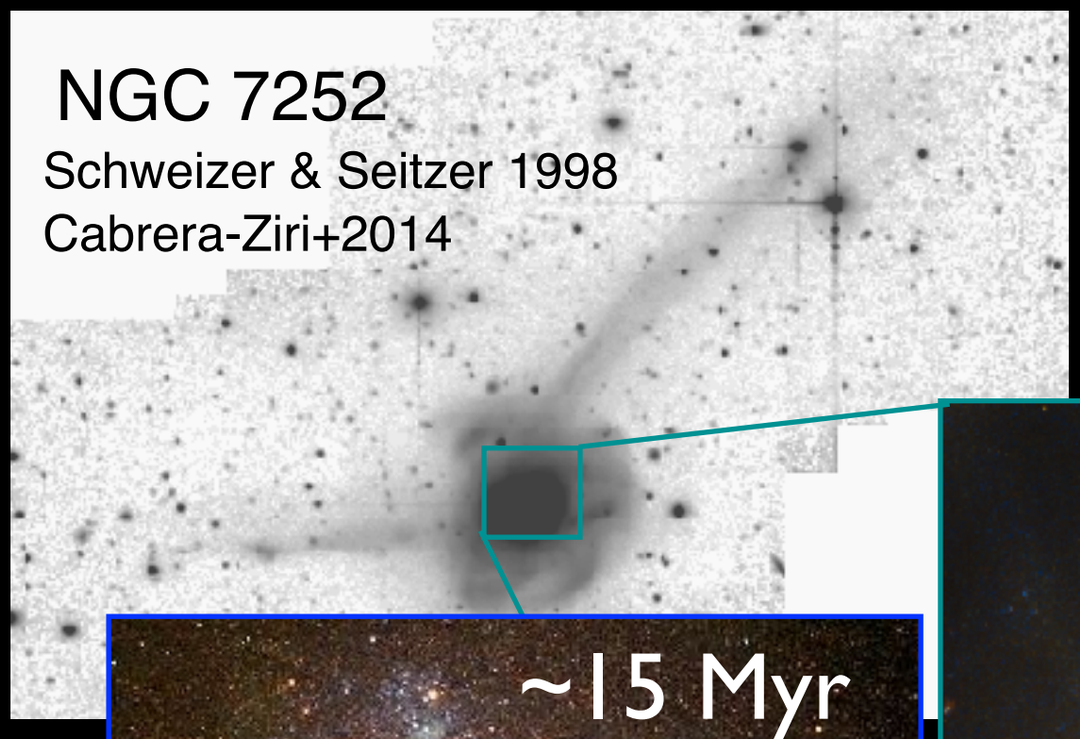
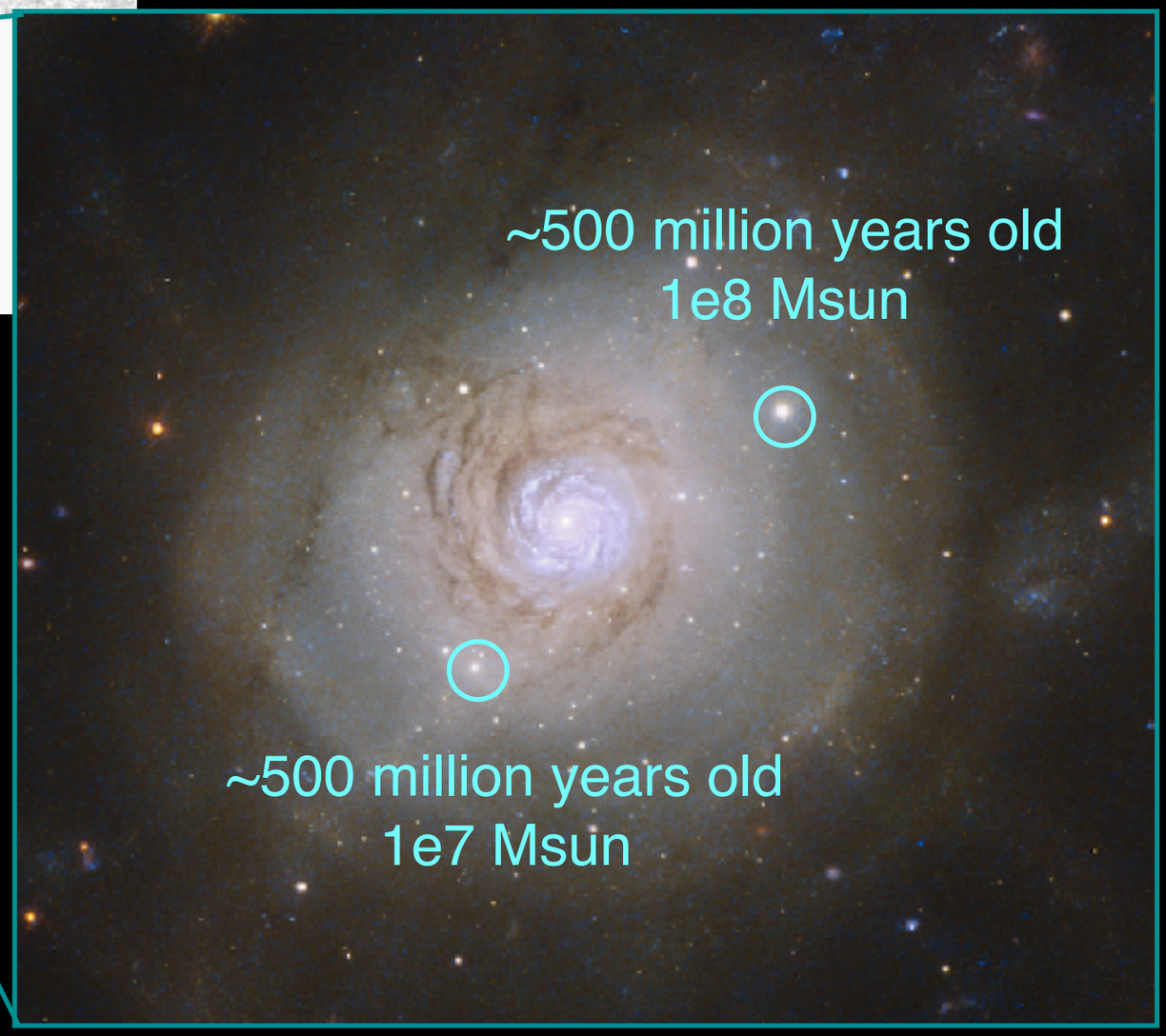




