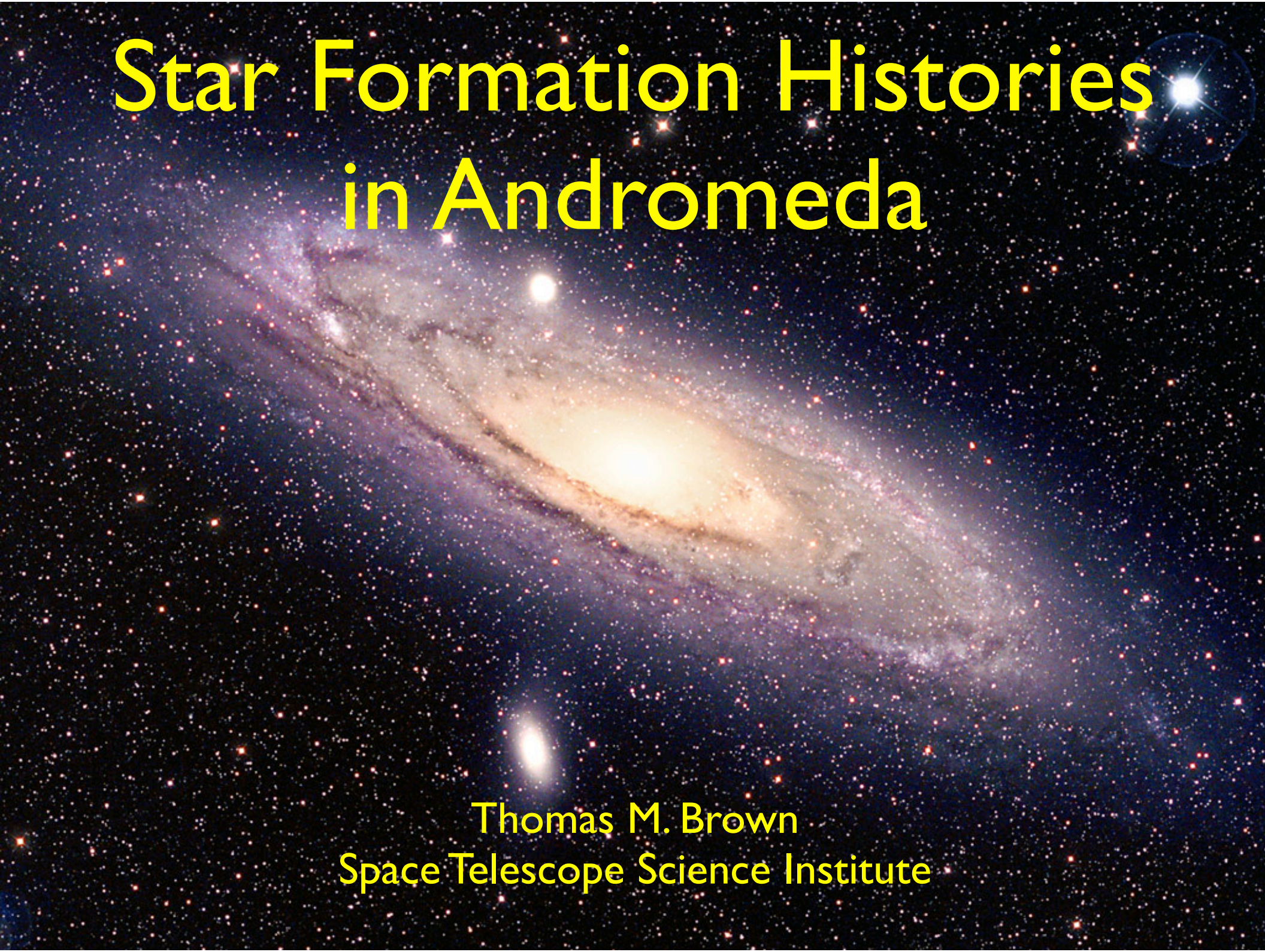

Star Formation Histories in Andromeda

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Collaborators

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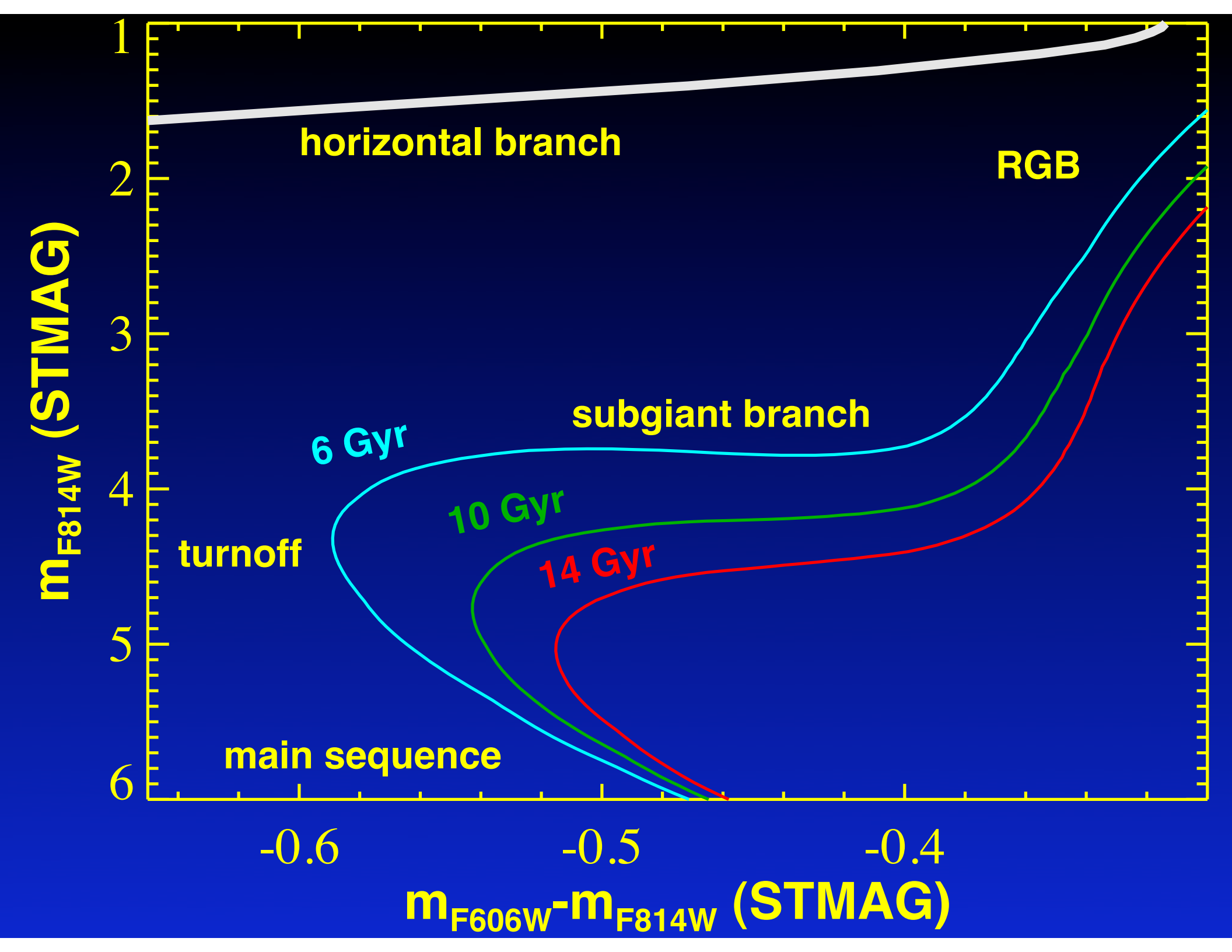
