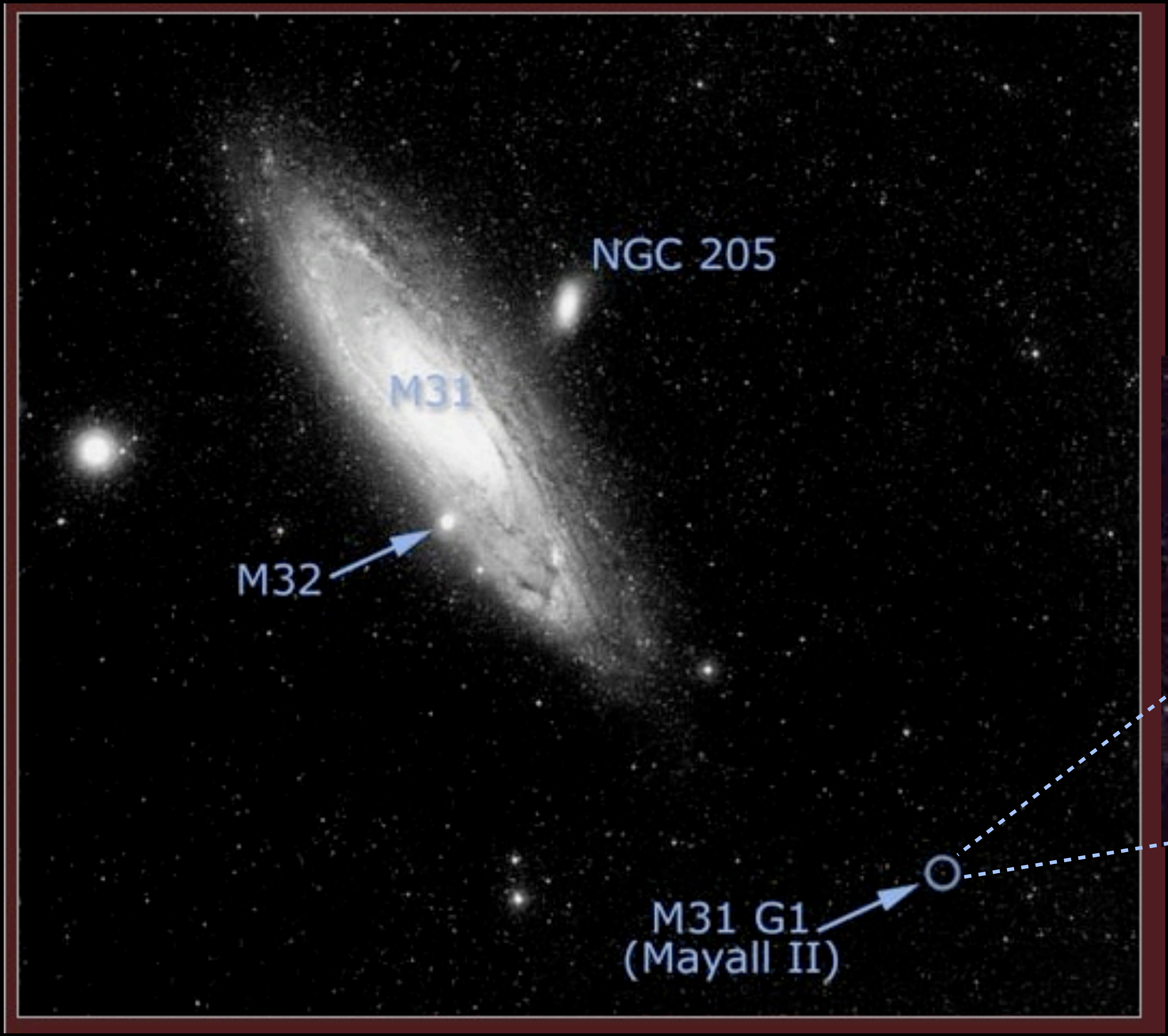
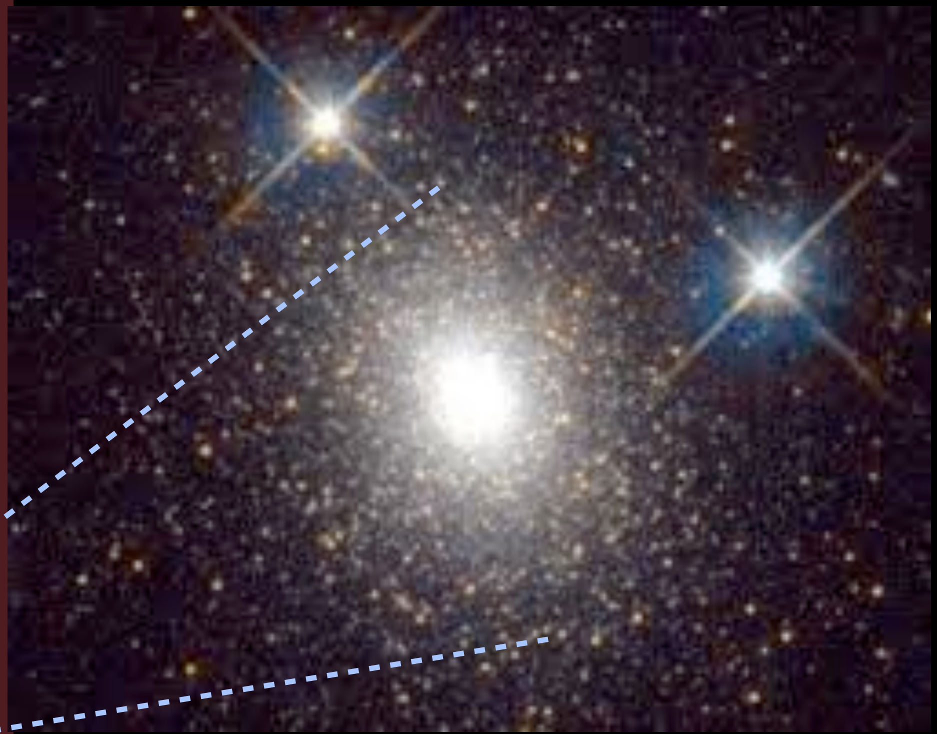
The M31 Globular Cluster System

How alike are the GC systems of the Milky Way and M31?



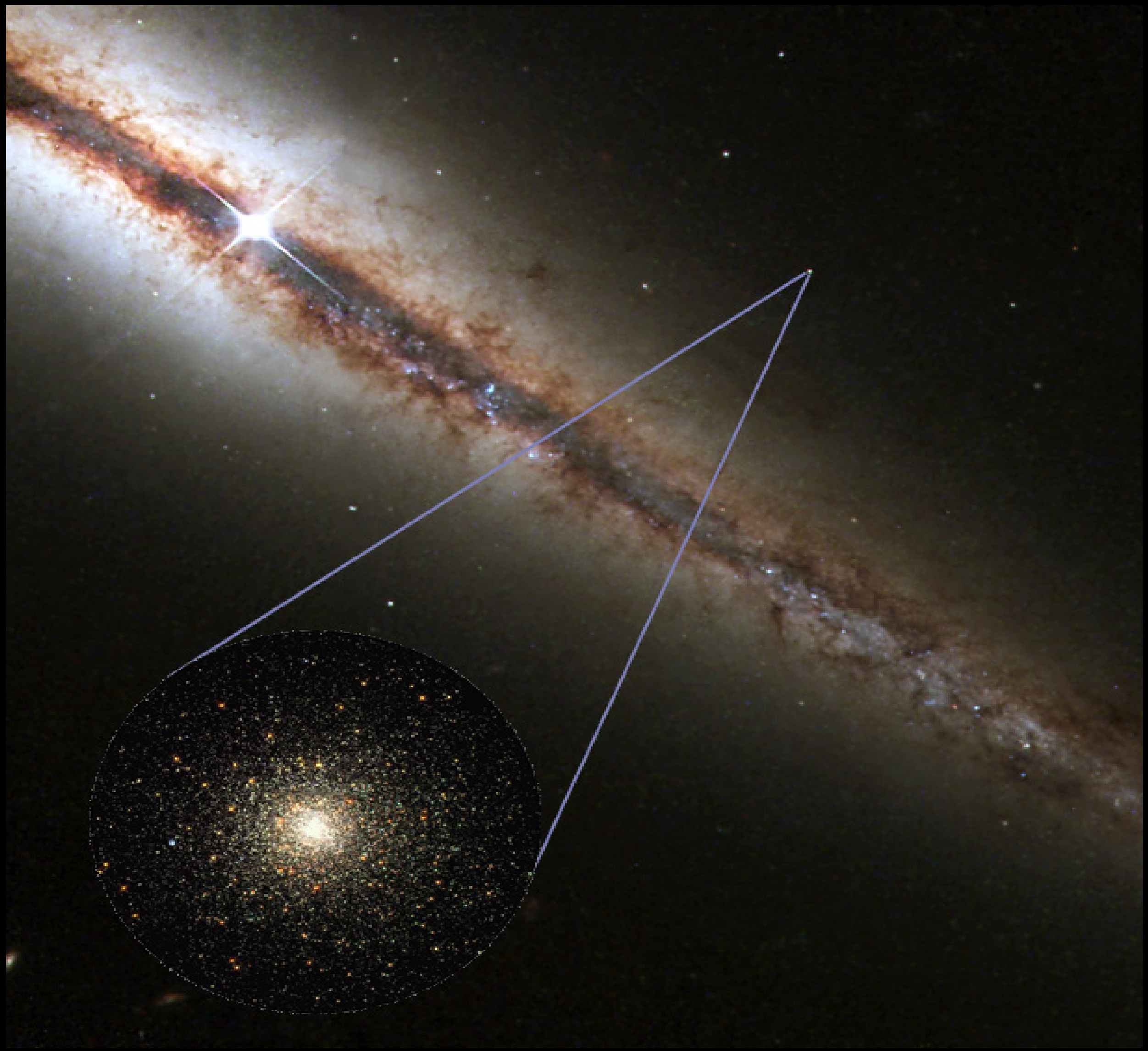
Jean Brodie
UCO/Lick Observatory
UCSC



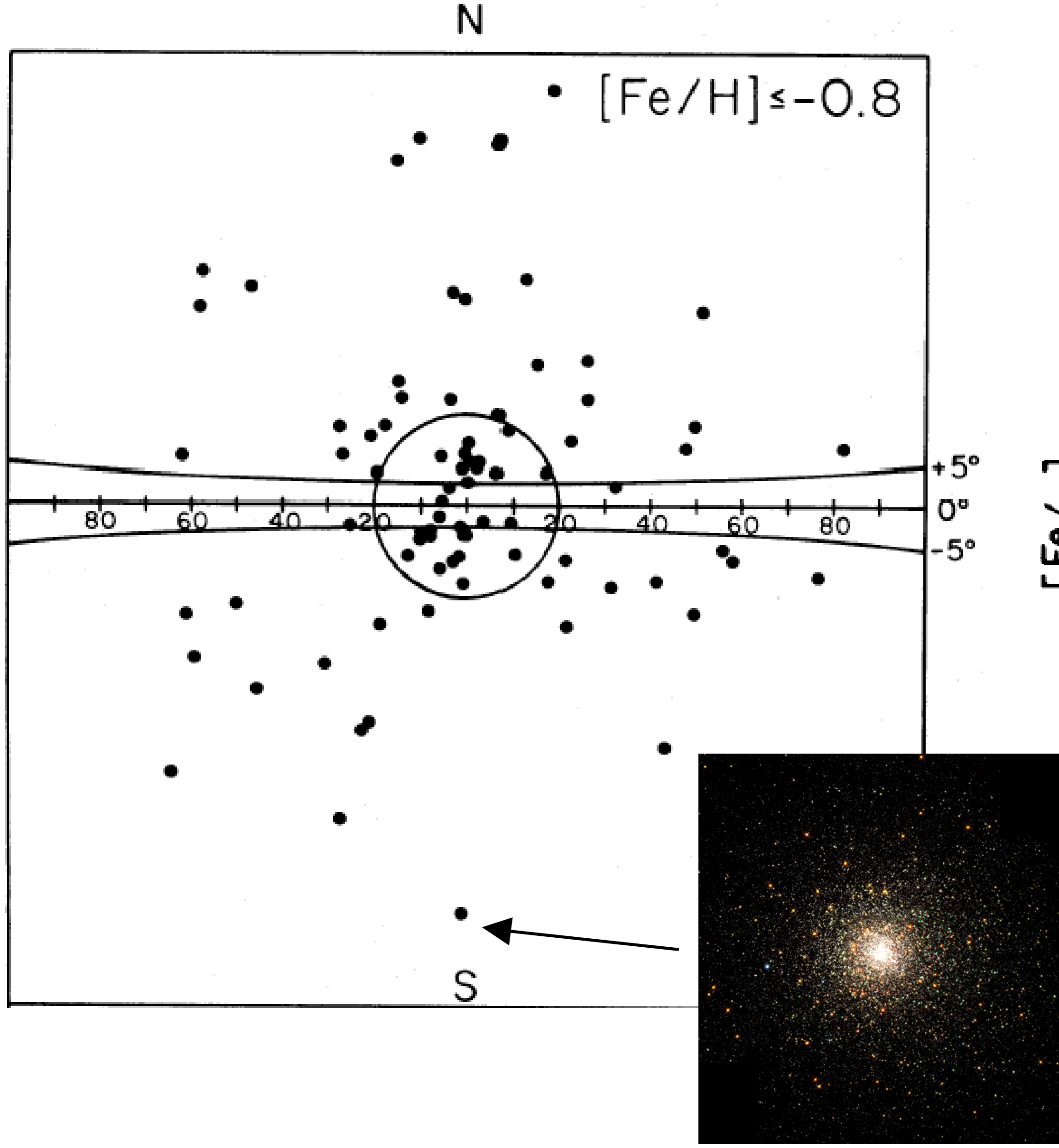
GCs trace the star formation and assembly histories of galaxies