Age Distributions:
YMCs

NGC 7252
Schweizer & Seitzer 1998
Cabrera-Ziri+2014

~15 Myr
10^6 Msun

NGC 1705
Larsen+2011

NGC 1316
HST ACS/WFC
Hubble Heritage
Goudfrooij+2001

E
N

3 Gyr
1e7 Msun

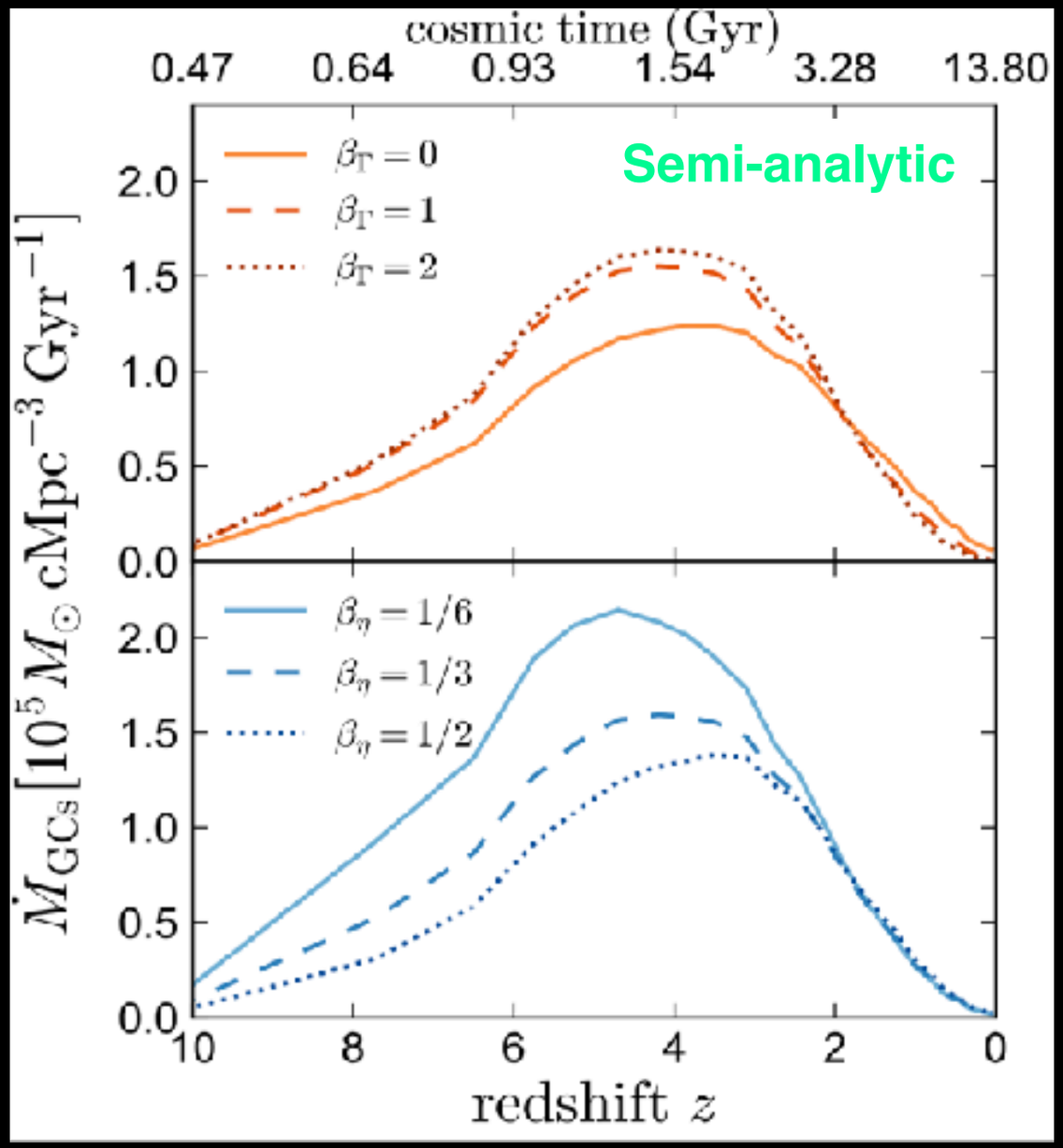
F814W *I*
F555W *V*
F435W *B*

20,000 light-years
6000 parsecs 42″

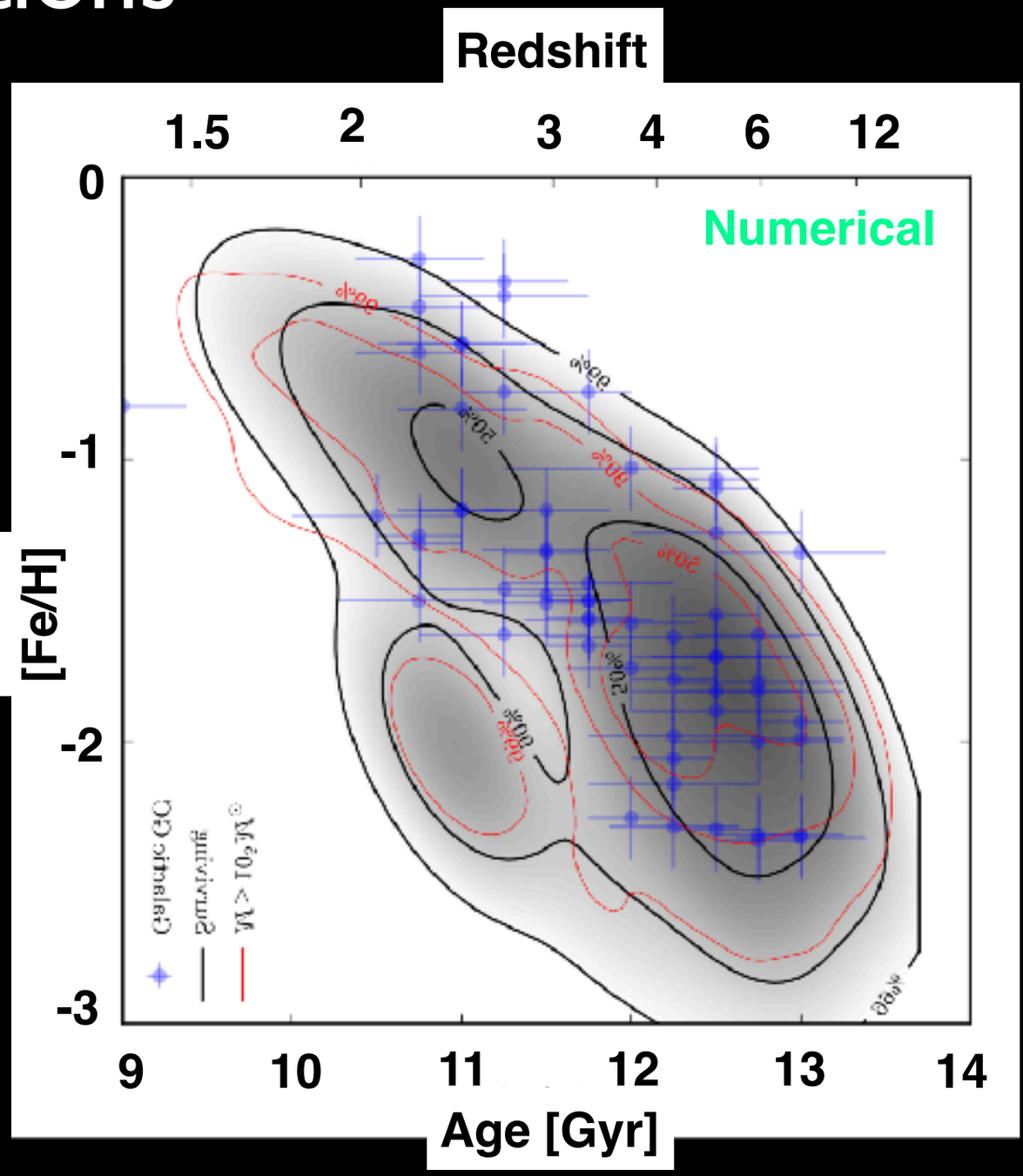
~5(

1e7 Msun

Age Distributions:
Simulations



El-Badry+2019
Reina-Campos+2019 (E-MOSAICS)
Choksi & Gnedin 2019; Lahen+19
Muratov & Gnedin2013



Li & Gnedin 2019

Age Distributions:
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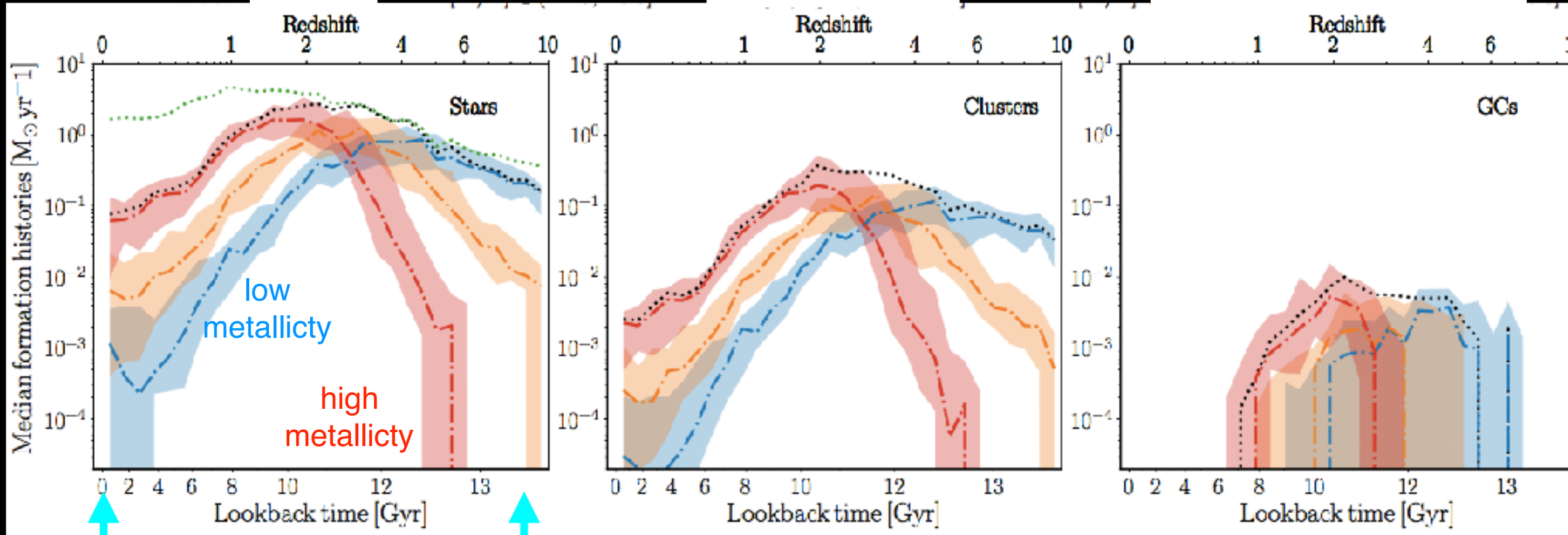
Stars | **All clusters** | **Globular clusters**



Today

Early Universe

Reina-Campos+2019 (EMOSAICS)

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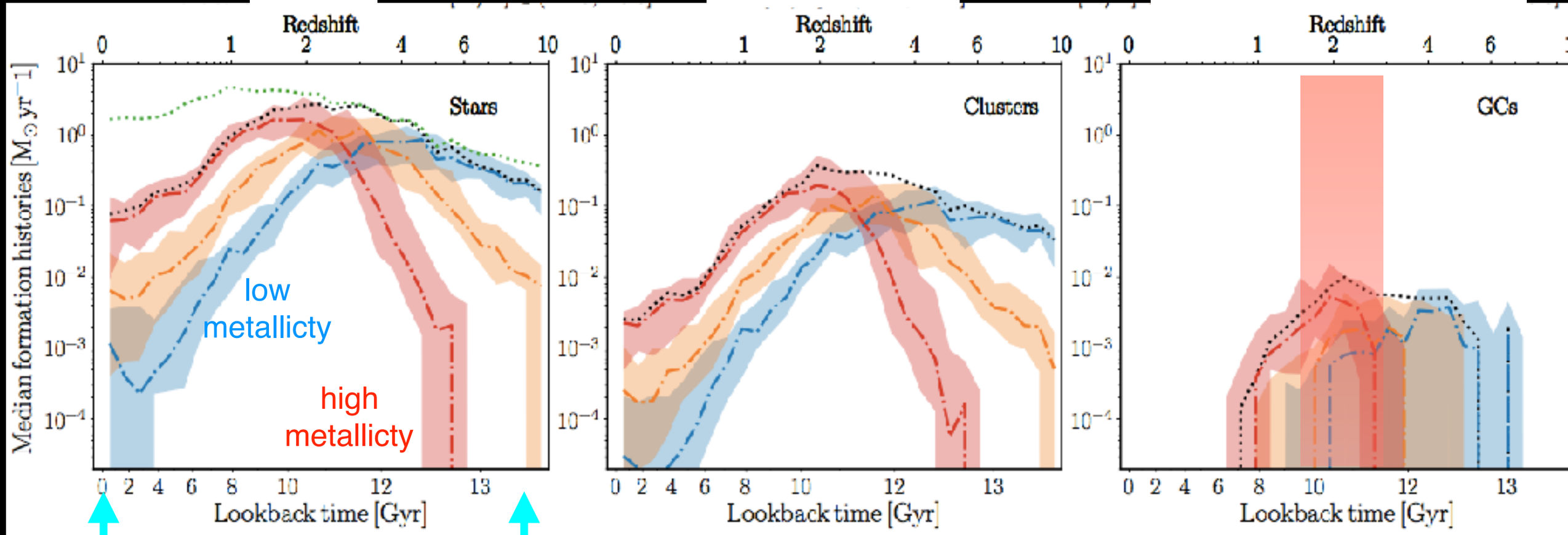

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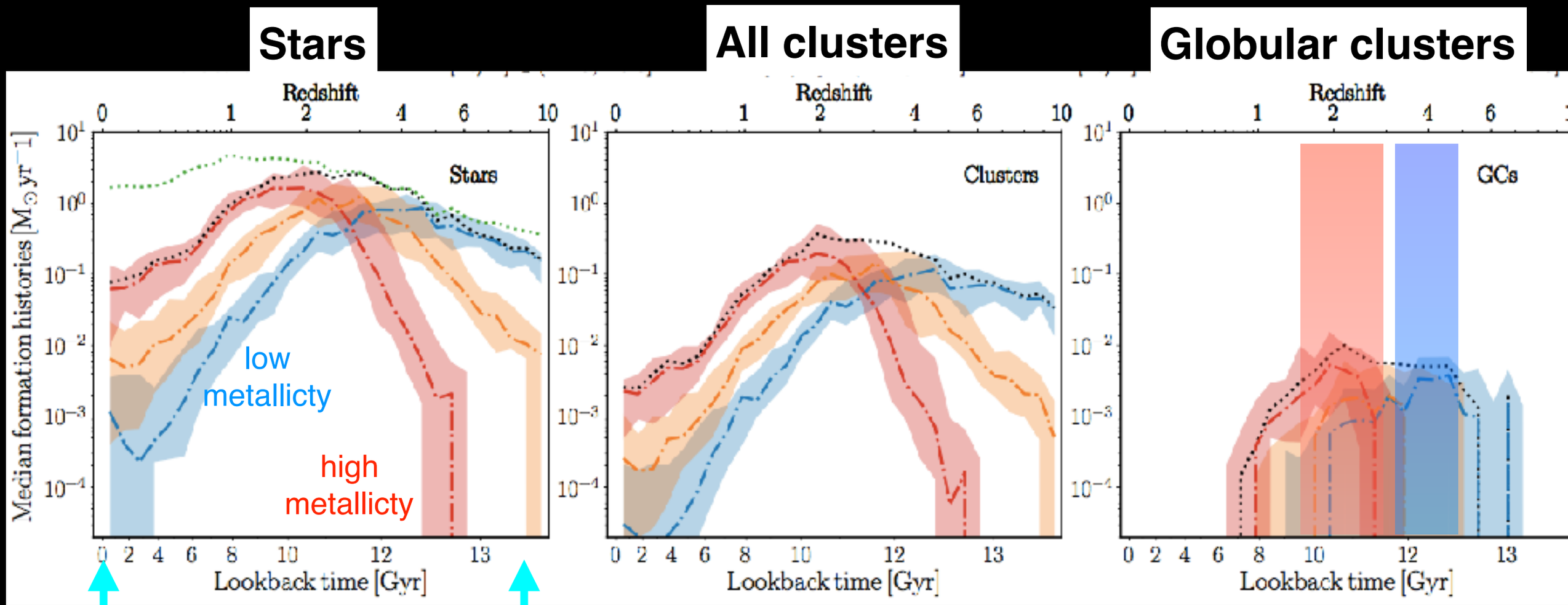