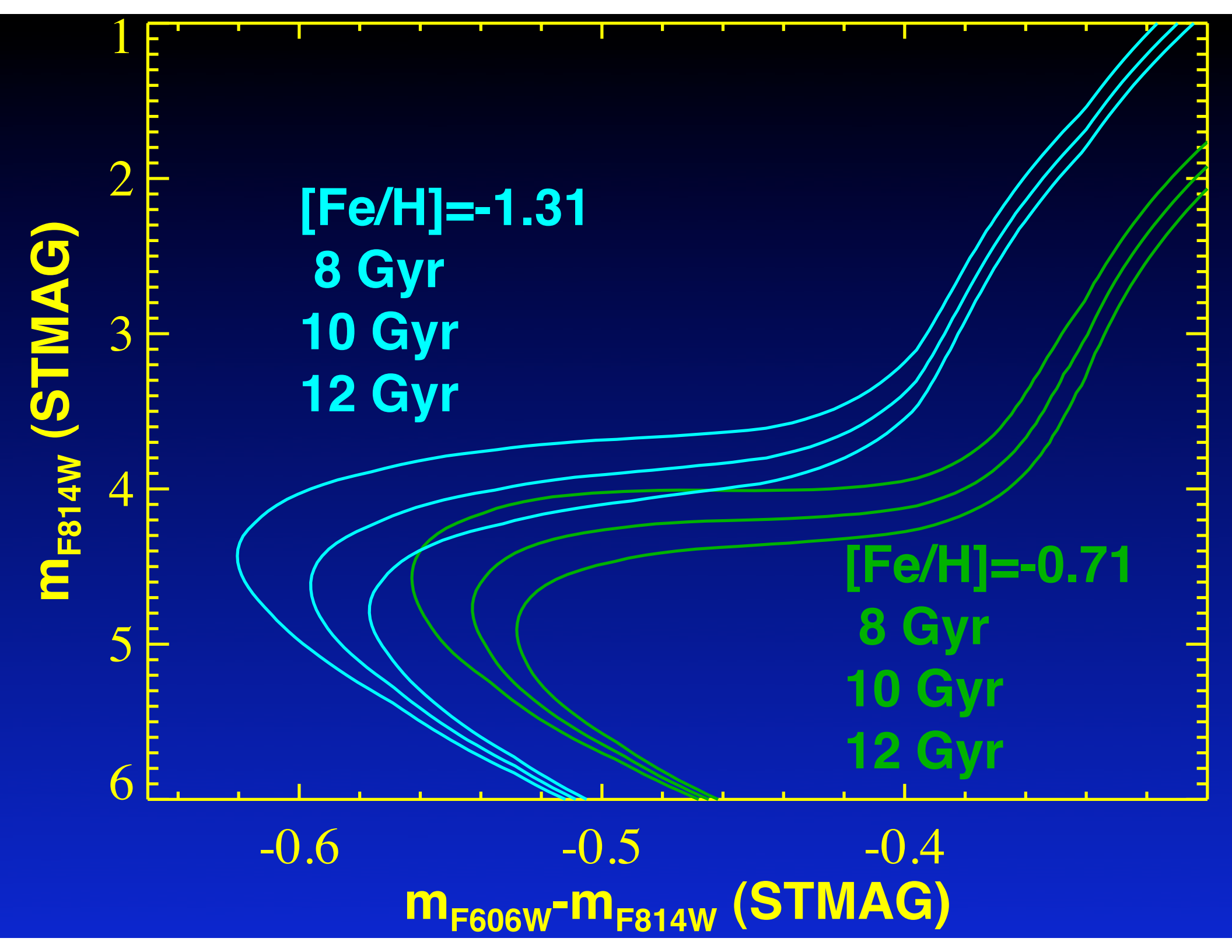
K. Gilbert, R.M. Rich, D. Reitzel, A. Koch, A. Sweigart,
R. Kimble, A. Renzini, M. Geha, D. VandenBerg,
E. Kirby, R. Munoz, J. Simon, R. Avila