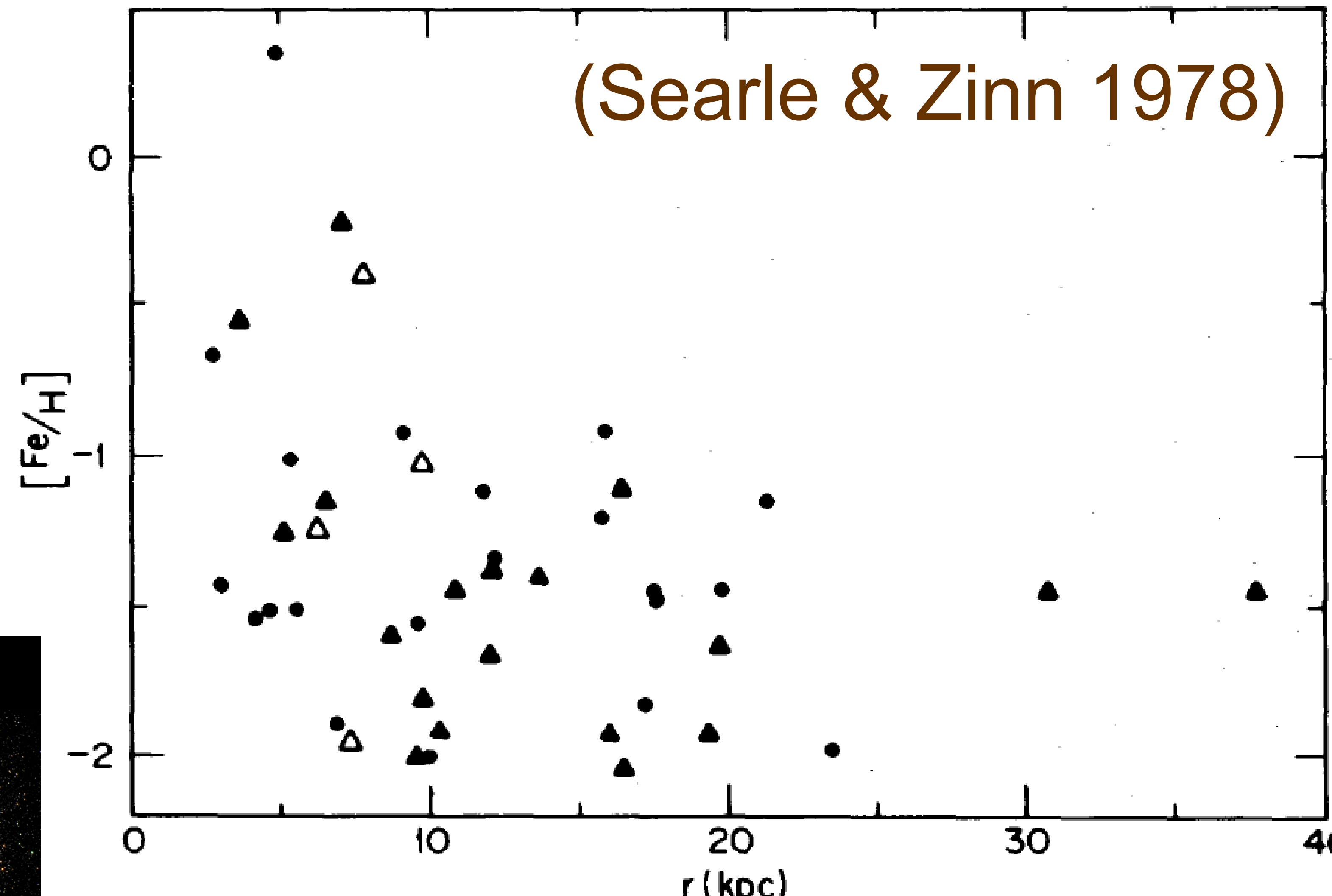
(+ useful for understand stellar evolution fundamentals)

- GC formation occurs early
- Accompanies all major star forming episodes in a galaxy's history
- Unchanging bright beacons
- Accompany and witness hierarchical merging over cosmic time
- GC properties linked to fundamentals (age, metallicity...)



Tracing the Milky Way halo assembly *with **globular cluster** chemodynamics*

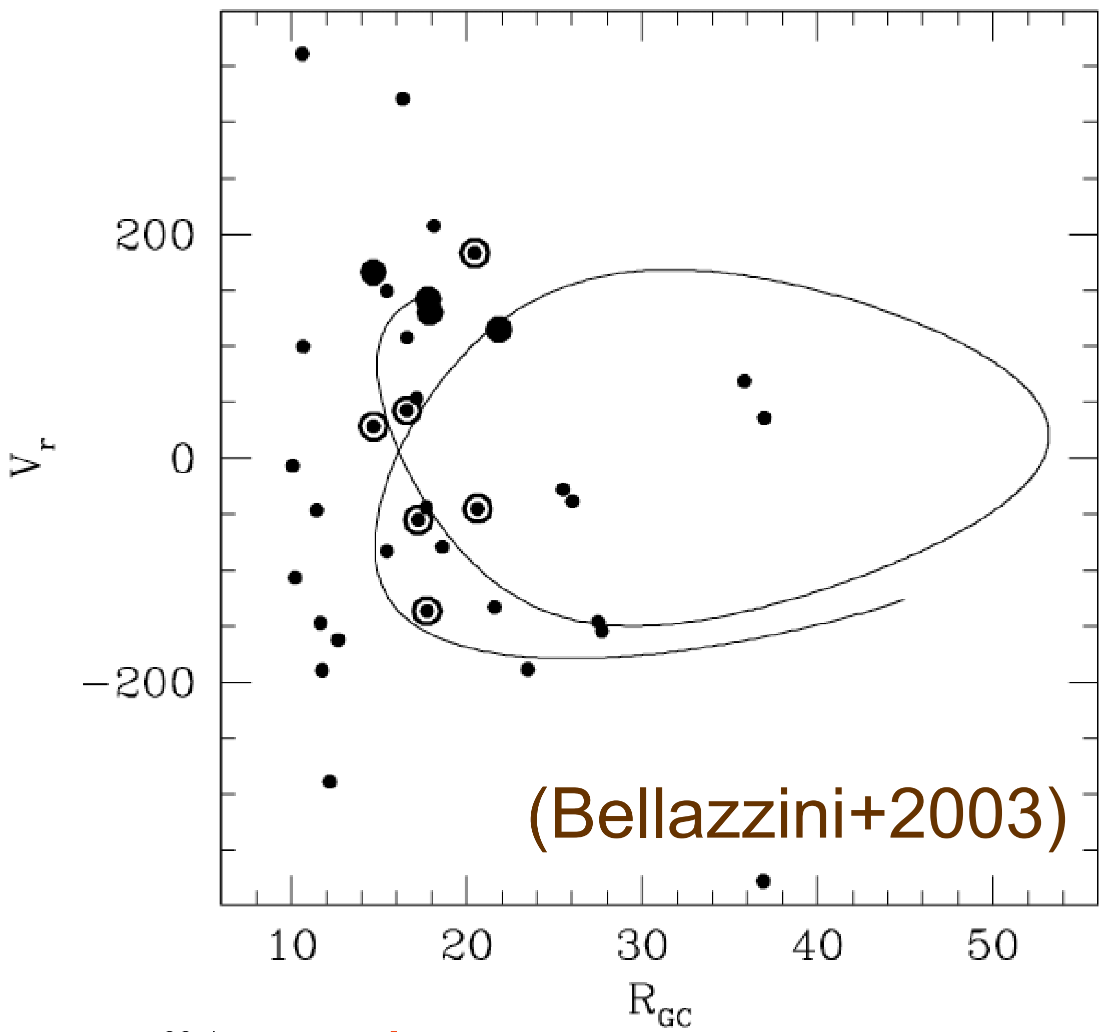


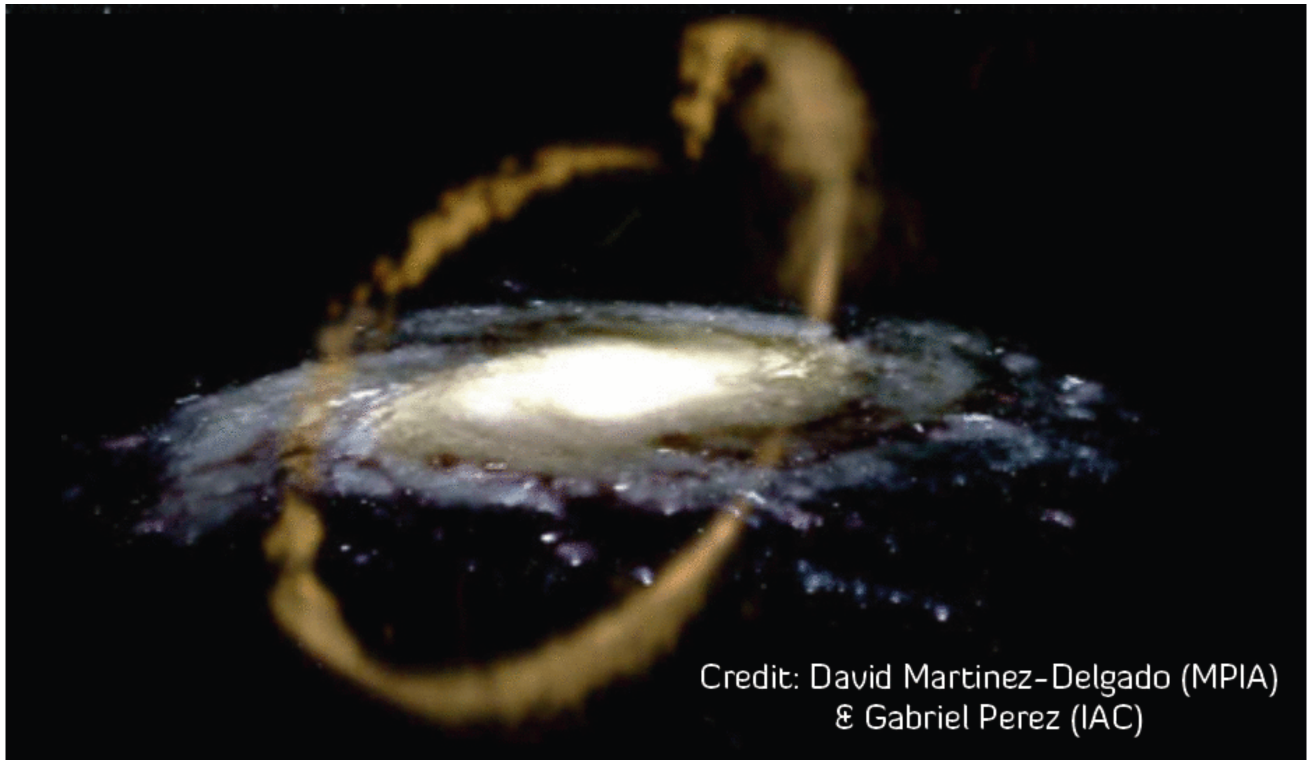


GC positions, velocities, metallicities *jointly* used to infer accretion origin of MW halo