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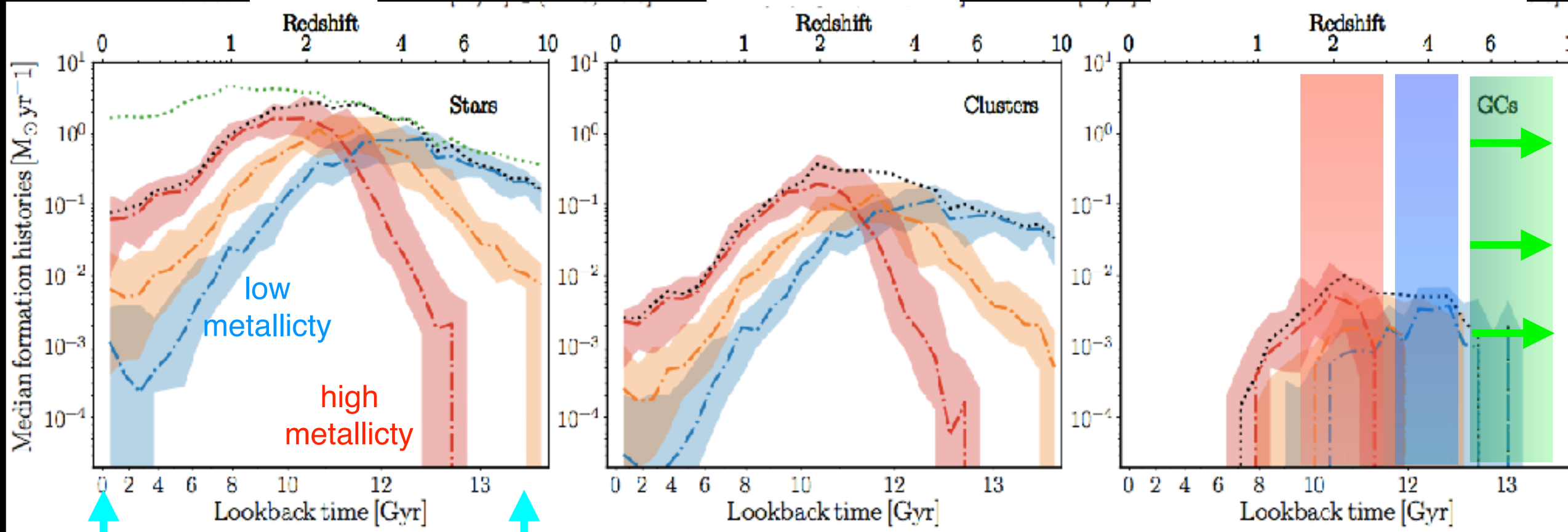

Today

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Observations:
Forbes+2015

Early GC formation models
(e.g., Trenti+2015)

Age Distributions:
The role of major mergers

Keller+20 (E-MOSAICS)
Choksi & Gnedin 2019

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The role of major mergers

- For many, YMCs have become synonymous of major mergers

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- At higher redshift, those conditions can be met within normal (turbulent) galaxies
- Major mergers play a minor role in the formation of GCs (<25%)

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Questions and Outlook

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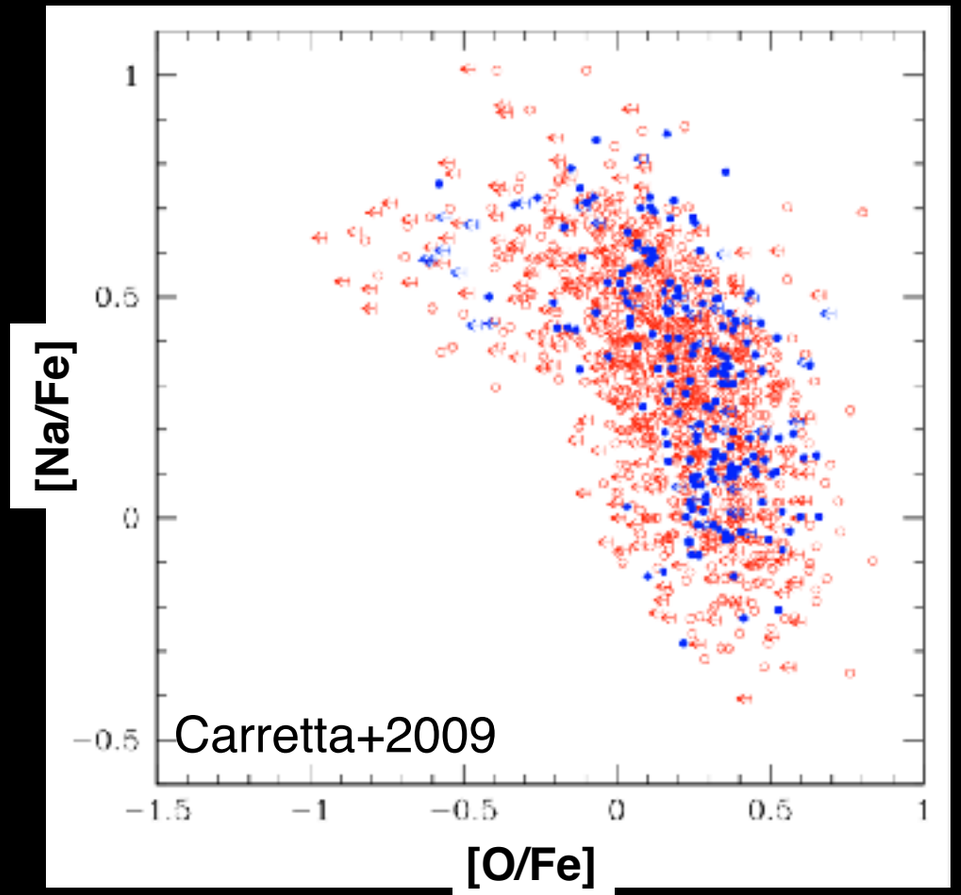
- JWST surveys should find loads of proto-GCs at z=1-5, with a decreasing number beyond z=6 (opposite if GCs only form in the early Universe)
- Can we do better in extragalactic age determinations?

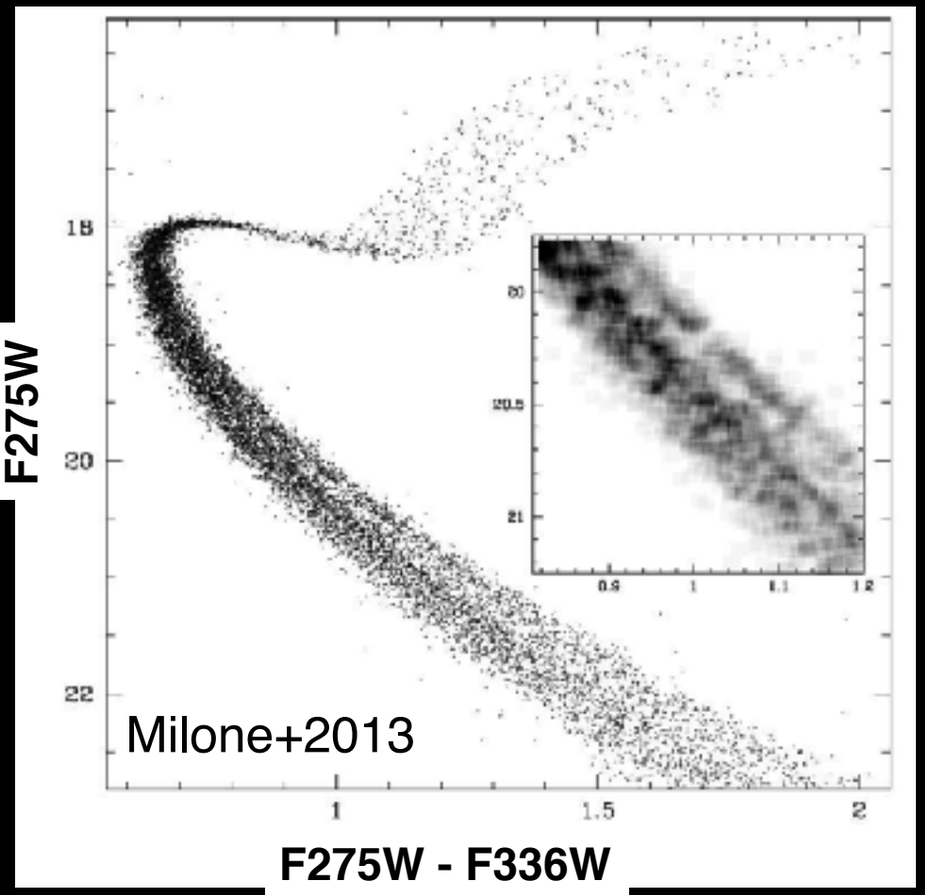
Definition of a Globular Cluster

"Multiple Populations"

The ancient GCs are not simple stellar populations, instead they host light element abundance spreads (e.g., He, C, N, O, Na, Al)