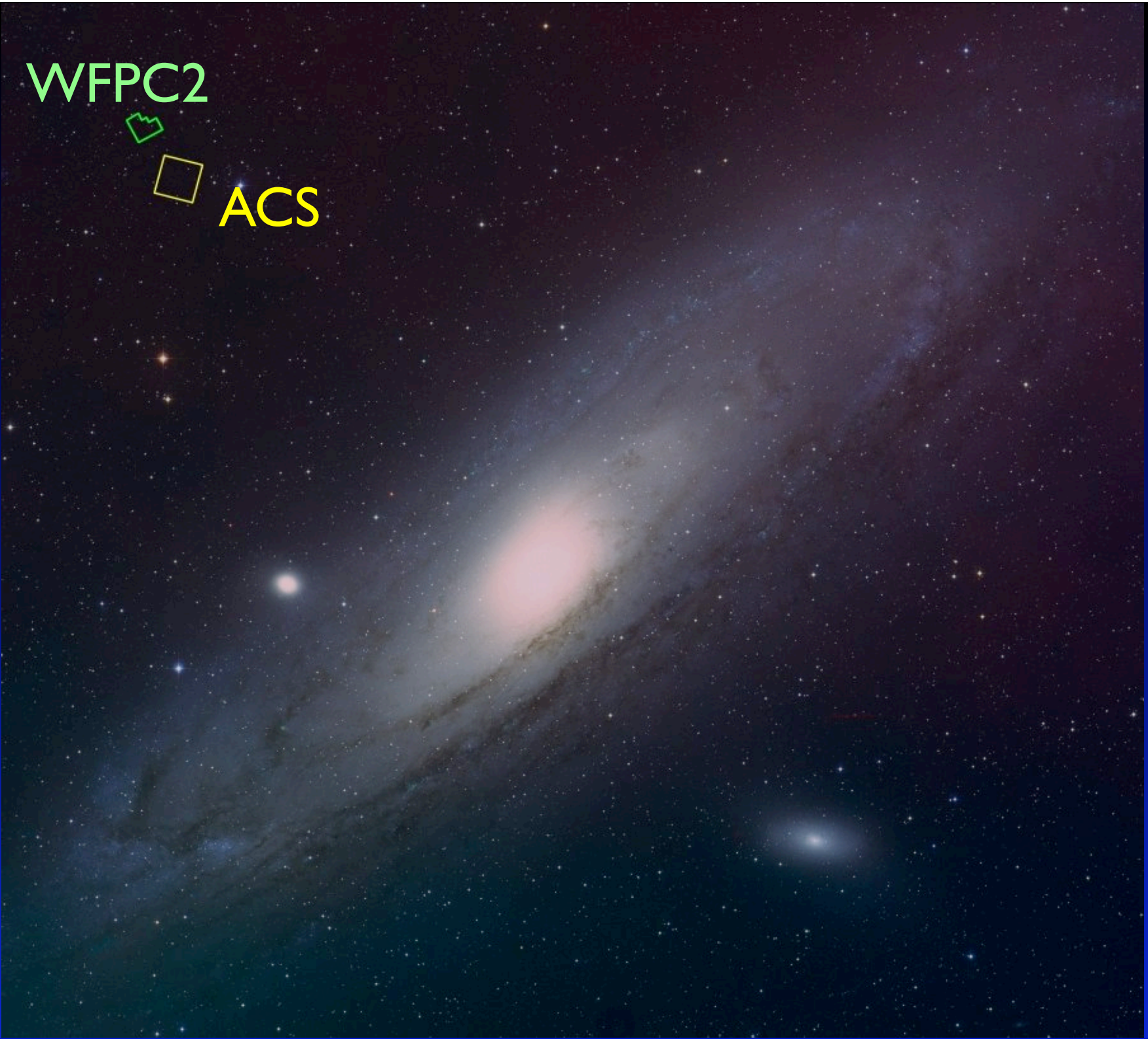
Courtesy of Jason Ware:
http://galaxyphoto.com

Stellar archaeology in nearby galaxies

- The most direct age diagnostic comes from resolving both the dwarf and giant stars, including the "main sequence turnoff"
- In the 1950s, this technique was applied to star clusters in our own Galaxy
- In the 1990s, such studies were expanded to the satellite galaxies of the Milky Way
- With the launch of the Advanced Camera for Surveys (ACS) on Hubble, it became feasible to apply this technique in populations 1 Mpc away (Andromeda)