Precursor to today's full phase-space studies of stars

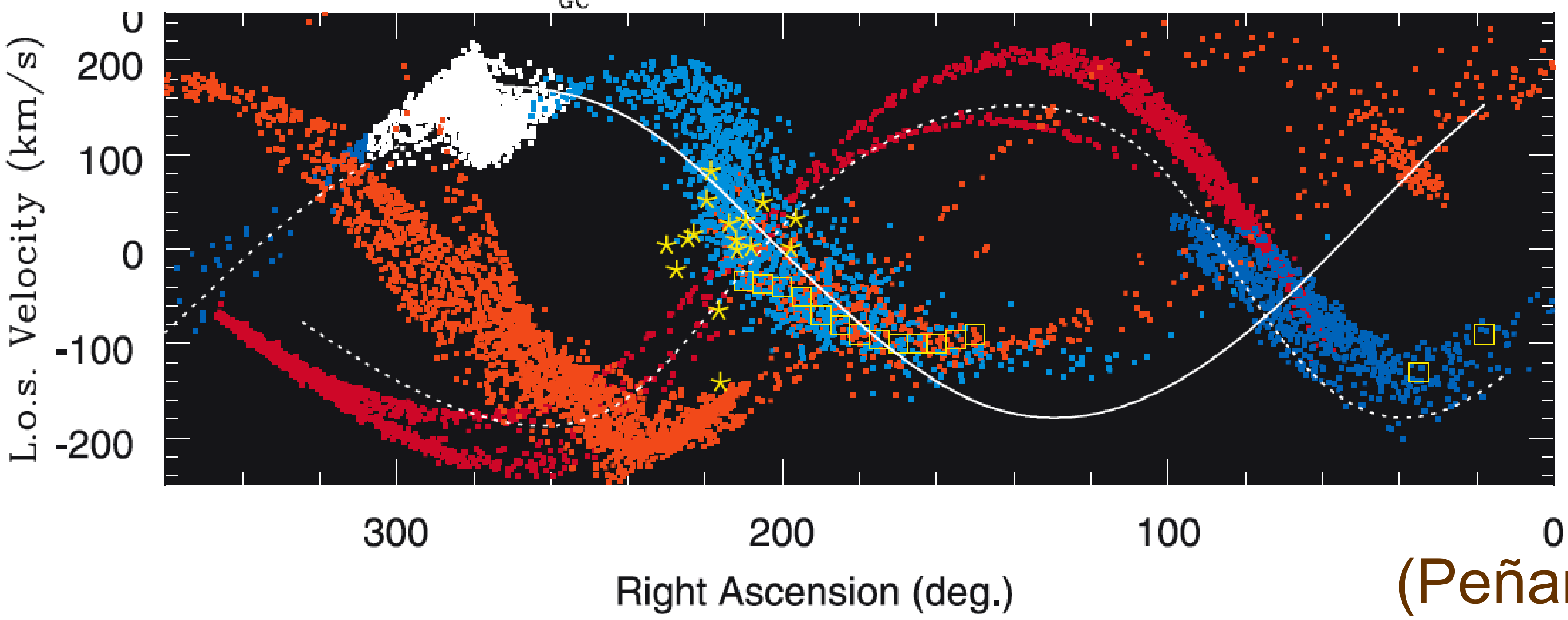
Accretion in the Milky Way halo





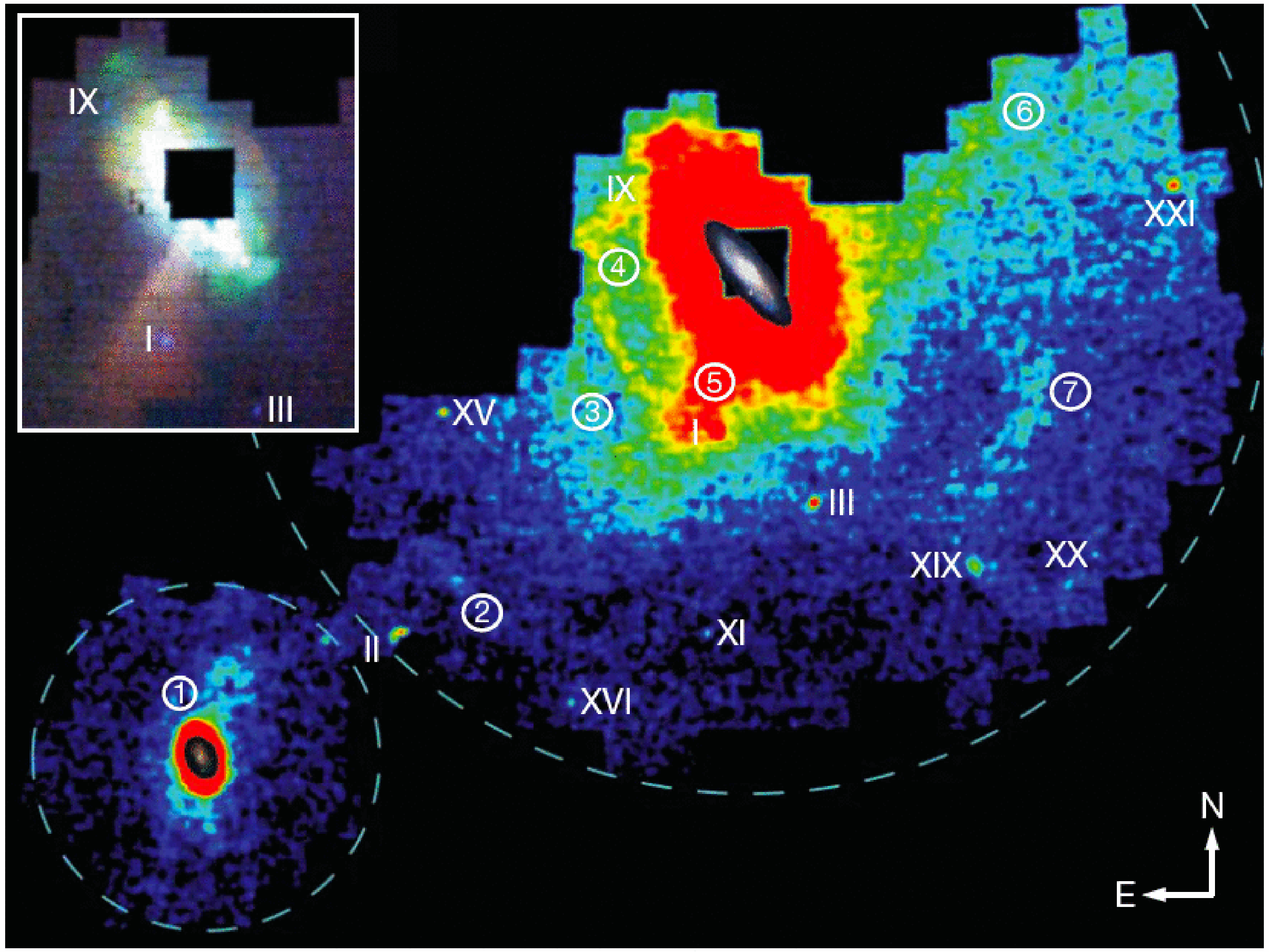
Sagittarius stream:

disrupting dwarf galaxy along with four accreting globular clusters

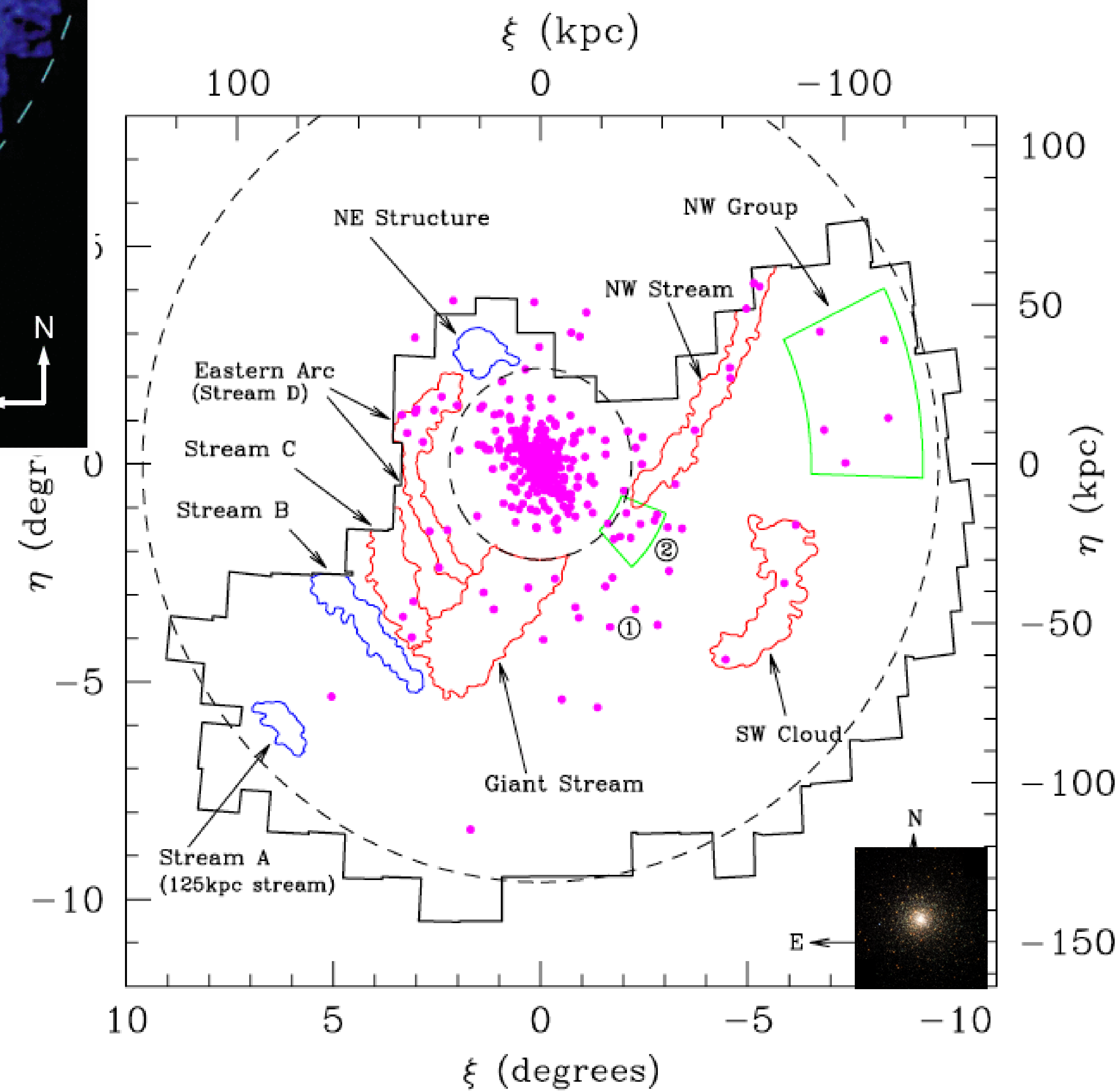


(Peñarrubia et al. 2010)

Substructure in M31 halo



Low-surface brightness substructures traced with globular clusters



(Ibata+2001; Merrett+2003; McConnachie+2009; Mackey+2010)

See Mackey poster

How alike are the GC systems of the Milky Way and M31?

We care because we want to use GCs to trace the star formation and assembly histories of galaxies + understand GC fundamentals

First steps:

Imaging/cataloging/reddening

- Hubble 1932, Seyfert & Nassau 1945, Mayall & Eggen 1953, Kron & Mayall 1960, Vetesnik 1962, Sargent + 1977, Battistini + 1980, Buonano + 1982, Crampton + 1985, Battistini + 1987
- Barmby + 1999 reddening estimates

Dec 23, 1948 - Oct 8, 2010

Early spectroscopy
with 4 and 5m telescopes - ouch!

van den Bergh 1969, Spinrad & Schweizer 1972, Huchra + 1982, Freeman 1983, 1985, Searle 1983, Elson & Wlaterbos 1988, Kent + 1989, Brodie & Huchra 1990, 1991, Huchra + 1991

How alike are the GC systems of the Milky Way and M31?

What we thought we knew ~ 20 years ago

M31 GC system is remarkably similar to the MW's

150 M31 GC spectra: Huchra, Brodie & Kent (1991):

- *Wide range of metallicity (x100) comparable to MW*
- *Slightly higher (0.2 dex) mean metallicity, consistent with GC metallicity − host galaxy L relation* (Brodie & Huchra 1991)
- *No dependence of metallicity on cluster L (no self enrichment)*
- *GC system rotates, most MR like a disk*
- *Both MR and MP rotate at large radii (~ 60 km/s at >2 kpc) similar to MW*

Unlike the MW

M31 GCs are CN enhanced

(Burstein + 1984, Davidge 1990, Brodie & Huchra 1990)

What was added ~ 5-10 years ago

M31 GCs have thin disk kinematics →
no merger > 10% of disk mass
(Morrison + 2004)

Some M31 GCs have intermediate ages (2-6 Gyr)
(Beasley + 2005, Puzia + 2005, Fusi Pecci + 2005)

Consistent with equal mass merger 6-8 Gyr ago
(Brown+ 2003) — ***but problem with thin disk constraint***

More evidence that M31 GCs were CN enhanced compared to MW
(Beasley +2004, Puzia + 2005)

Both MW and M31 GCs host LMXBs, inc. candidate BH binaries, preferentially in GCs that are MR, massive, w/ high collision rates
(Di Stefano+ 2002, Peacock+ 2010, Barnard+ 2011)

What we know now

333 M31 GC spectra

Caldwell+ 2011, Morrison+ 2011, Schiavon+ 2012, Romanowsky+ 2012

M31 GC system is remarkably similar to the MW's ✓

- *Wide range of metallicity (x100) comparable to MW* ✓
- *Slightly higher (0.2 dex) mean metallicity, consistent with GC metallicity − host galaxy L relation (Brodie & Huchra 1991)* ✓
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What we know now

333 M31 GC spectra

Caldwell + 2011, Morrison + 2011, Schiavon + 2012, Romanowsky + 2012

M31 GCs have thin disk kinematics →
no merger > 10% of disk mass (Morrison + 2004) ✘
Open clusters had been included (MR GCs respond to bar)

Some M31 GCs have intermediate ages (2-6 Gyr) (Beasley + 2005, Puzia + 2005, Fusi Pecci + 2005) ✘
Low [Fe/H], not young

More evidence that M31 GCs are CN enhanced compared to MW (Beasley +2004, Puzia + 2005) ✘
Flux calibration uncertainties for weak blue lines (see Schiavon poster N - mass relation)

How alike are the GC systems of the Milky Way and M31?