Gratton+2012
Bastian & Lardo 2018





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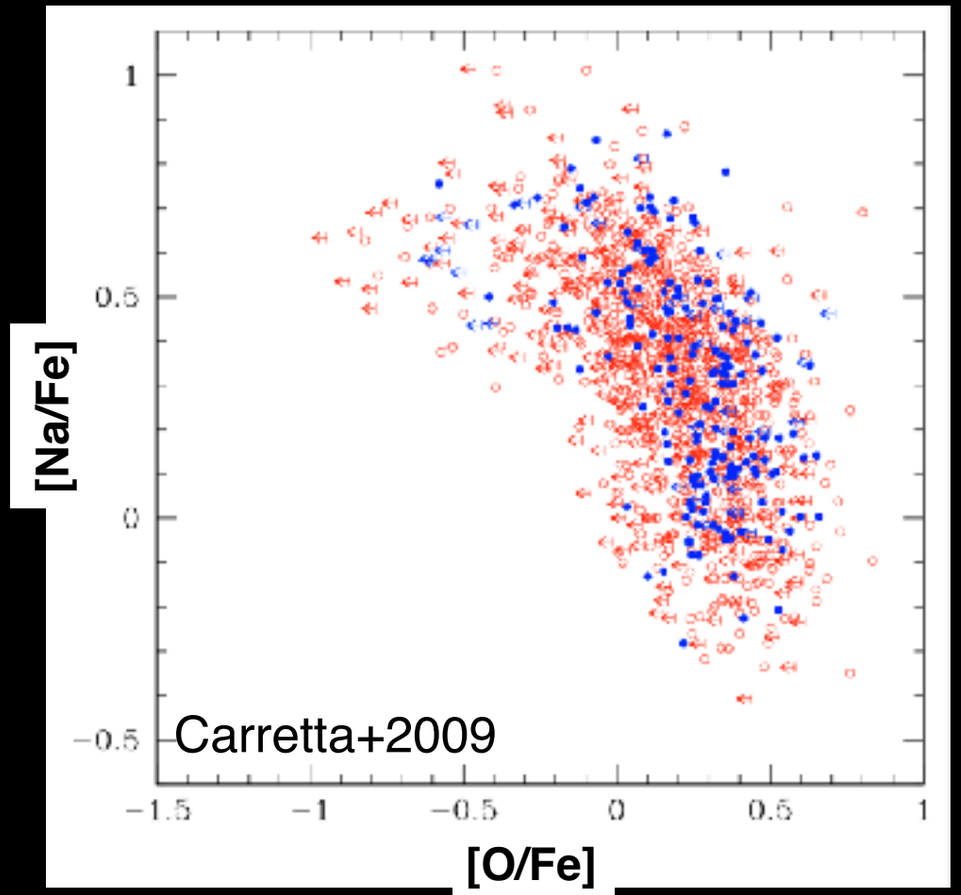
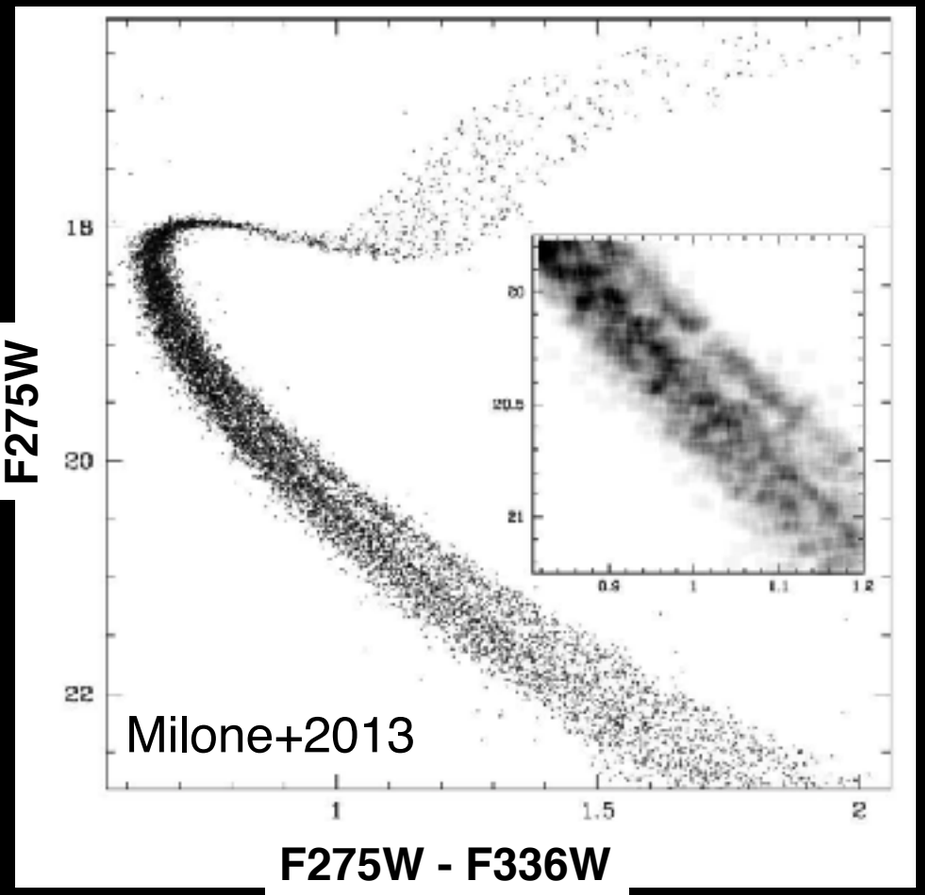
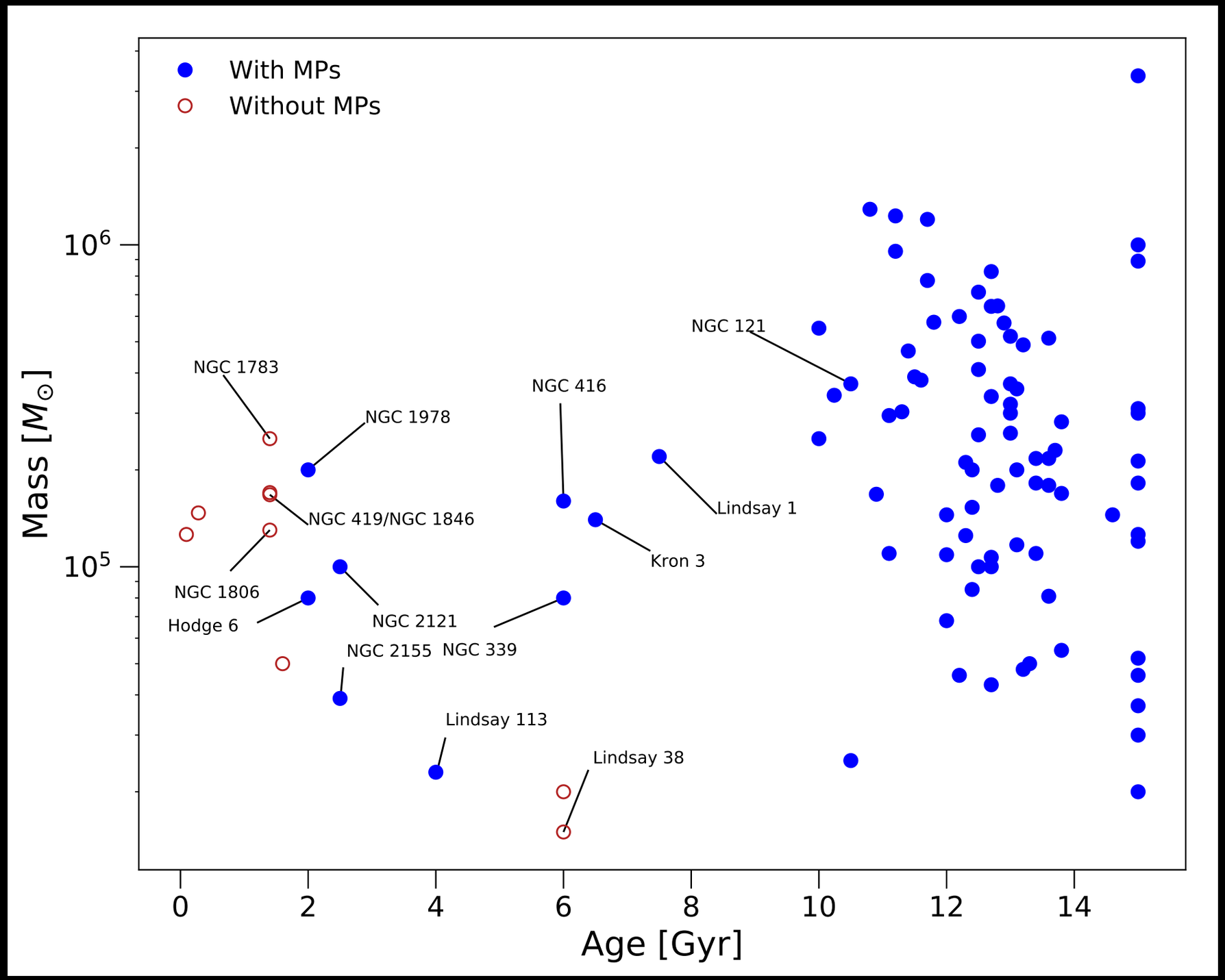
Carretta+2010 suggest that: GCs are clusters that host multiple populations