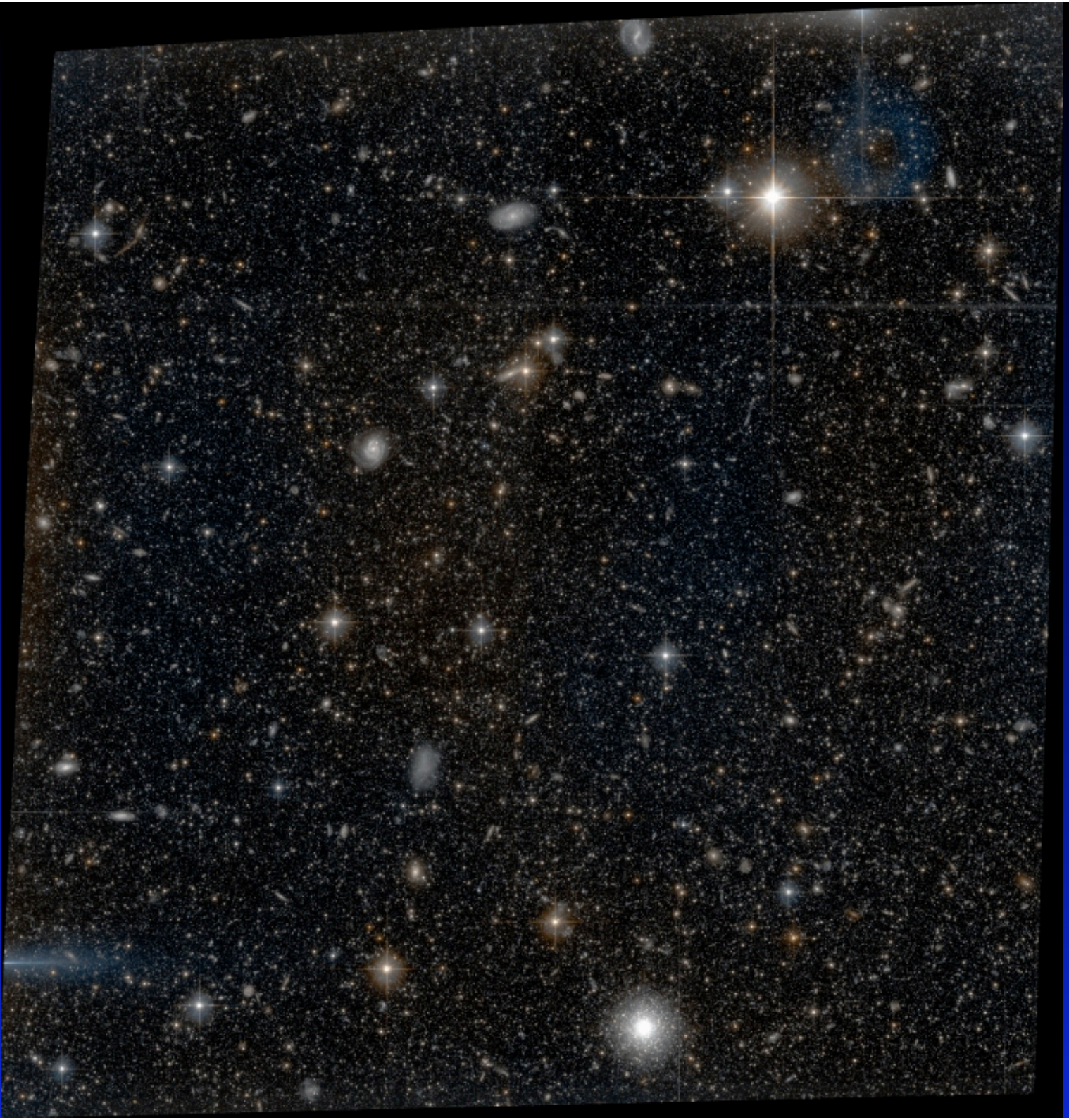

horizontal branch
RGB
subgiant branch
6 Gyr
10 Gyr
14 Gyr
turnoff
main sequence
1
2
3
4
5
6
-0.6
-0.5
-0.4
m_{F814W} (STMAG)
m_{F606W}-m_{F814W} (STMAG)


[Fe/H]=-1.31
8 Gyr
10 Gyr
12 Gyr
[Fe/H]=-0.71
8 Gyr
10 Gyr
12 Gyr
1
2
3
4
5
6
-0.6
-0.5
-0.4
m_{F814W} (STMAG)
m_{F606W}-m_{F814W} (STMAG)