~150 GCs in MW
~400 GCs in M31

M31	Milky Way
$N_{MP} \approx N_{MR}$	$N_{MP} \approx 2 \times N_{MR}$

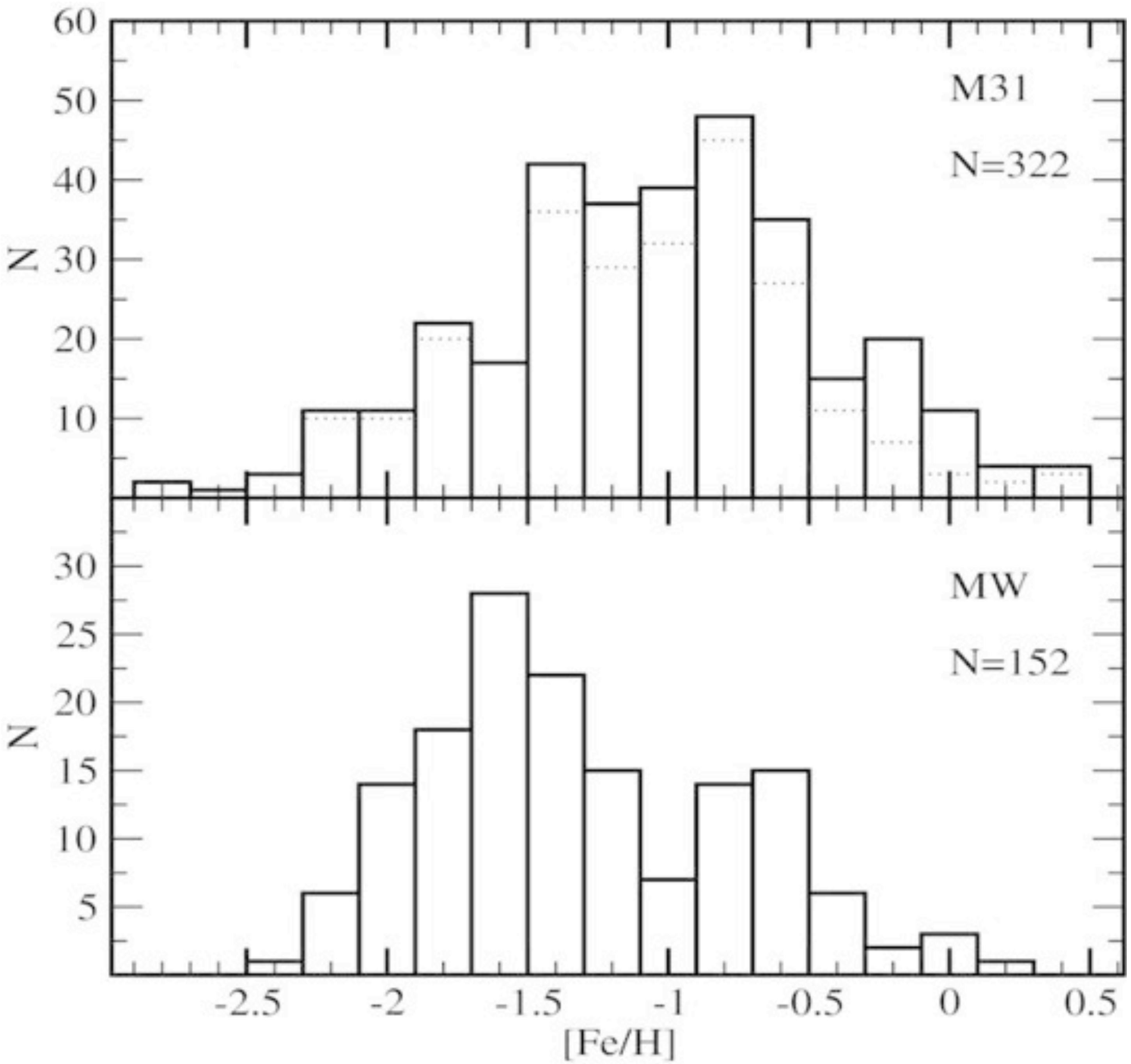
Number of MR GCs per unit bulge light is very similar

MR GCs trace build up of bulges
MR GCs form with similar efficiencies w.r.t. stars in M31 and MW bulges

Significant number of MP GCs revealed MP halo in M31 long before discovery in halo starlight

What else have we discovered?

Caldwell et al. 2011



M31 GC metallicity distribution is *not obviously bimodal* – different from MW

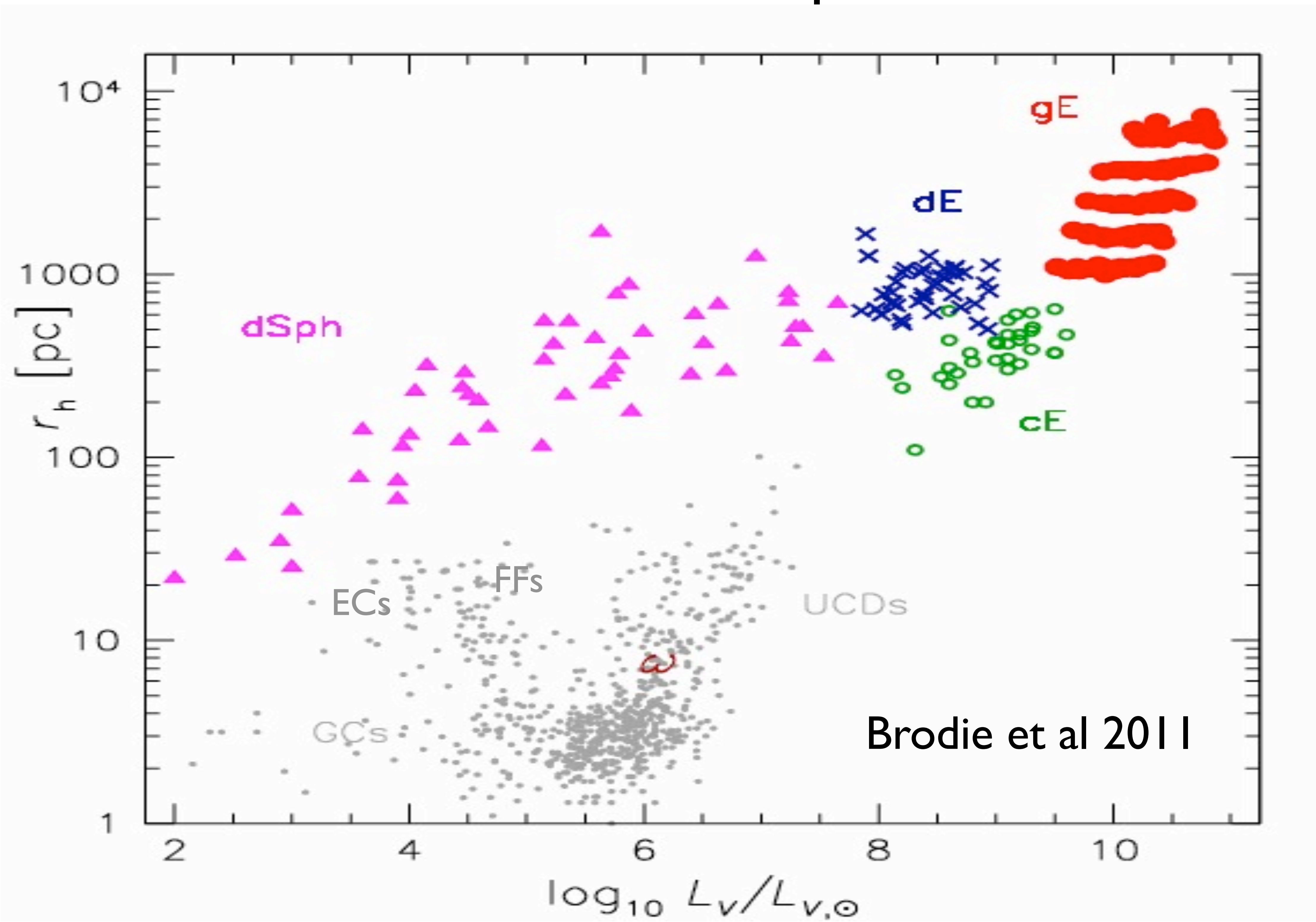
Hints of multi-modality with minor peaks at [Fe/H] = −1.4, −0.7, −0.2

Indicates different formation for MW and M31 GC systems

Lack of simple bimodality in M31 → more complex history of minor mergers and accretions compared to MW

The Everything Plot

Extended clusters discovered in M31 (Huxor et al.)
No MW counterparts



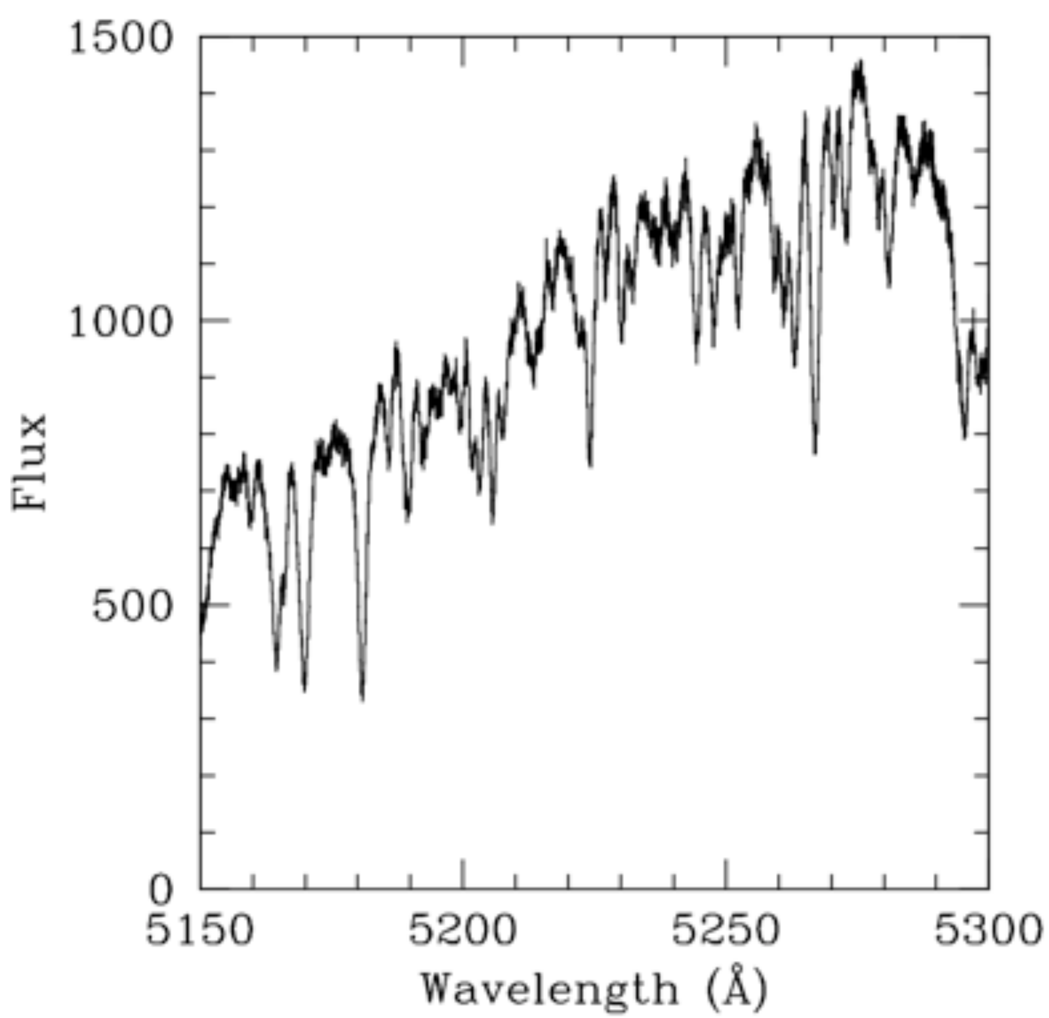
See Huxor poster

Mass-to-Light Ratios of Globular Clusters in M31 (and the Milky Way)

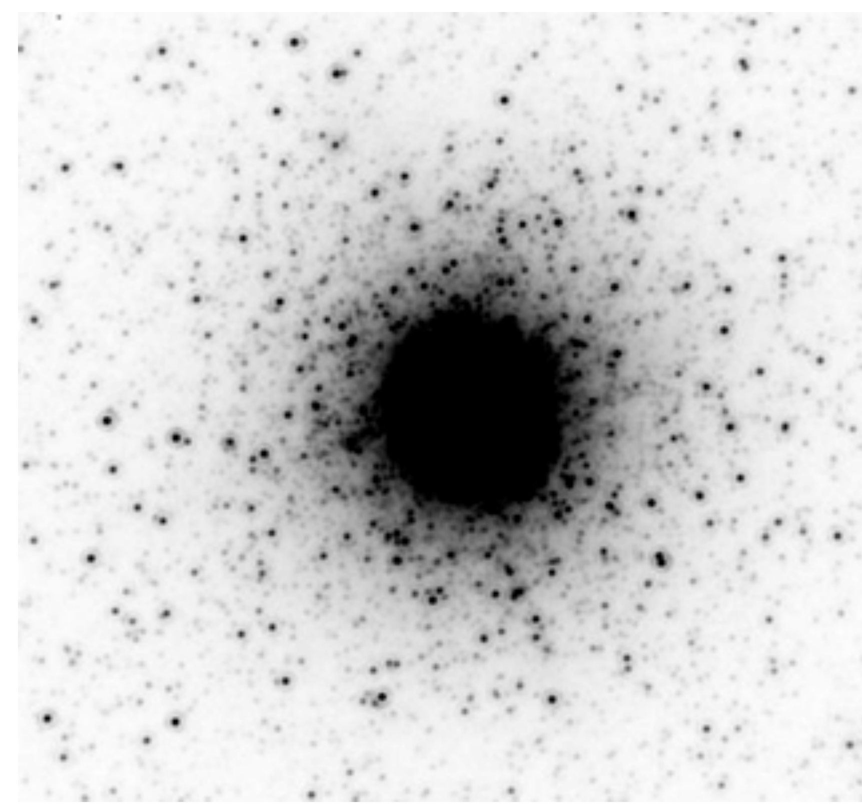
Strader et al 2009, 2011

High-resolution spectra from MMT, Keck, Shane ⟶
Internal velocity dispersions + precise radial velocities for 200 GCs