Stellar Populations

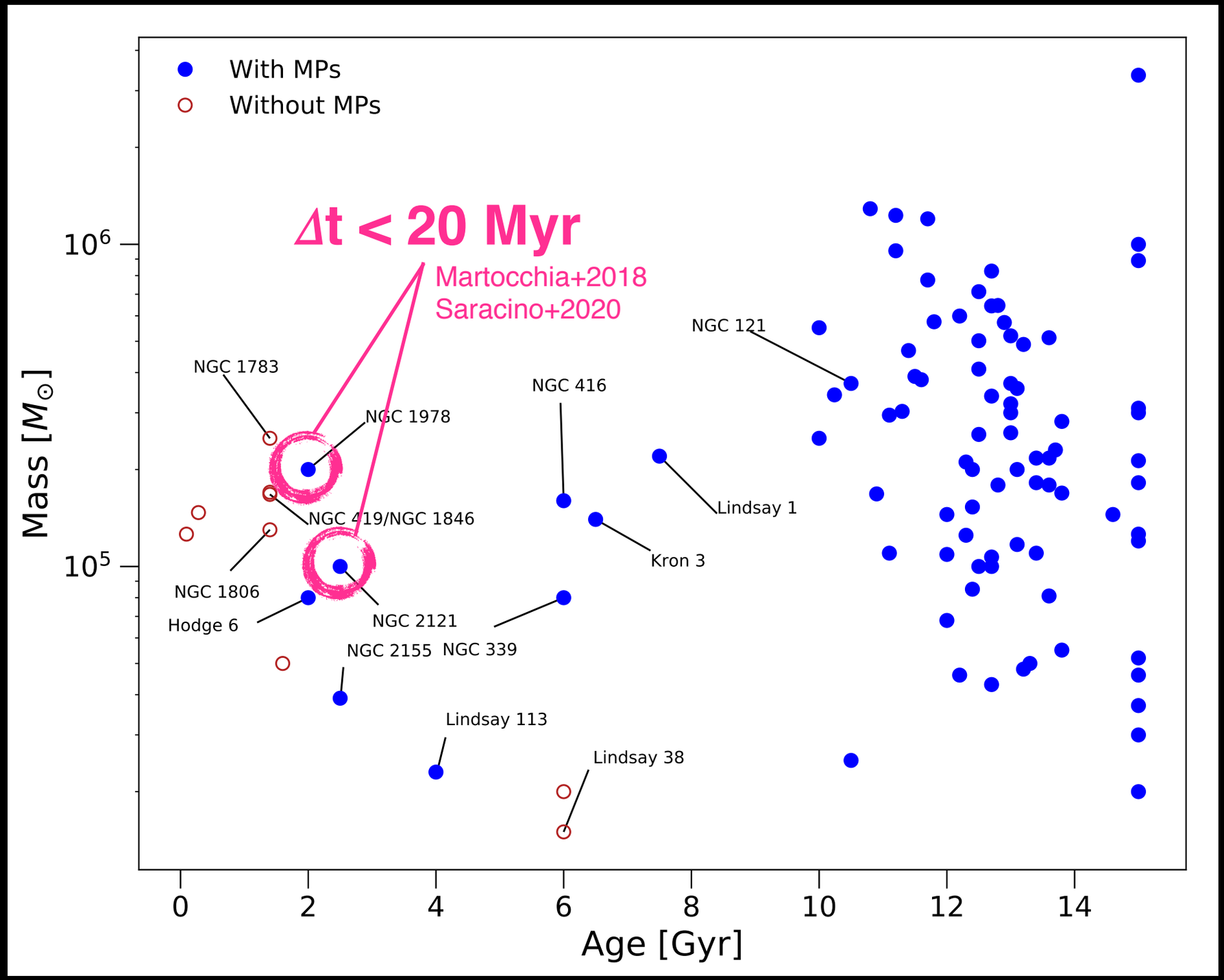


Martocchia+19b

Resolved

Niederhofer+17a,b
Hollyhead+17,18,19
Martocchia+18a,19a,b
Saracino+19,20

Stellar Populations

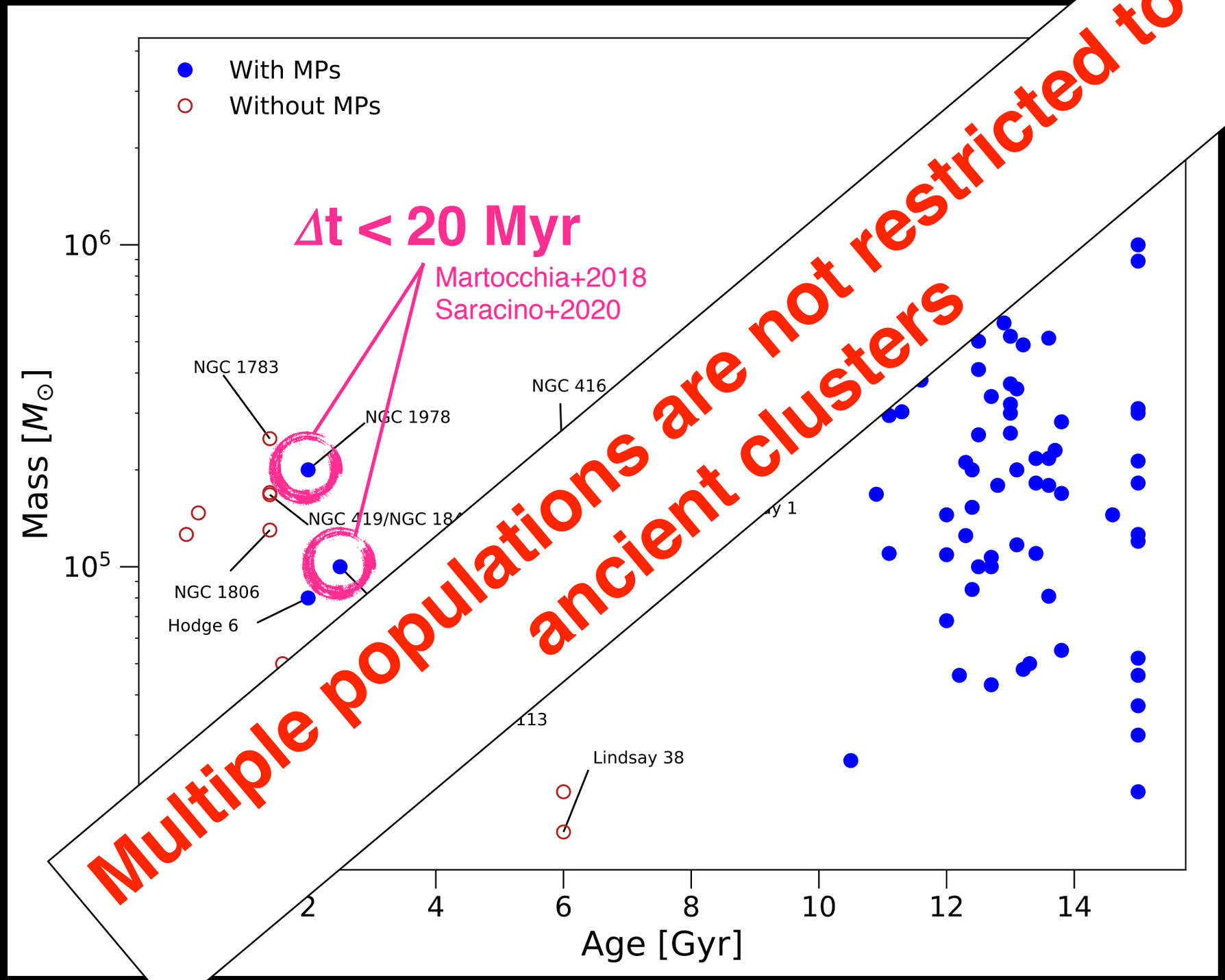


Resolved

Niederhofer+17a,b
Hollyhead+17,18,19
Martocchia+18a,19a,b
Saracino+19,20

Martocchia+19b

Stellar Populations



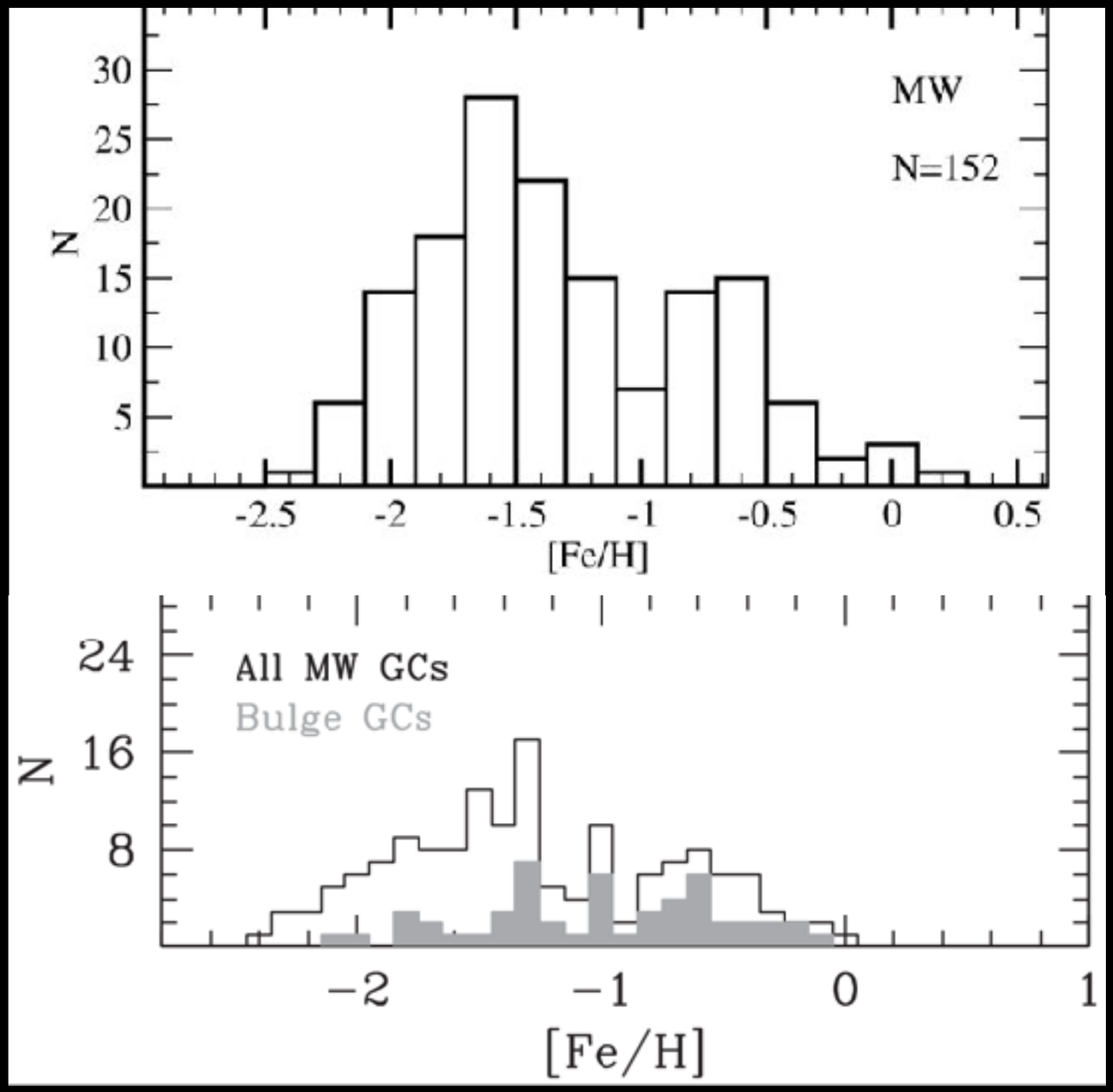
Multiple populations are not restricted to the ancient clusters