First M31 deep field

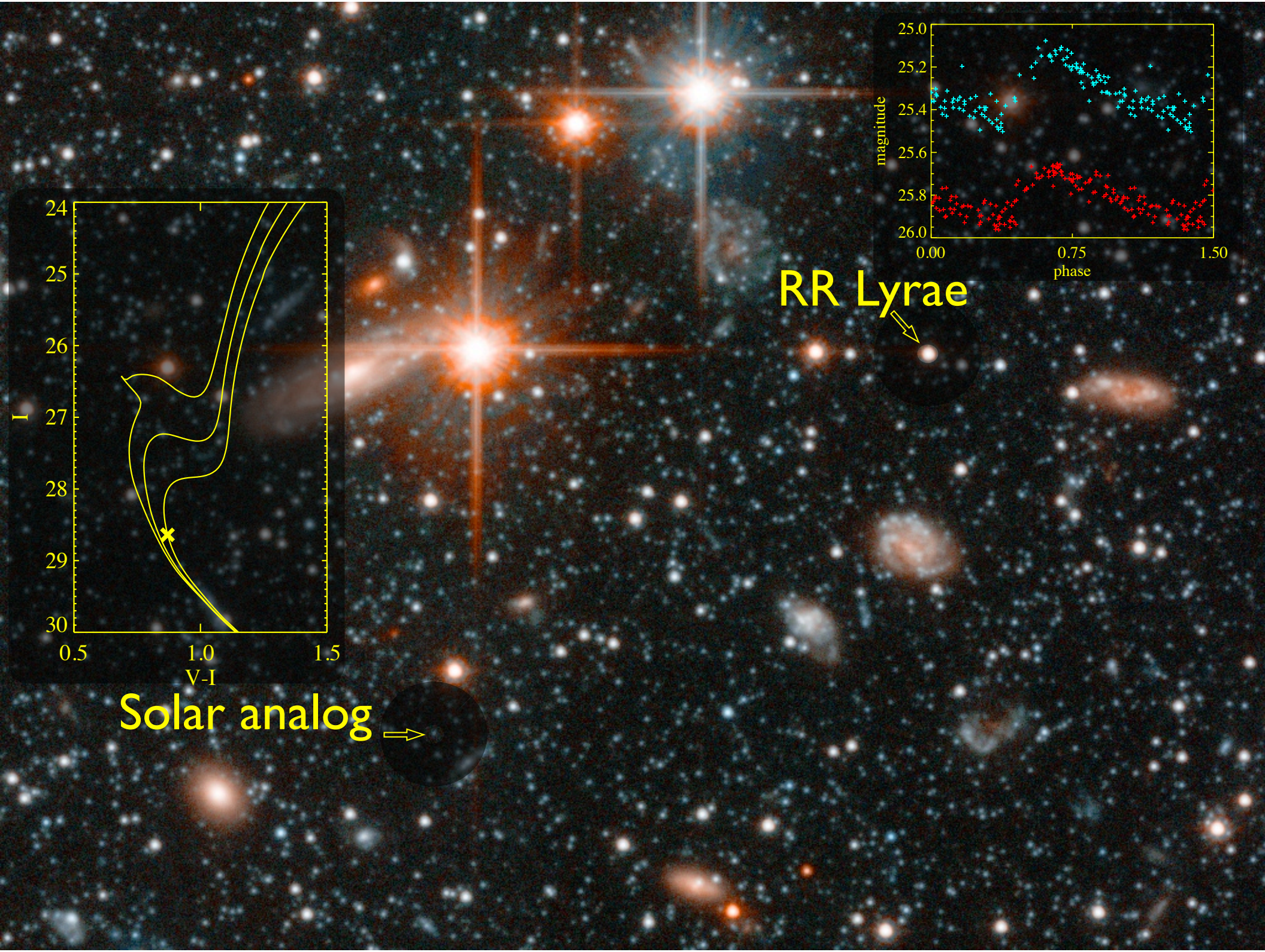
51 arcmin (11 kpc) from nucleus



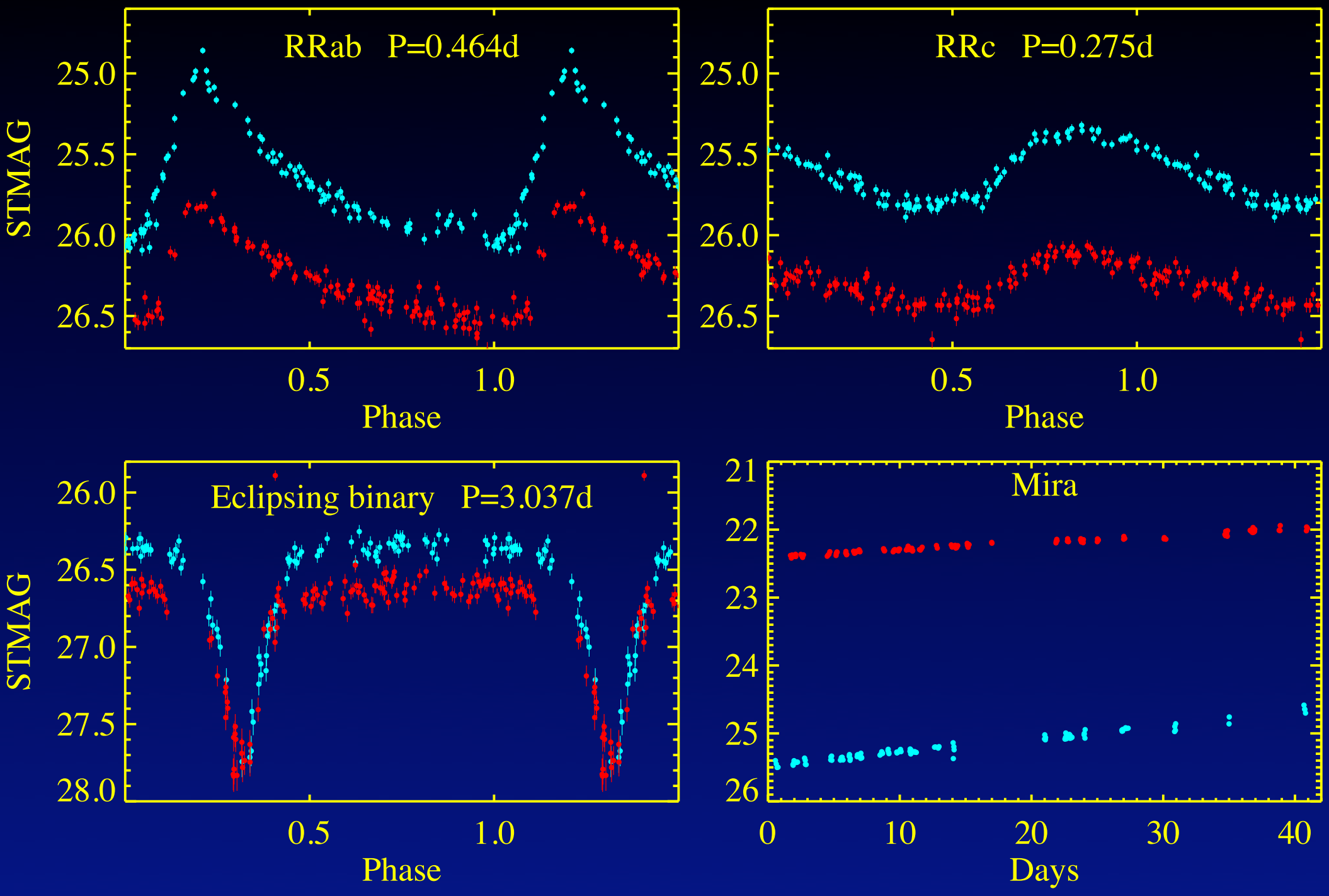
M31 halo
(11 kpc)