M31: 225-280

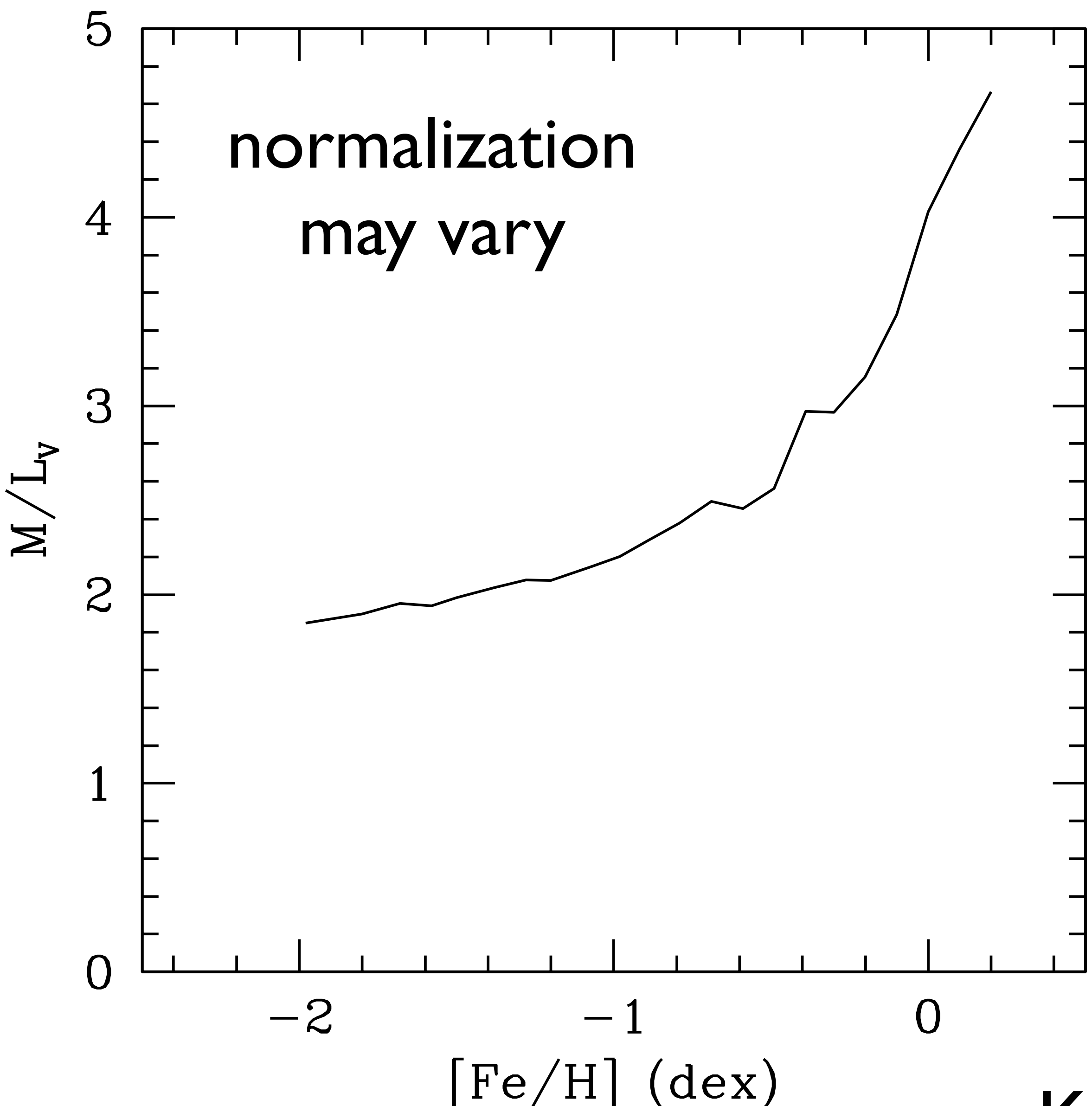


HST

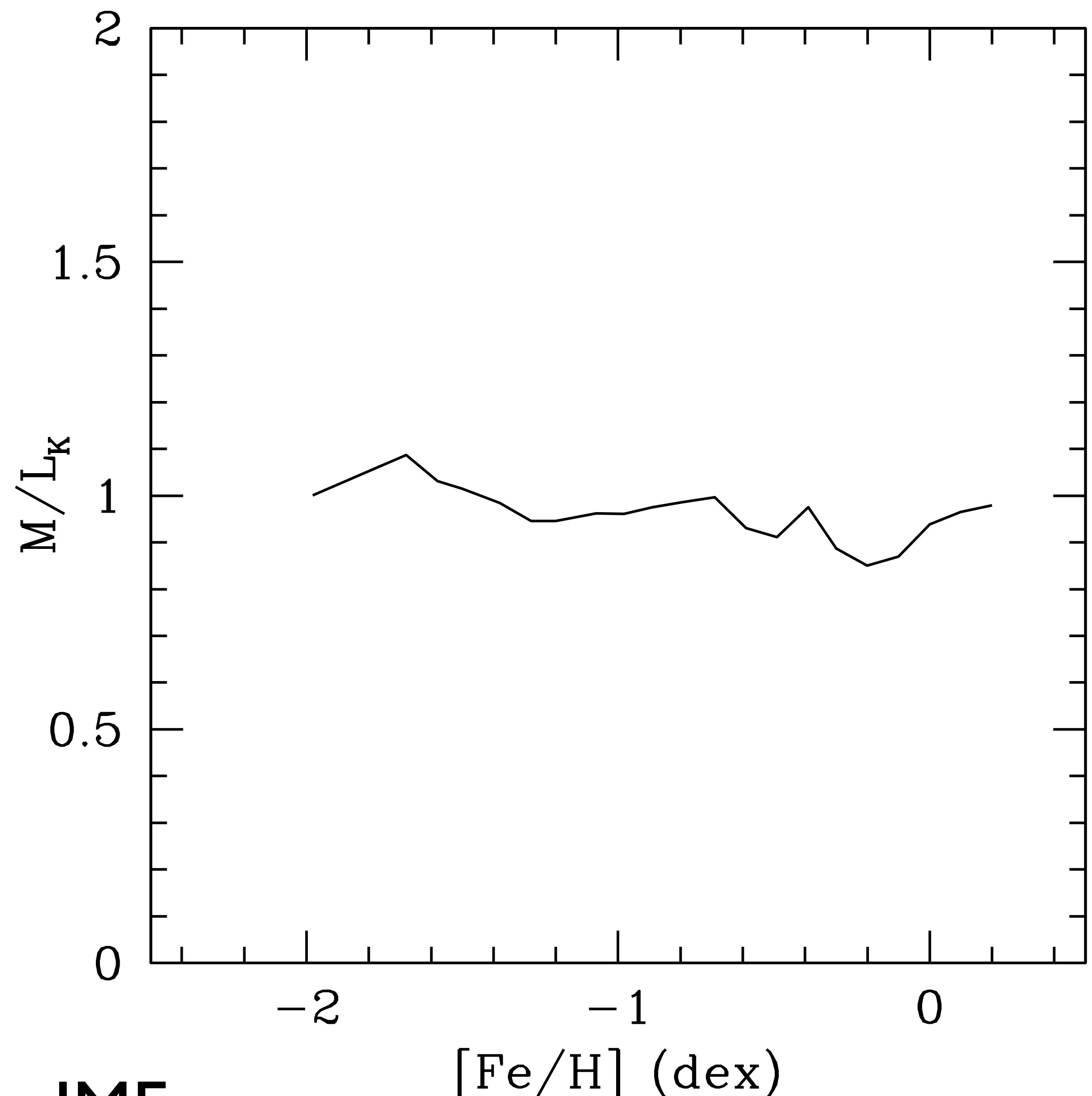


Mass-to-Light and [Fe/H]

(optical)



(near IR)



Kroupa IMF

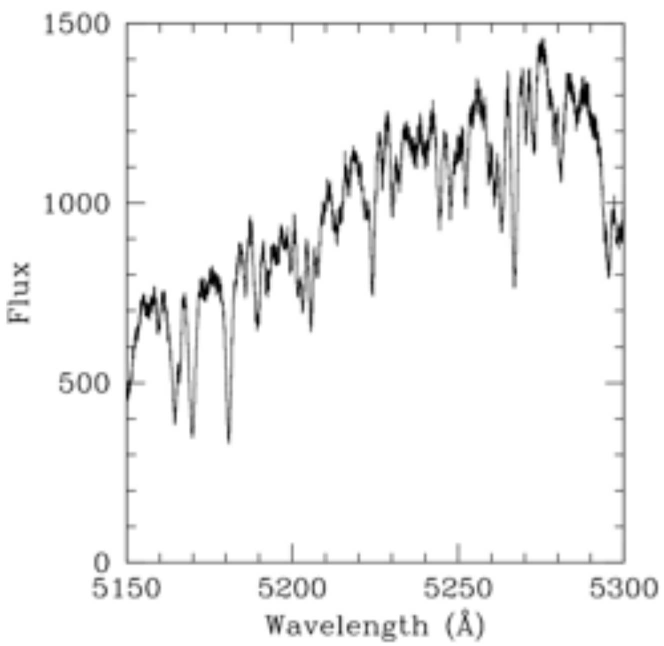
12.5 Gyr

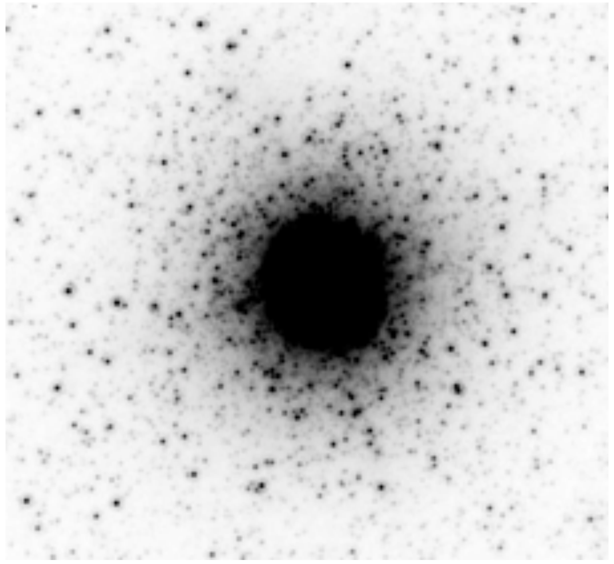
M31 GCs: Calculating M/L

$$M_{\rm vir} = \frac{7.5\sigma_\infty^2 r_{hm}}{G}$$

high-res spectra + cluster structure

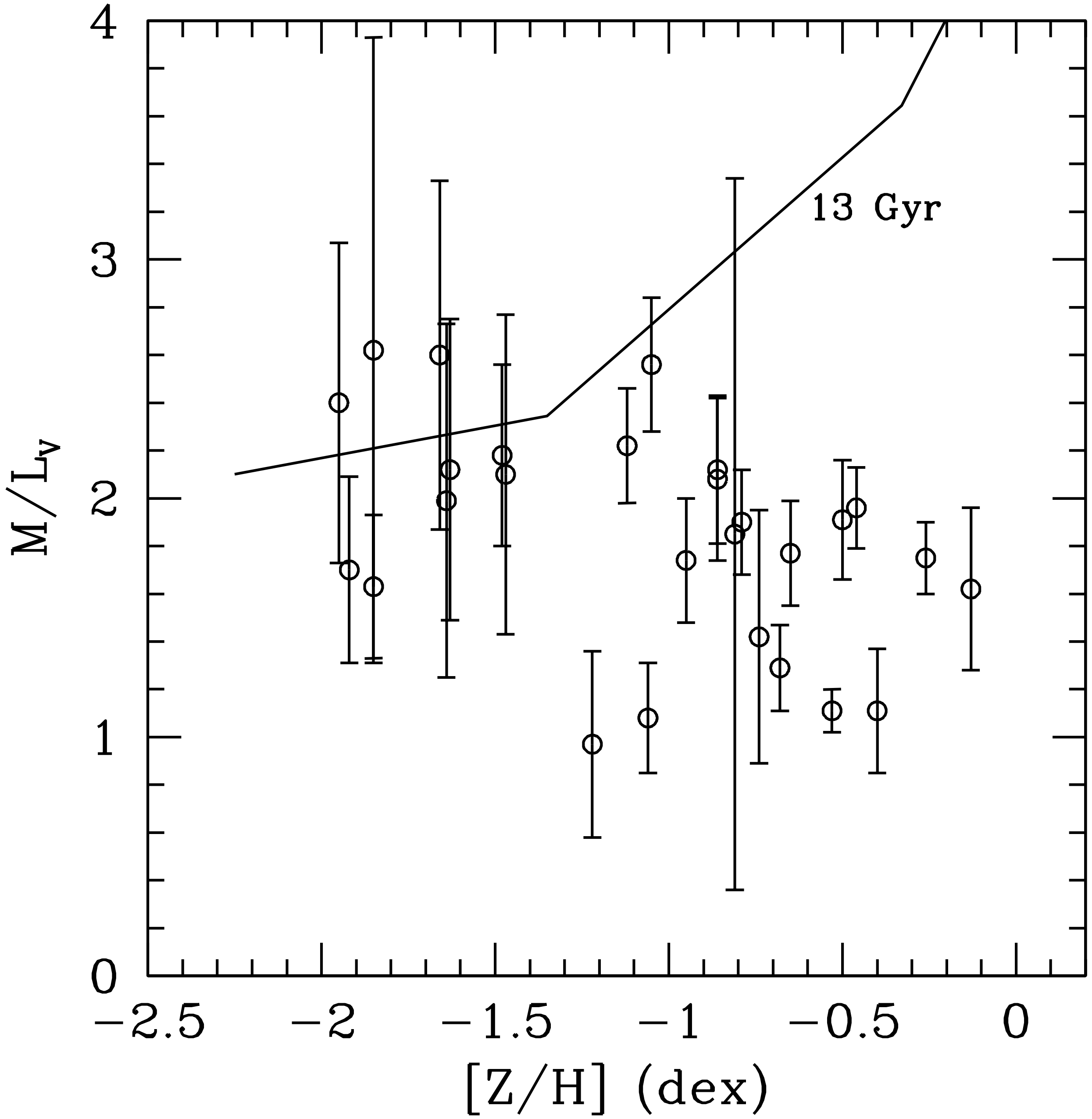
good imaging (pref HST)