Resolved

Niederhofer+17a,b
Hollyhead+17,18,19
Martocchia+18a,19a,b
Saracino+19,20

Martocchia+19b

Metallicity Distributions:
The Milky Way



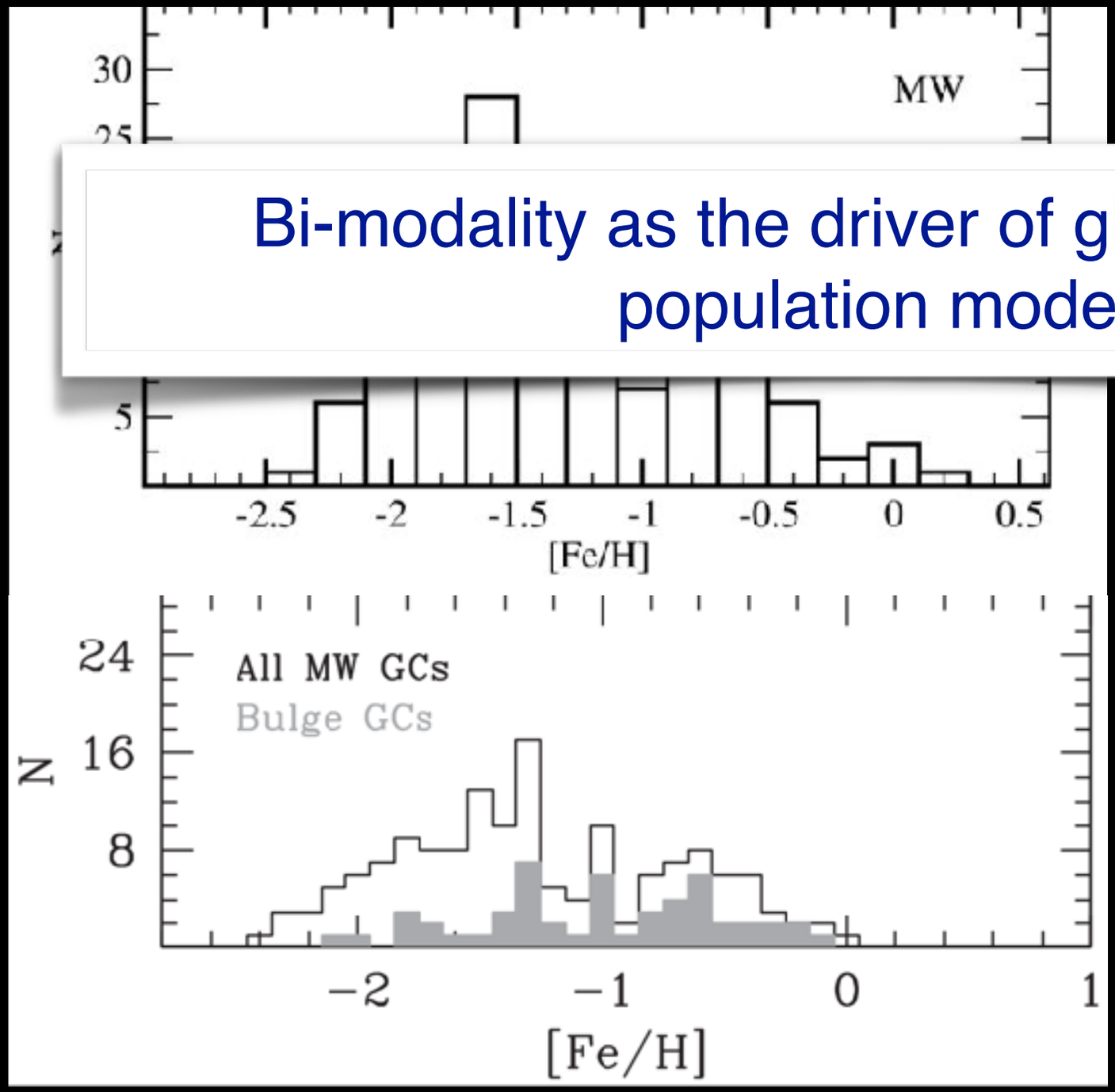
Metallicities

Bi-modal metallicity distribution

Peaks at [Fe/H] ~ -1.5 & -0.7

Harris 2010
Schiavon+2017

Metallicity Distributions:
The Milky Way



Metallicities

Bi-modality as the driver of globular cluster population models

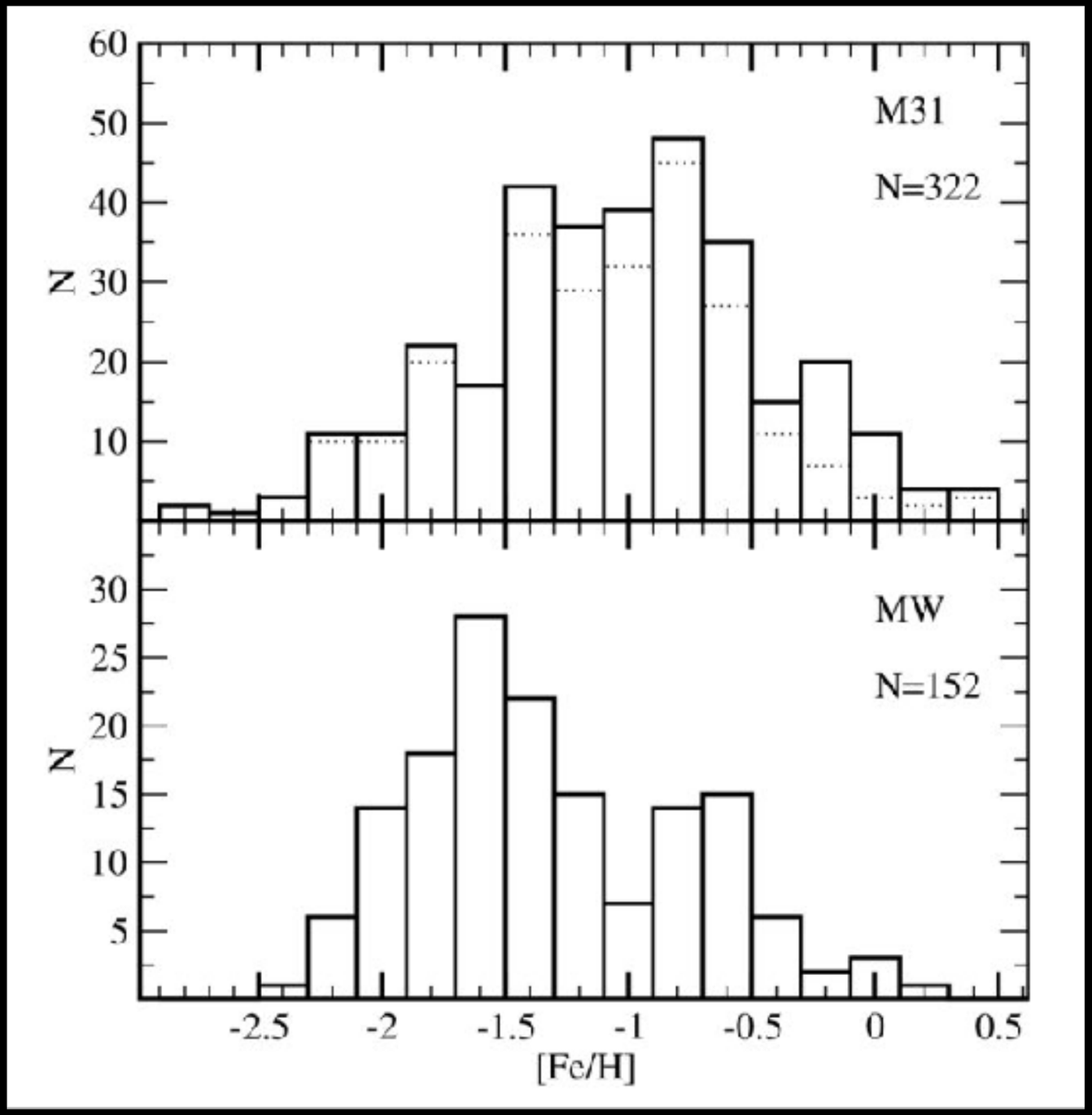
B on

P

e.g. Beasley+2002
Bekki+2008
Tonini 2013
Leaman+2013
Renaud+2017

Harris 2010
Schiavon+2017

Metallicity Distributions:
M31



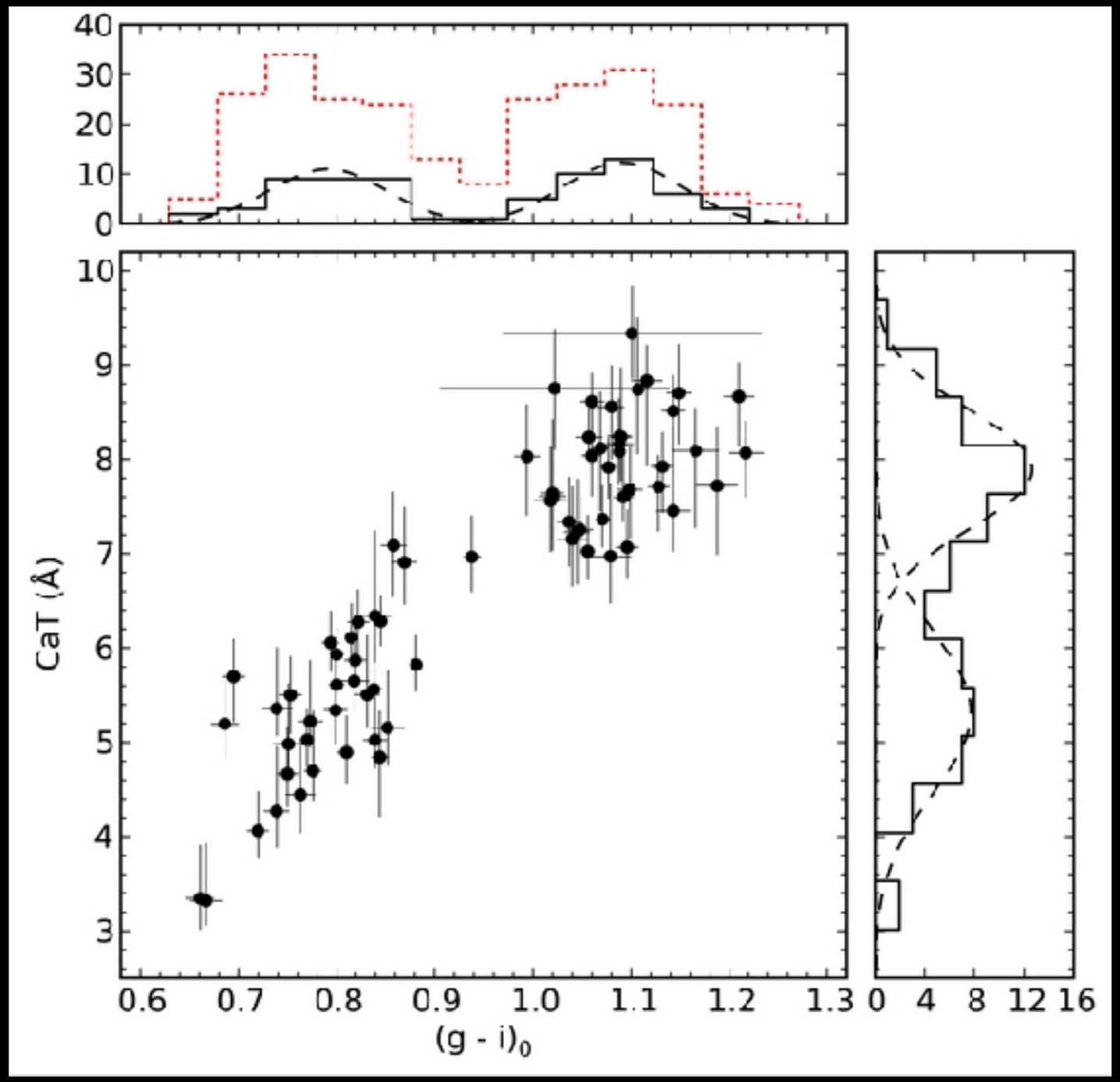
Broad Uni-modal metallicity distribution