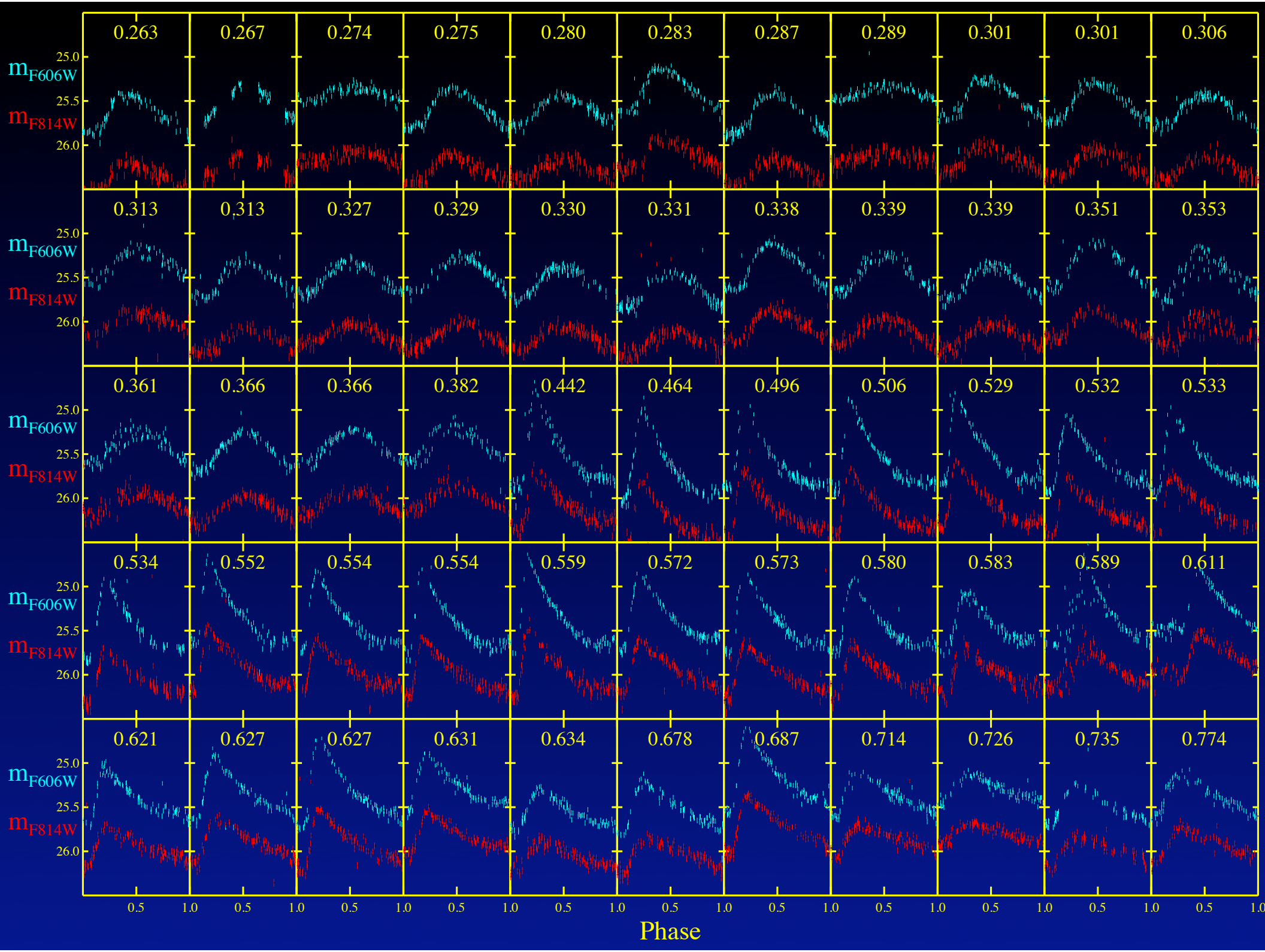
210 x 210
arcsec

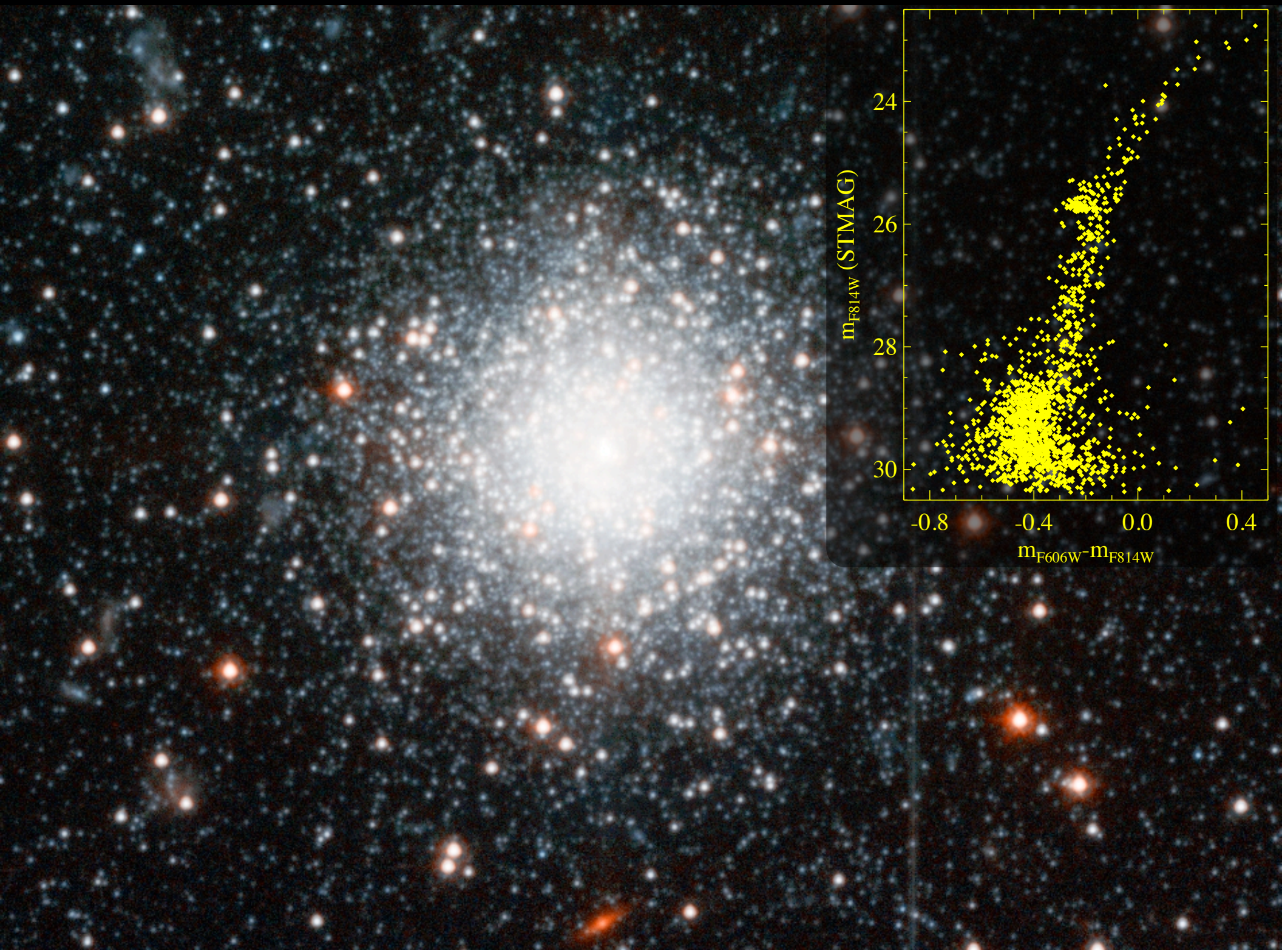
800 x 800 pc

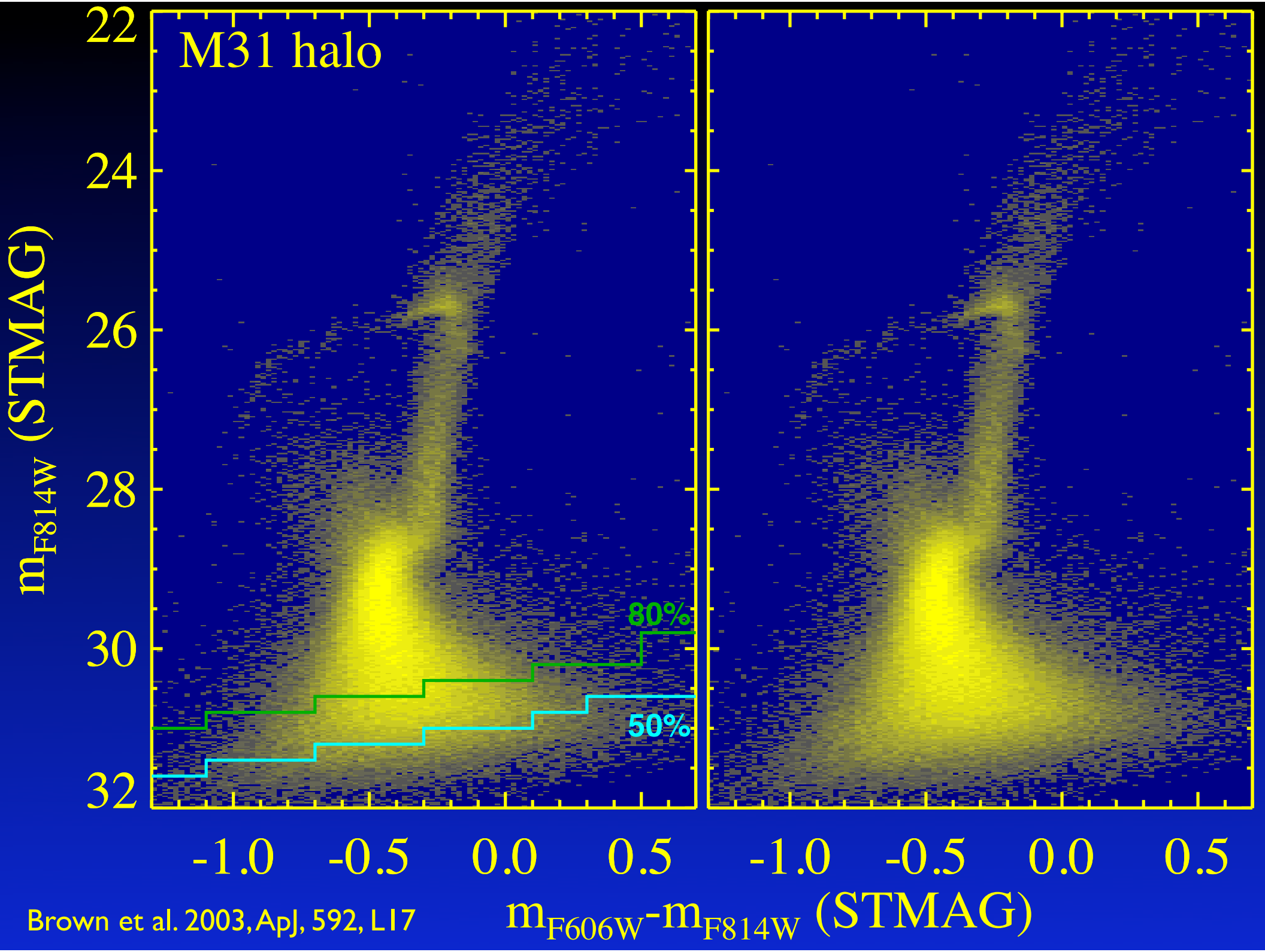

24
25
26
27
28
29
30
I
0.5
1.0
1.5
V-I
Solar analog
25.0
25.2
25.4
25.6
25.8
26.0
magnitude
0.00
0.75