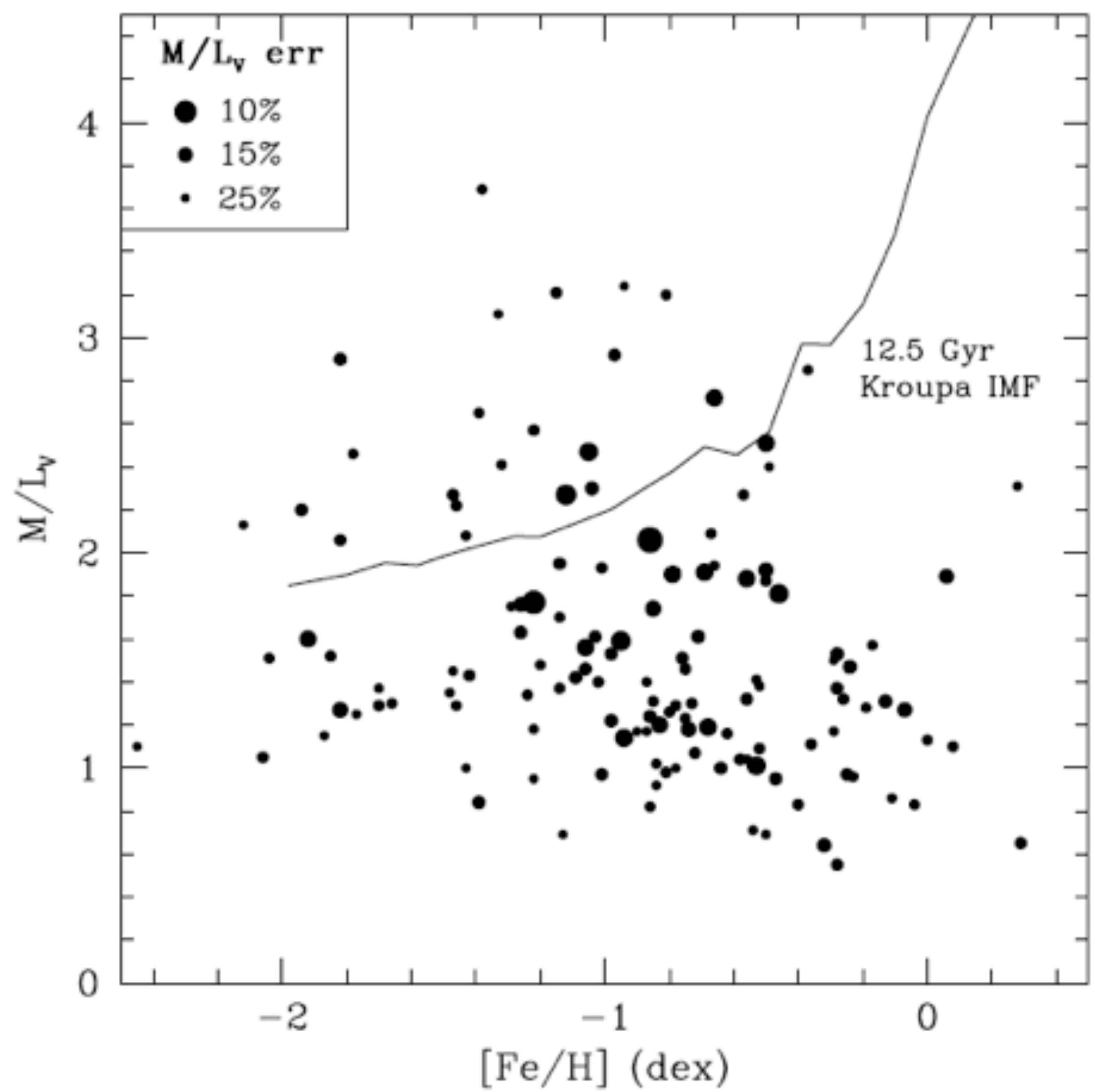


Measured M/L of M31 GCs

Strader et al. 2009
27 GCs



Strader et al. 2011
131 GCs

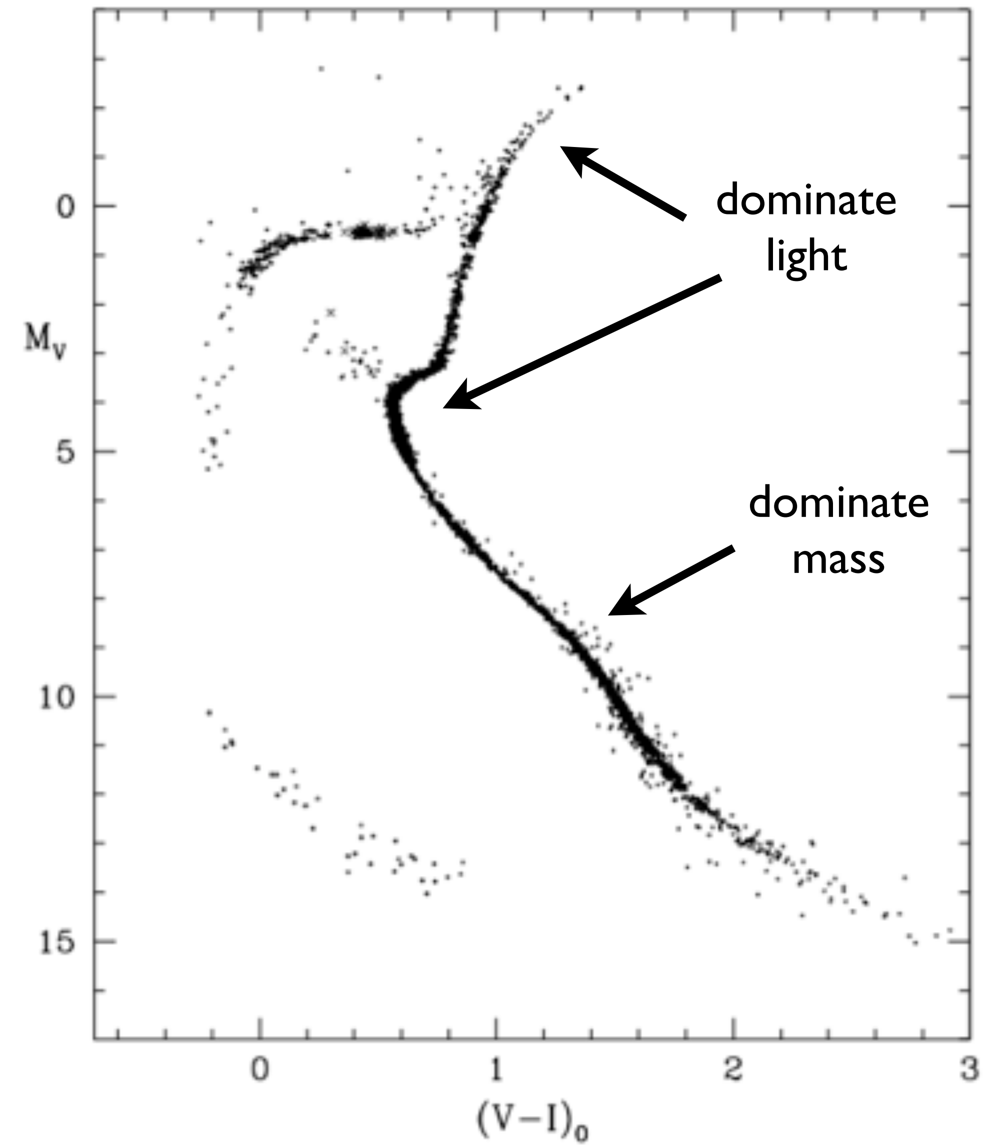


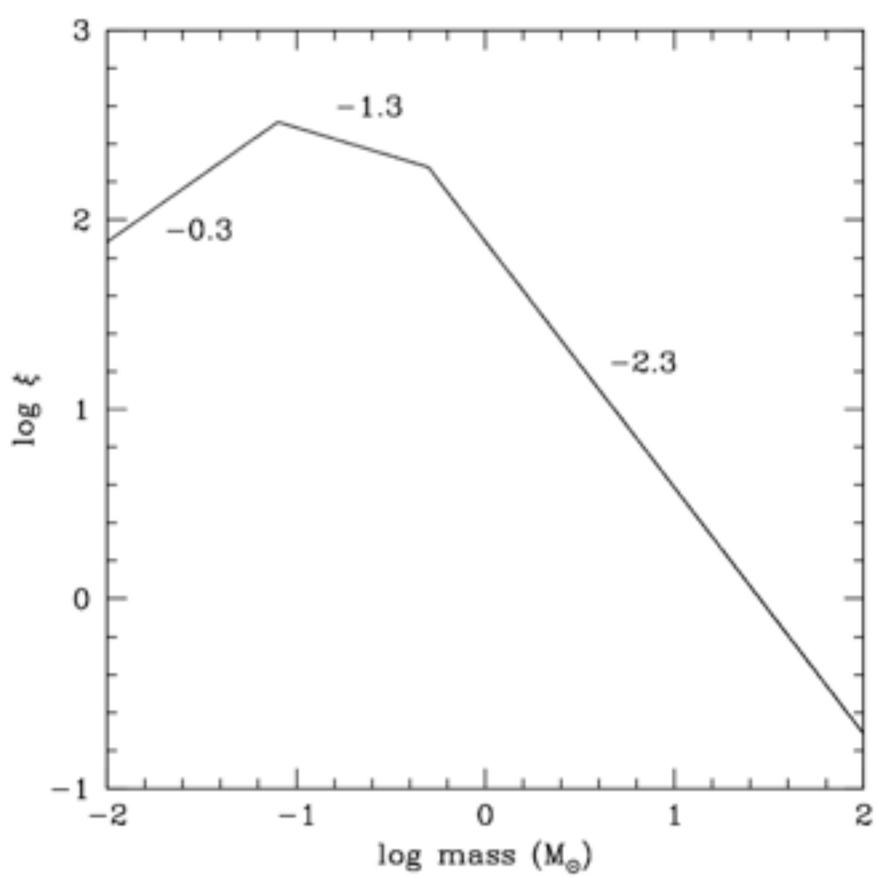
Ways to make M/L low

Harris 2000

(i) Add stars with low M/L
(RGB/AGB)