Bi-modal metallicity distribution

Caldwell+2011

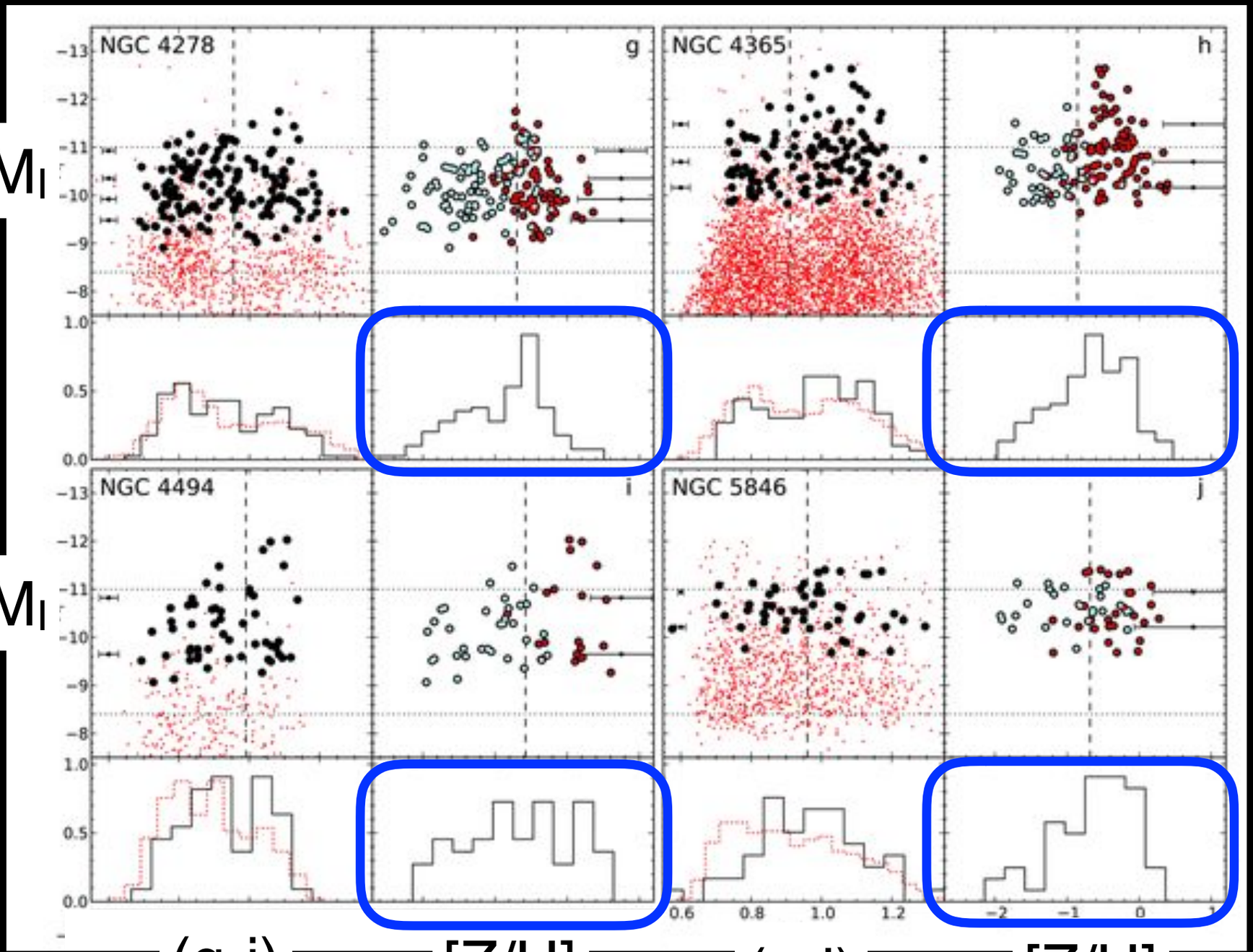
Metallicity Distributions:
Extragalactic GC systems

NGC 3115
clear bi-modality



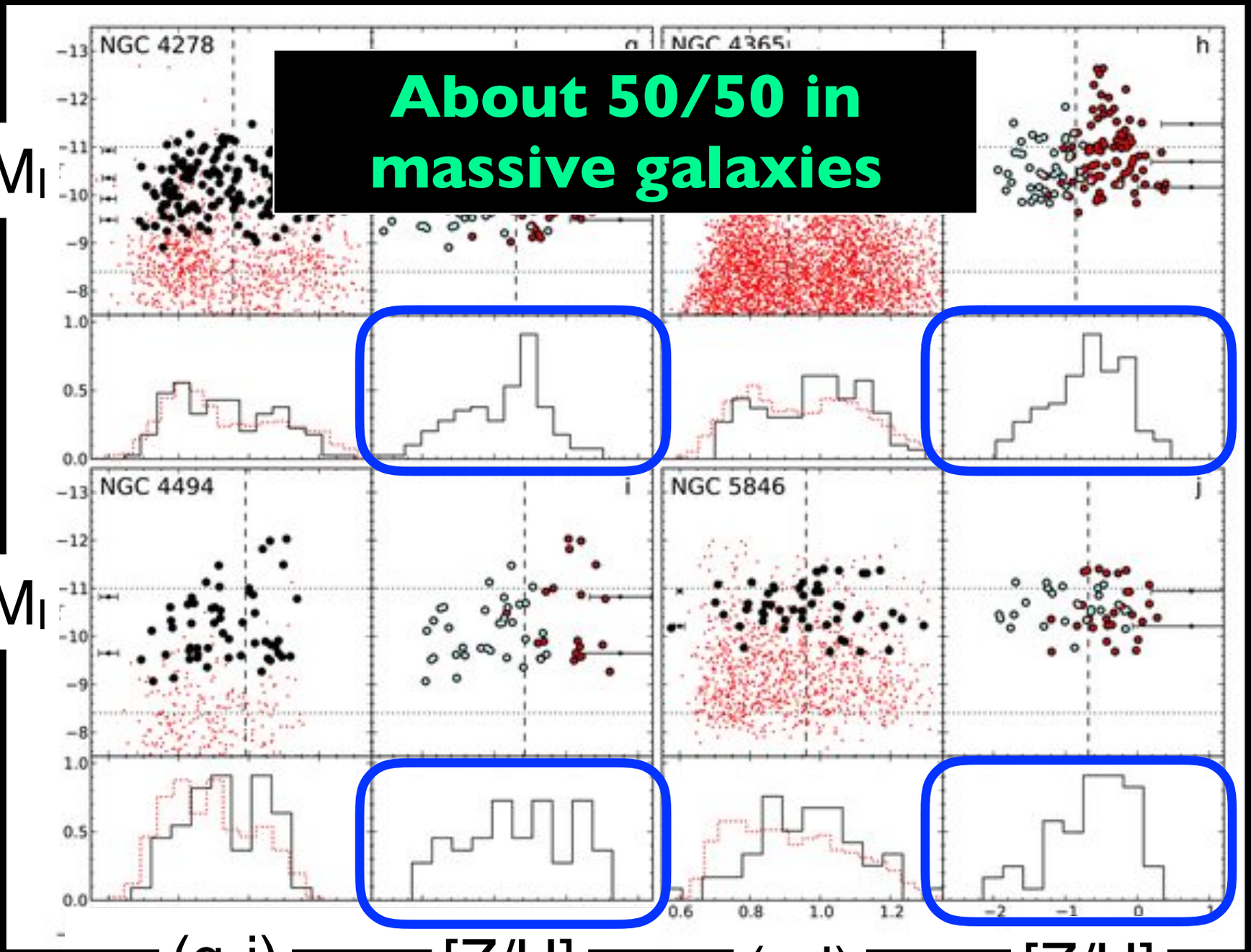
Brodie+2012
(from SLUGGS)

Metallicity Distributions:
Extragalactic GC systems



Usher+2012

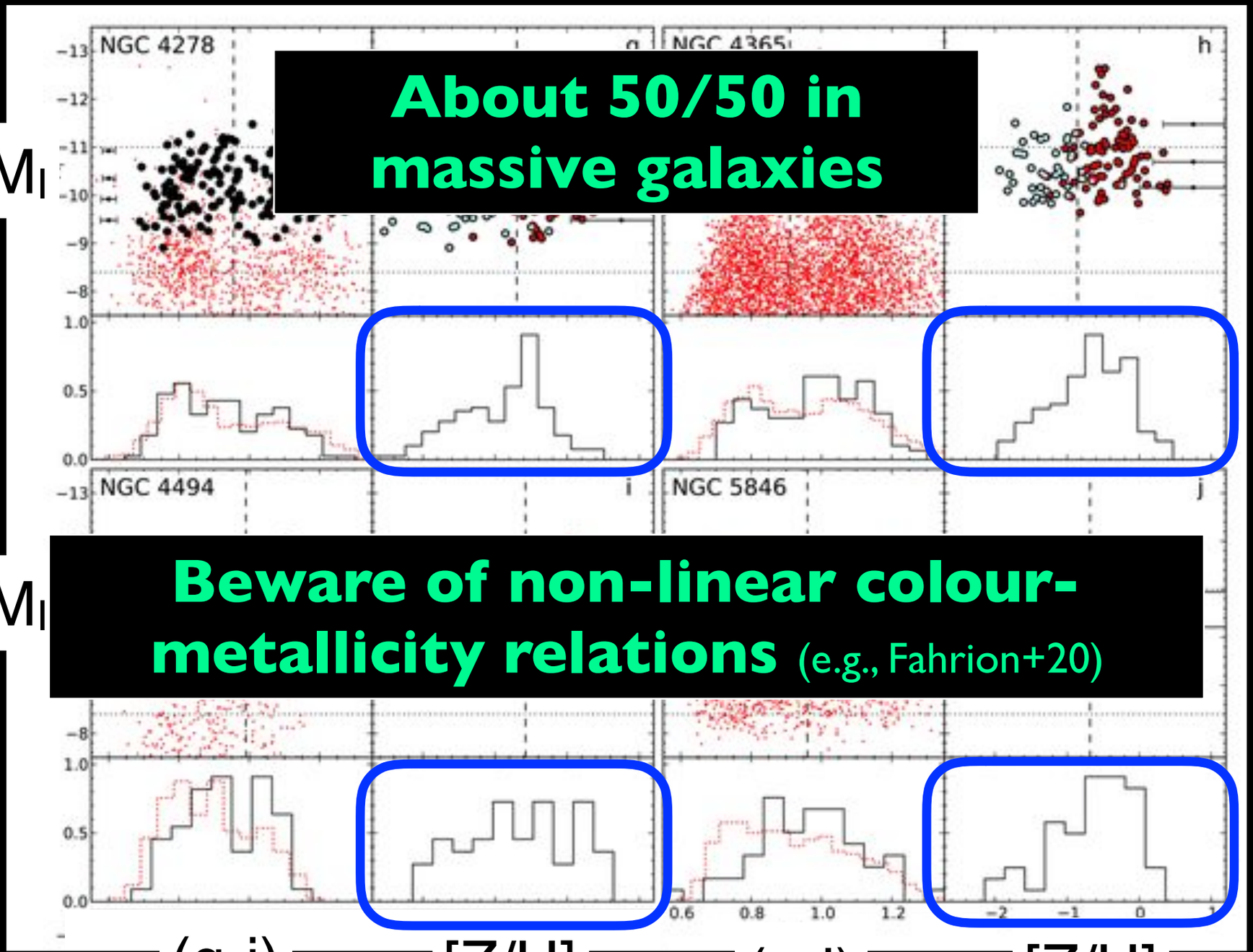
Metallicity Distributions:
Extragalactic GC systems