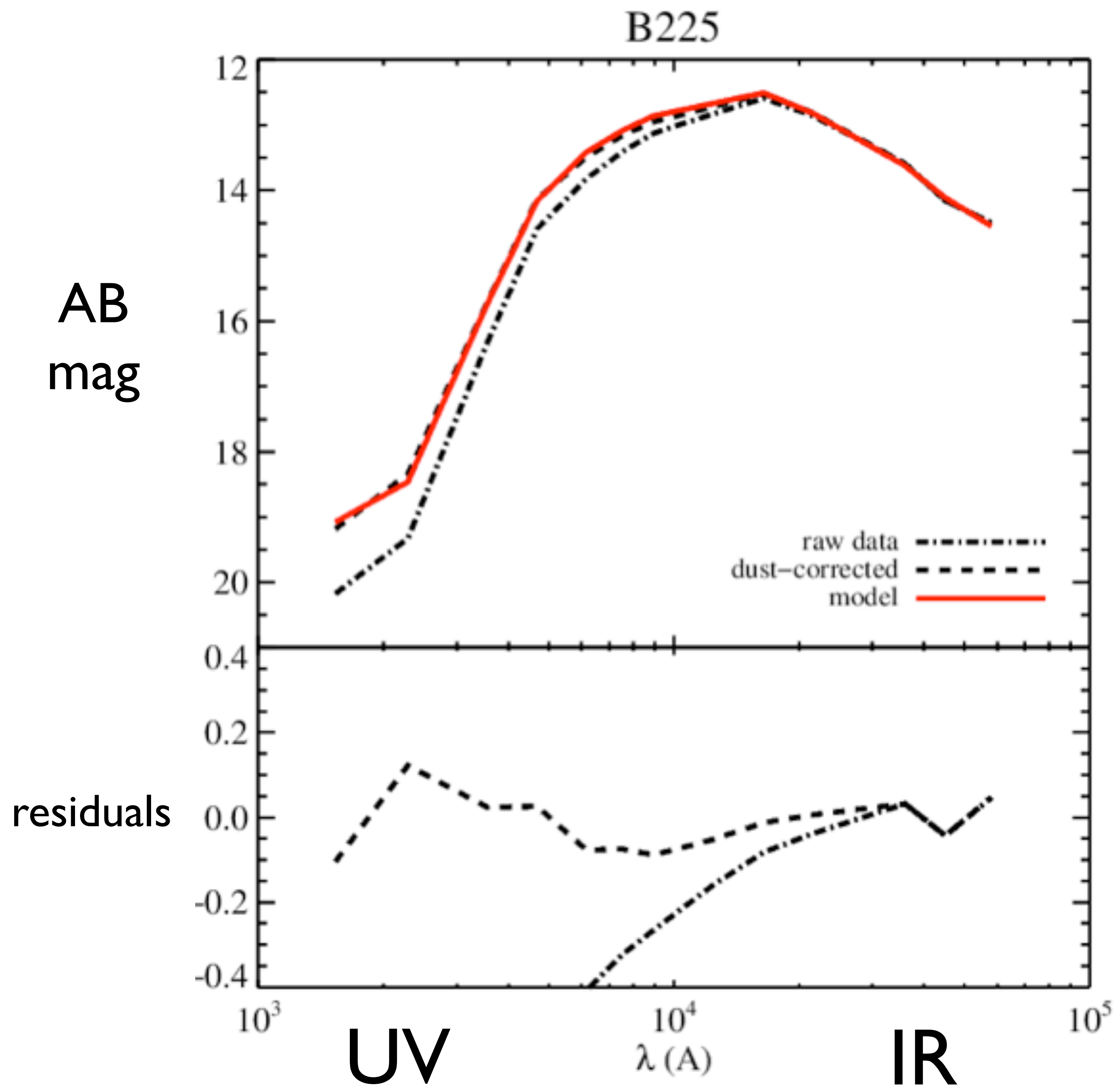
(ii) Remove stars with high M/L
(low-mass dwarfs)





Kroupa
IMF

Bolometric Comparison



Flux matches!

Models have about right number of red giants

Mass Function and M/L

Strader et al. 2011

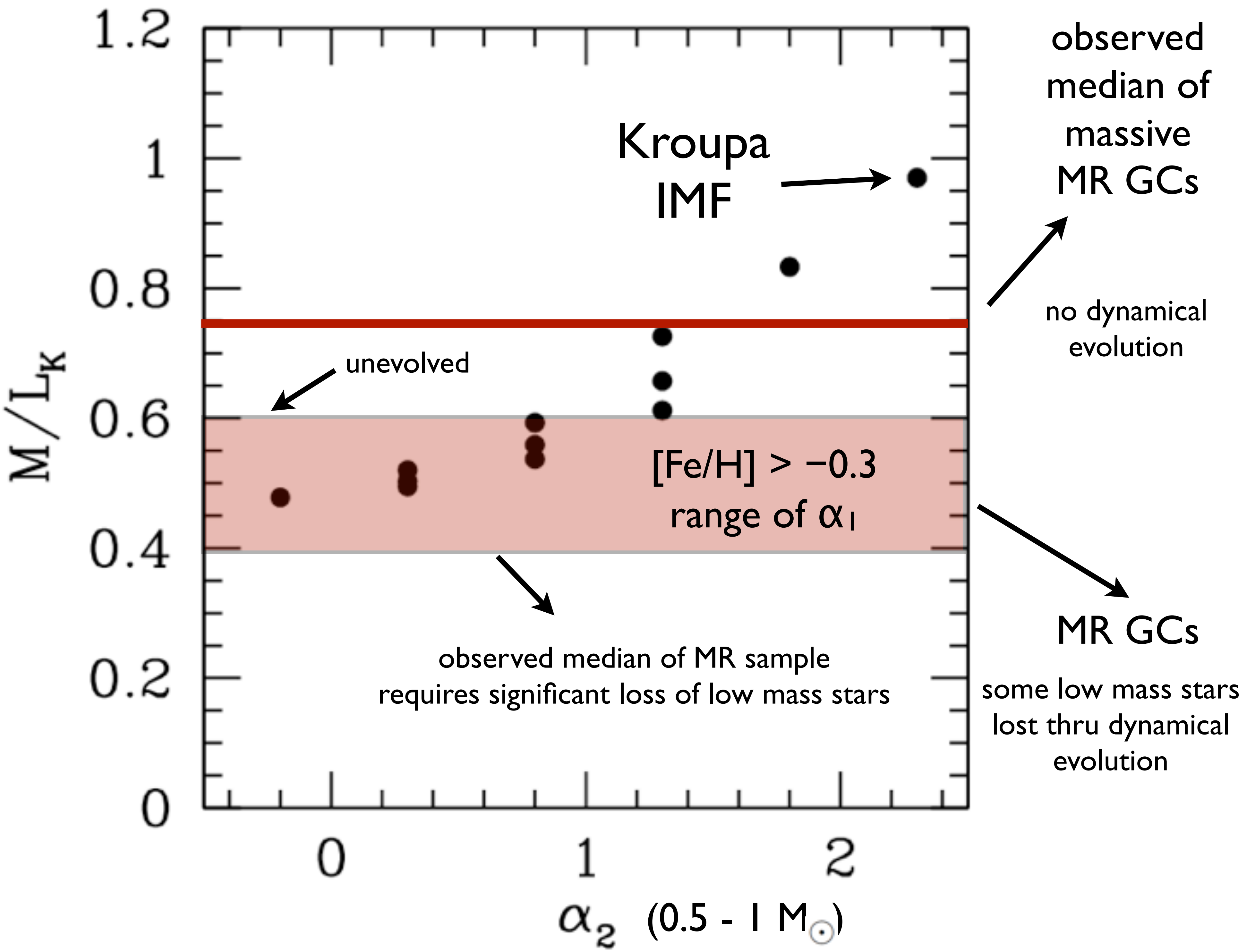
$dN/dM \propto M^{-\alpha}$

$\alpha_1 < 0.5\ M_\odot$,

$0.5 < \alpha_2 < 1\ M_\odot$

$\alpha_3 > 1\ M_\odot$

- Conroy & Gunn (2010) model predictions for range of α_1 and α_2 ($\alpha_3 \equiv 2.3$)



Conclude: Metal-rich globular clusters are surprisingly deficient in low-mass stars

One explanation is a shallow IMF in MR GCs of the form:

$$dN/dM \propto M^{-0.8} - M^{-1.3}$$

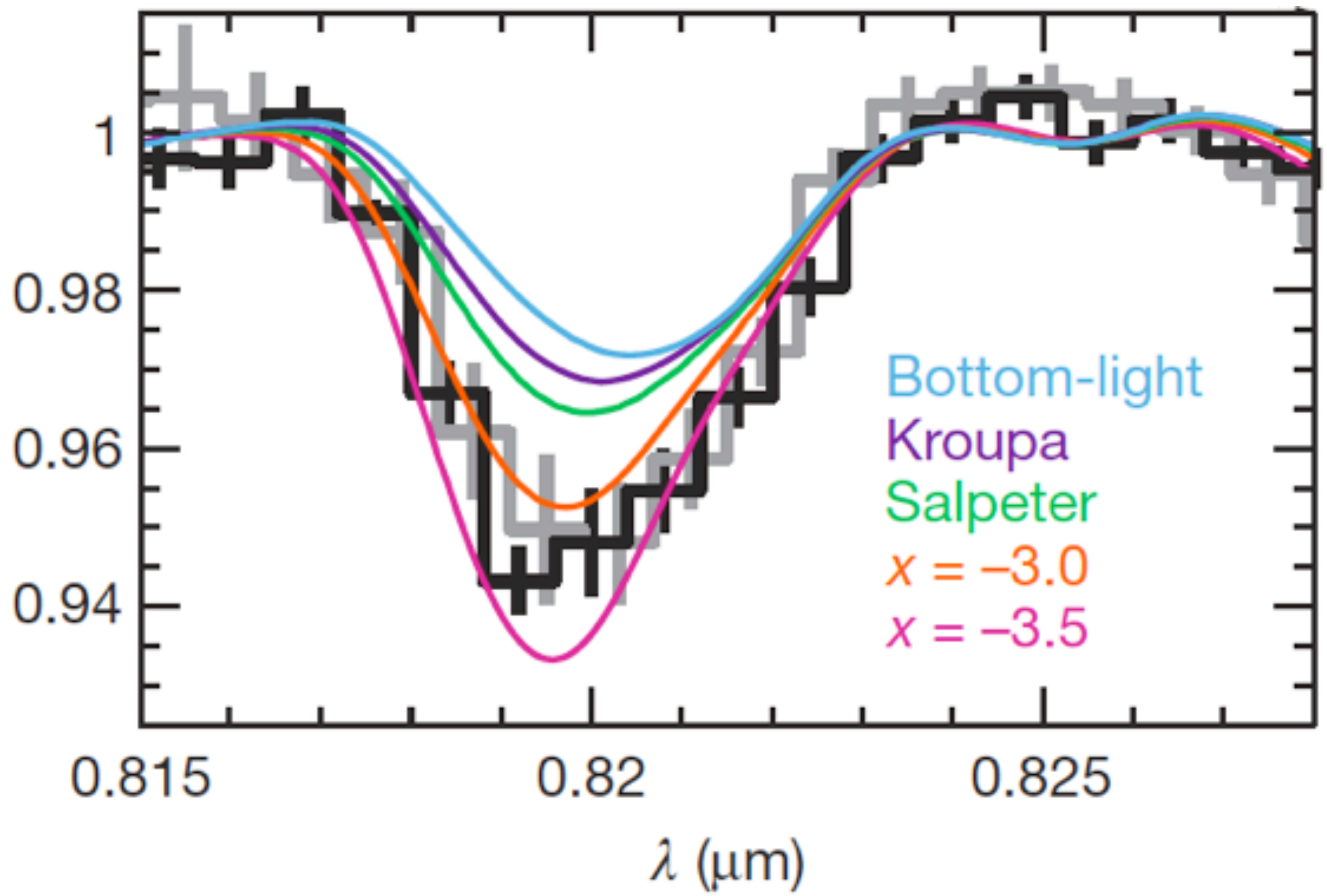
(or non-standard dynamical evolution??)

Other MF results

Virgo and Coma giant ellipticals have top heavy IMFs
M31 MR GCs are bottom light

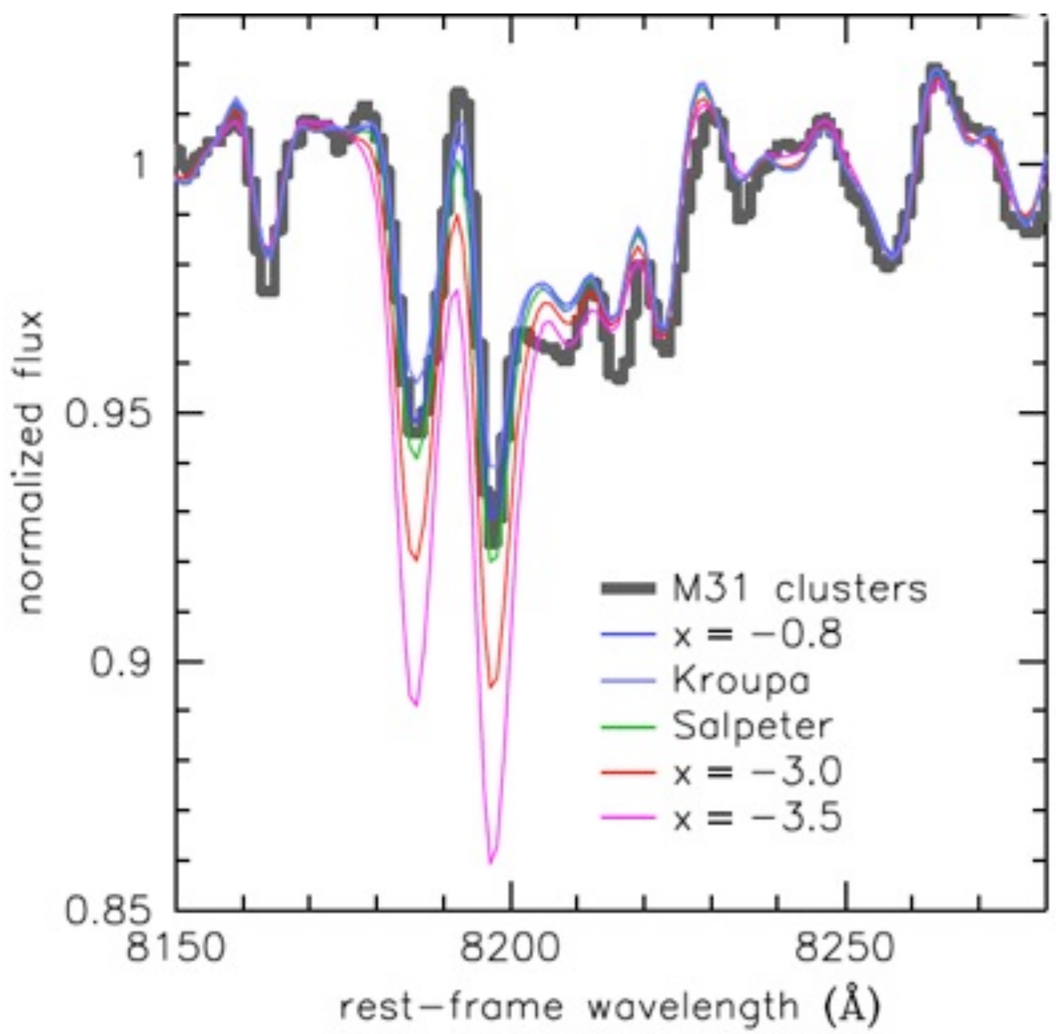
Elliptical Galaxies

van Dokkum & Conroy (2010)



M31 GCs

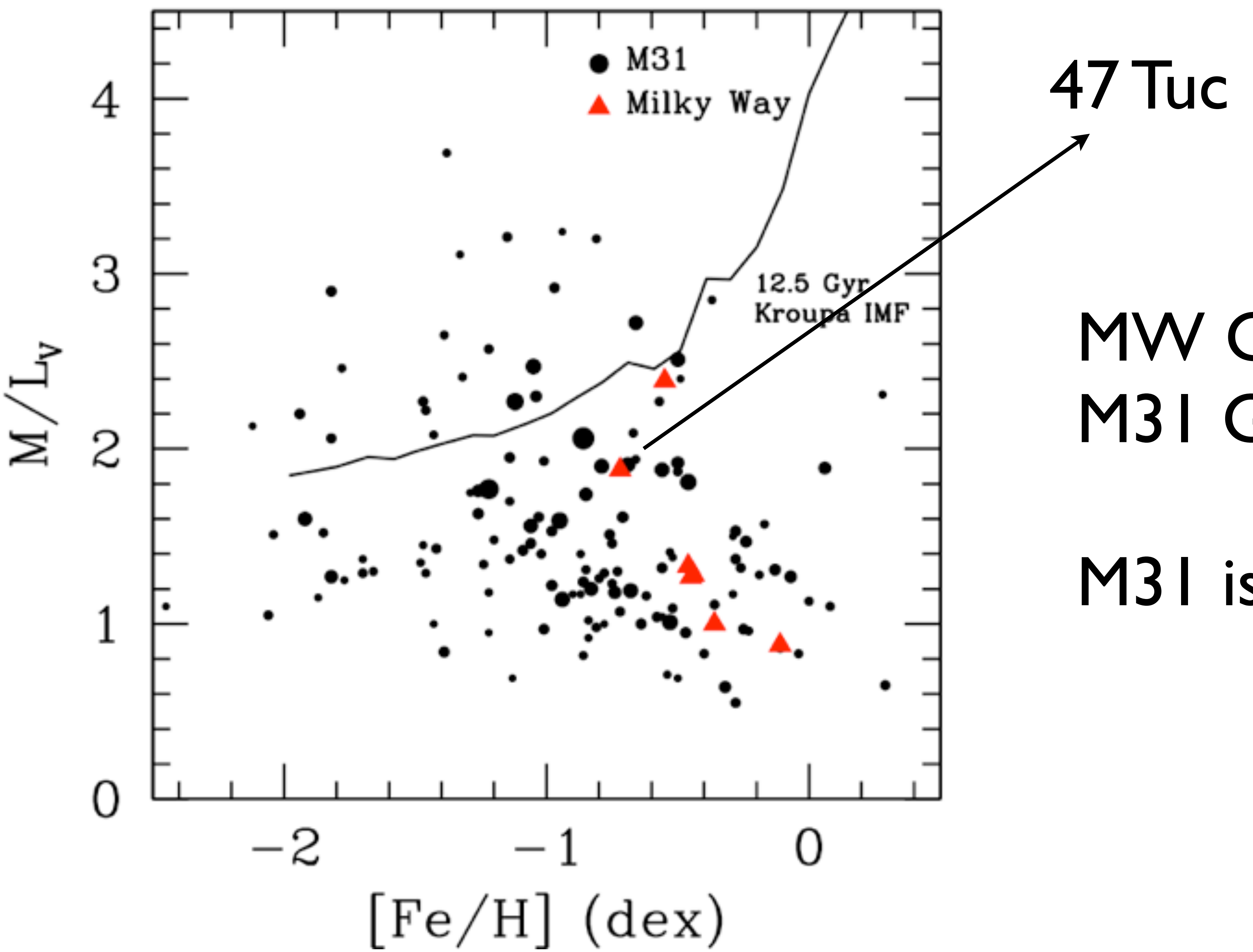
van Dokkum & Conroy (2011)



MFs in MR GCs and massive elliptical galaxies are different?

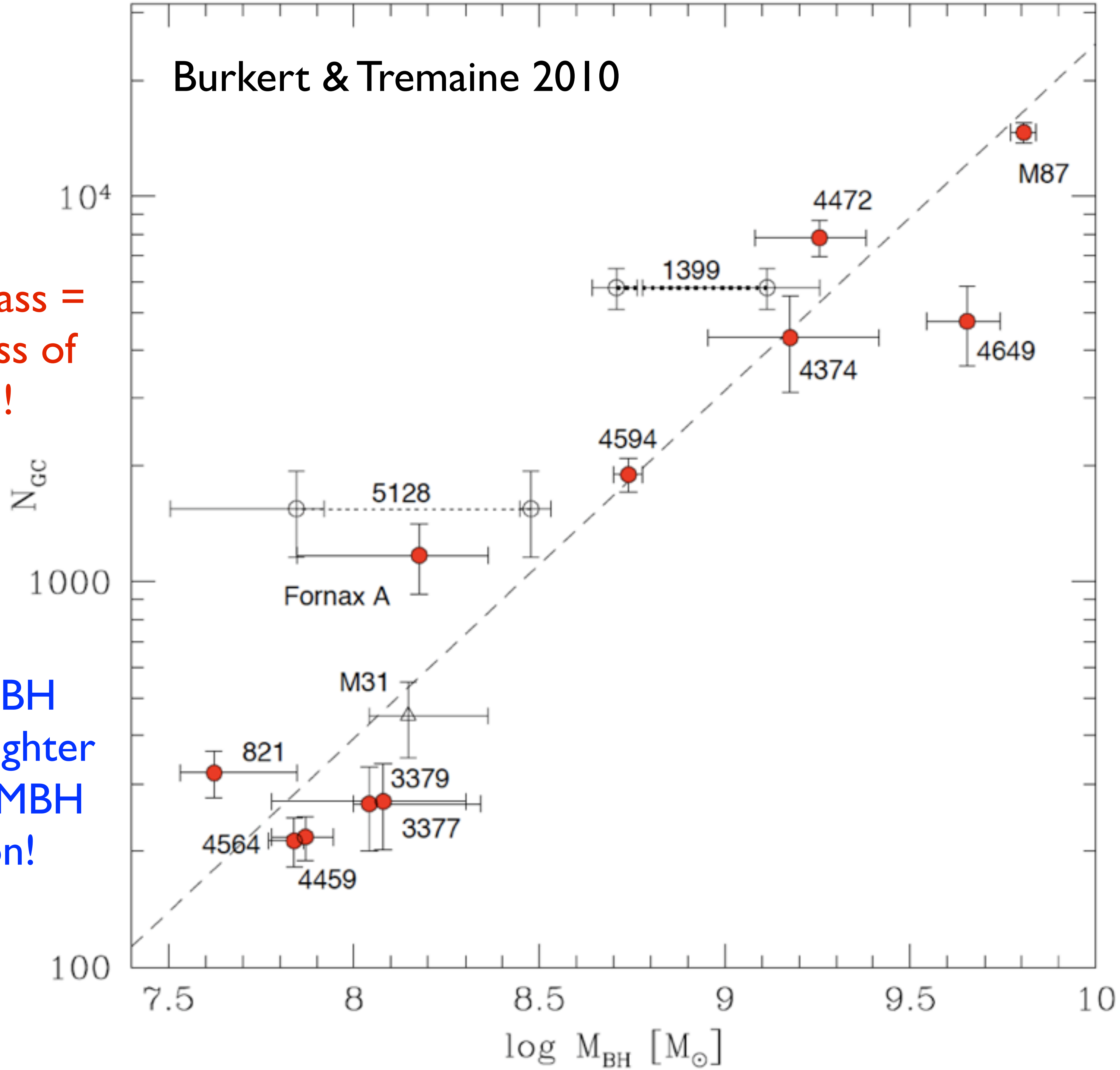
Milky Way GCs

Few MR GCs with dynamical measurements



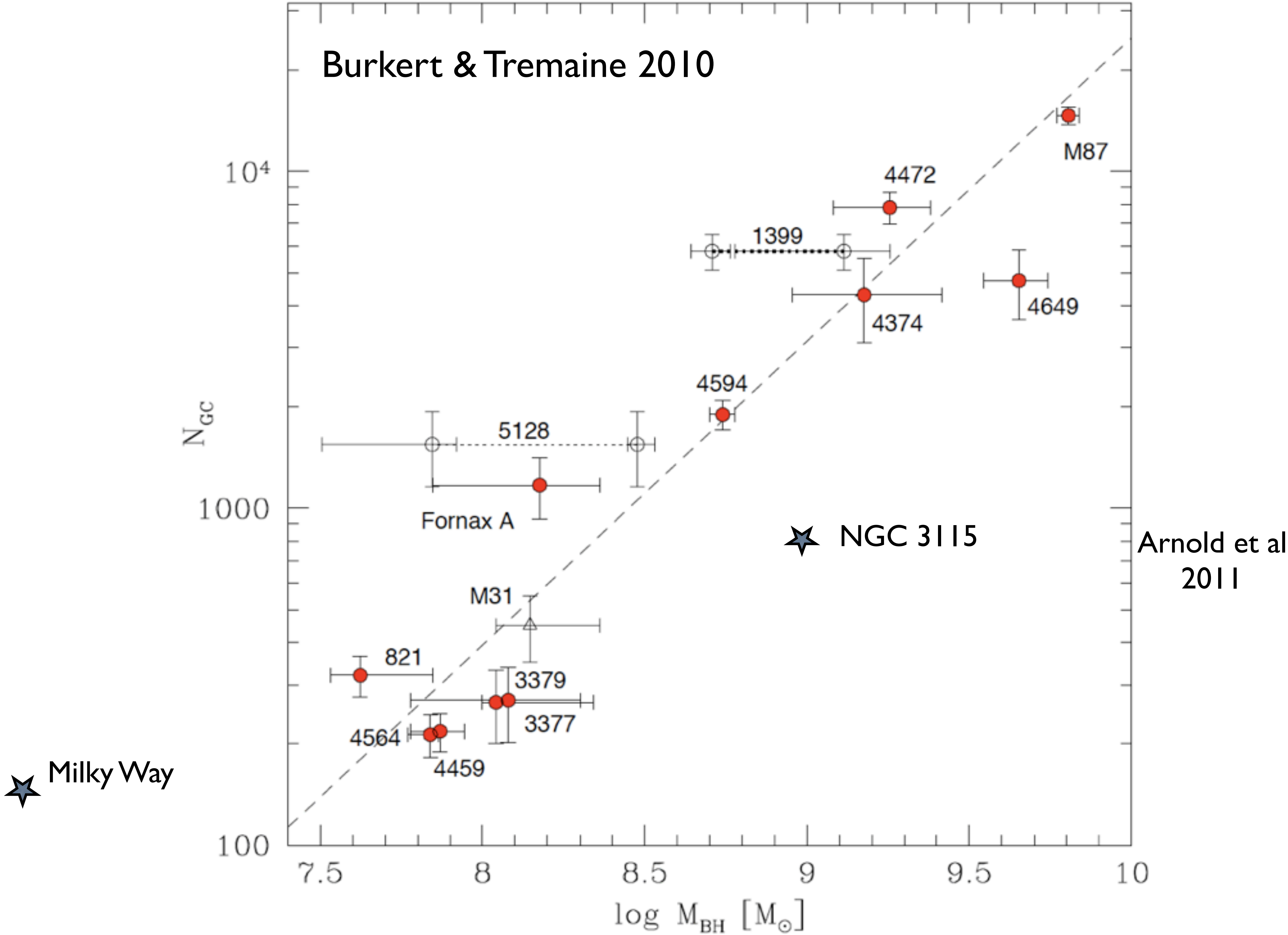
MW GCs look like M31 GCs

M31 isn't weird!



SMBH mass = total mass of GCs !

GC-SMBH relation tighter than σ-SMBH relation!


Burkert & Tremaine 2010
N_{GC}
10^4
1000
100
7.5
8
8.5
9
9.5
10
log M_{BH} [$M_\odot$]
M87
4472
1399
4649
4374
4594
5128
Fornax A
NGC 3115
Arnold et al 2011
M31
821
3379
3377
4564
4459
Milky Way

Conclusions

M31 GC system is *similar* to MW's

- Similar range (x 100) in [Fe/H]
- Similar (exclusively old) ages
- Similar individual element abundance ratios
- No self-enrichment
- MR population traces build up of bulge
- MPGCs trace MP halo
  - and offer the *only way* to study MP halos beyond the LG
- M/L declines with increasing metallicity (orthogonal to SSP model predictions)
  → Shallow (I)MF − opposite to E galaxy results

M31 GC system is *different* from MW's

- Slightly higher mean [Fe/H], but consistent with GC − host galaxy scaling relations
- M 31 is not obviously bimodal in [Fe/H] → different formation for MW and M31
- Hints of trimodality in M31 may indicate more complex accretion history
- Hosts faint extended clusters
- MW does not "play" N_{GC}−SMBH game, but M31 does

GCs are great tools for tracing the star formation and assembly histories of galaxies !