About 50/50 in massive galaxies

Usher+2012

Metallicity Distributions:
Extragalactic GC systems



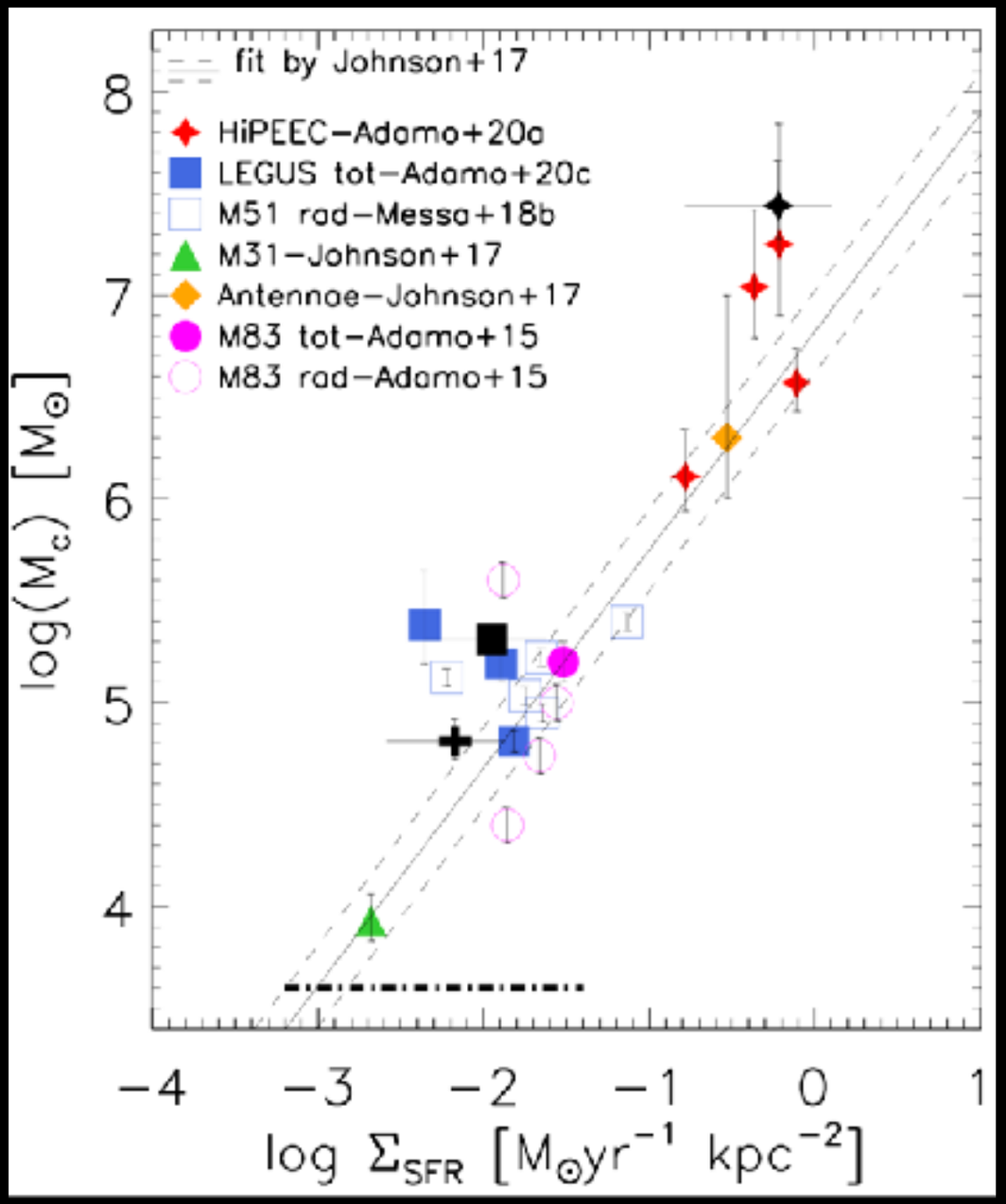
About 50/50 in massive galaxies

Beware of non-linear colour-metallicity relations (e.g., Fahrion+20)

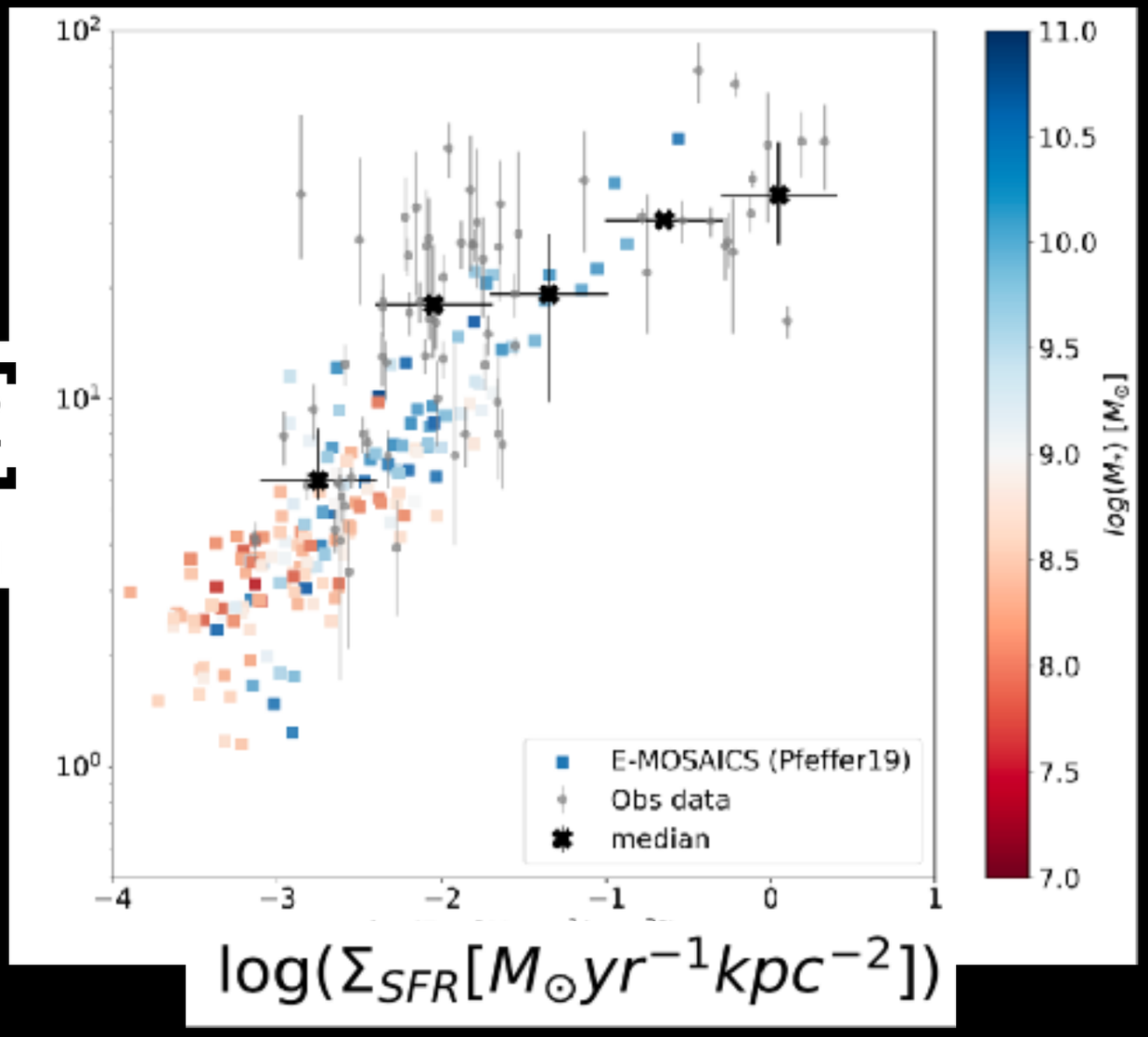
Usher+2012

Using YMCs to Understand GC Formation

Truncation mass

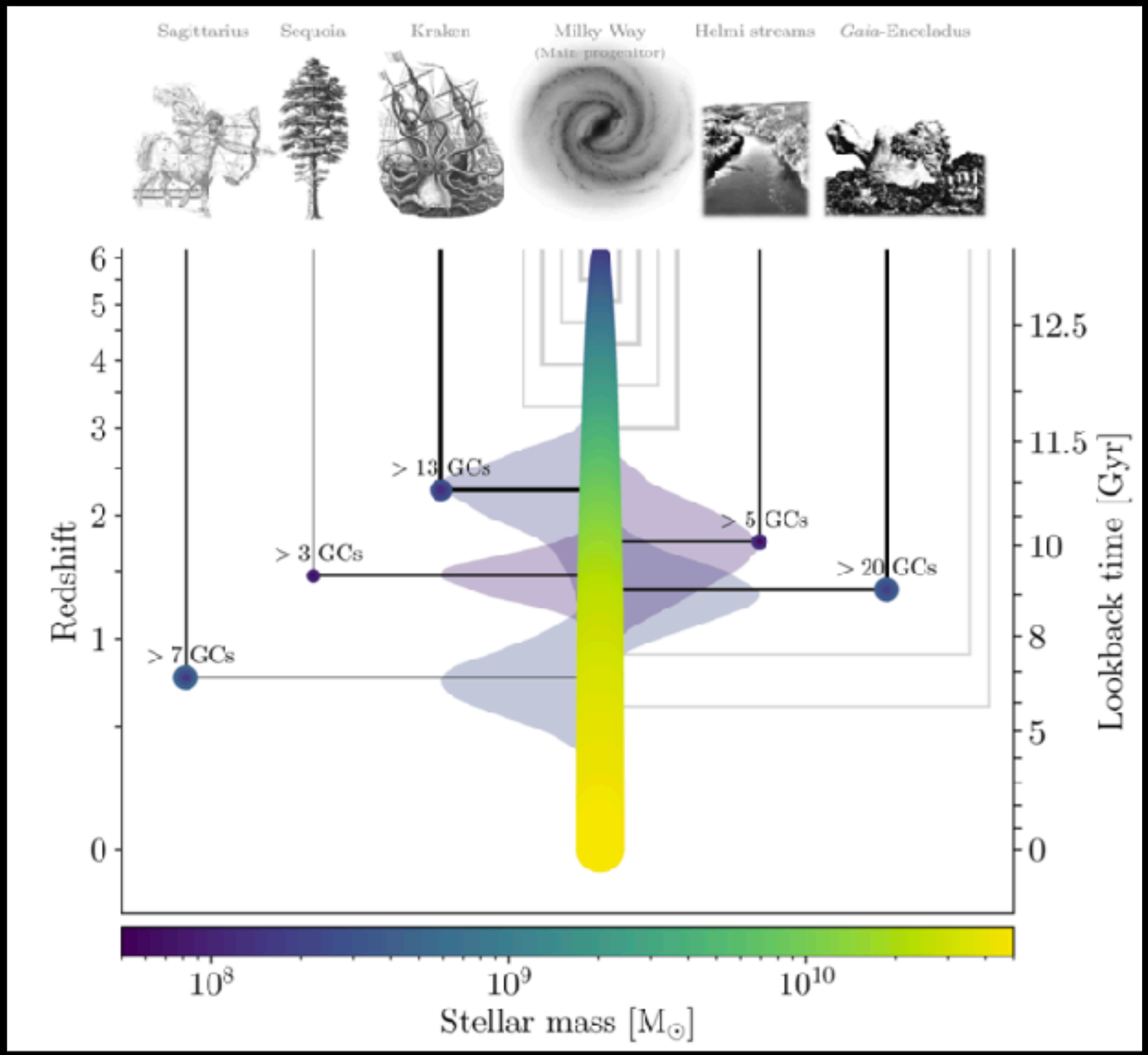


Fraction of stars forming in clusters



Adamo+2020

Reconstructing Galaxy Assembly From GCs



Kruijssen, Pfeffer+2020

Open Questions

- What is the age distribution of massive (i.e., globular) clusters?
- Are mass/luminosity distributions Universal? Is this worth a second look?
- Are most GC metallicity distributions bimodal? Is this worth a second look?
- Evidence points towards the Universality of massive cluster formation (GCs = YMCs+evolution). Can we prove/disprove this?
- For those who believe GCs are different, why? How can we test this?
- Further study of the YMC properties as a function of environment (truncation mass/cluster formation efficiency)
- Can we use GCs to trace the assembly of galaxies outside our own?