1.50
phase
RR Lyrae

Brown et al. 2004, AJ, 127, 2738; Jeffery et al. 2011, AJ, 141, 171

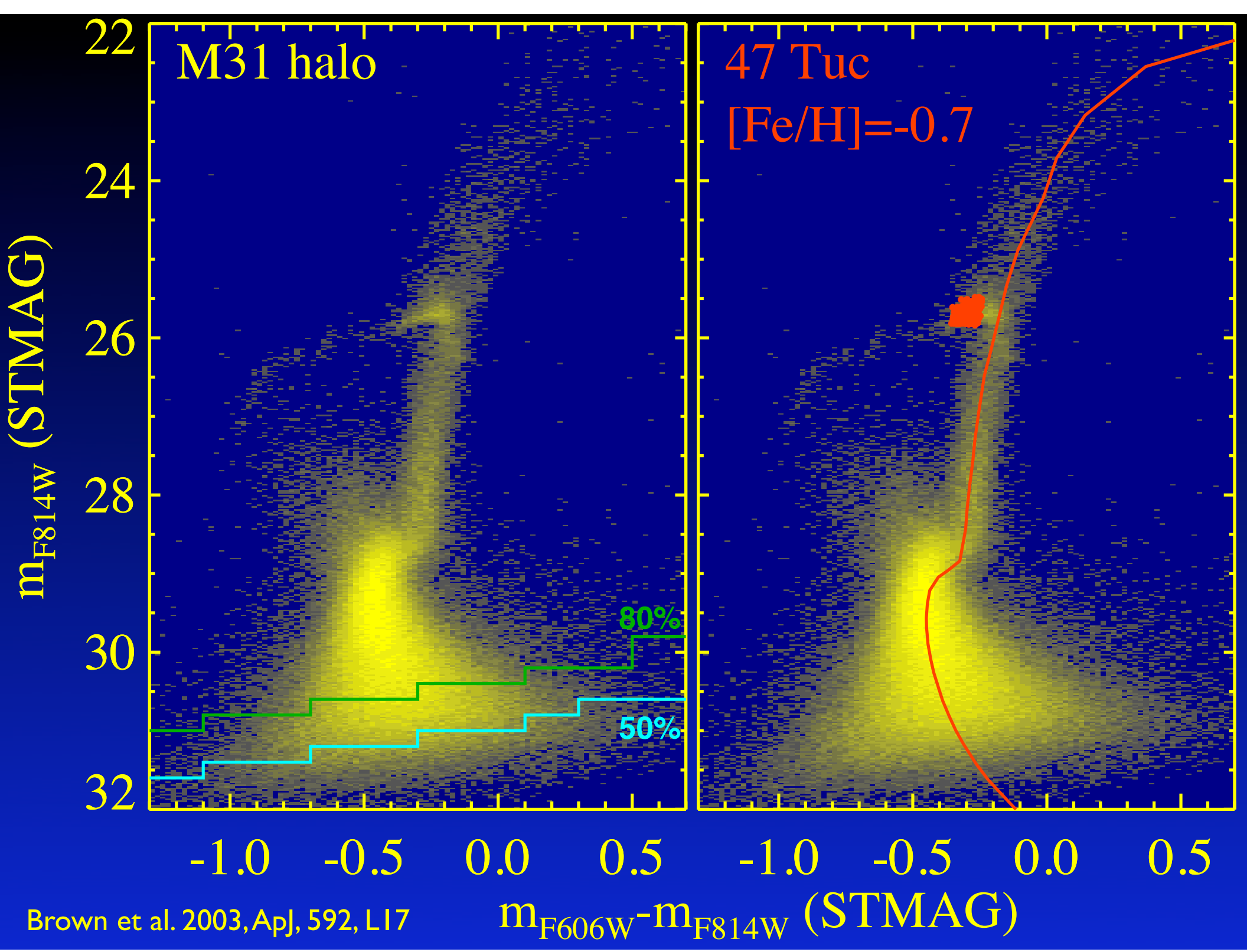



0.263
0.267
0.274
0.275
0.280
0.283
0.287
0.289
0.301
0.301
0.306
0.313
0.313
0.327
0.329
0.330
0.331
0.338
0.339
0.339
0.351
0.353
0.361
0.366
0.366
0.382
0.442
0.464
0.496
0.506
0.529
0.532
0.533
0.534
0.552
0.554
0.554
0.559
0.572
0.573
0.580
0.583
0.589
0.611
0.621
0.627
0.627
0.631
0.634
0.678
0.687
0.714
0.726
0.735
0.774
m_F606W
m_F814W
25.0
25.5
26.0
0.5
1.0
Phase

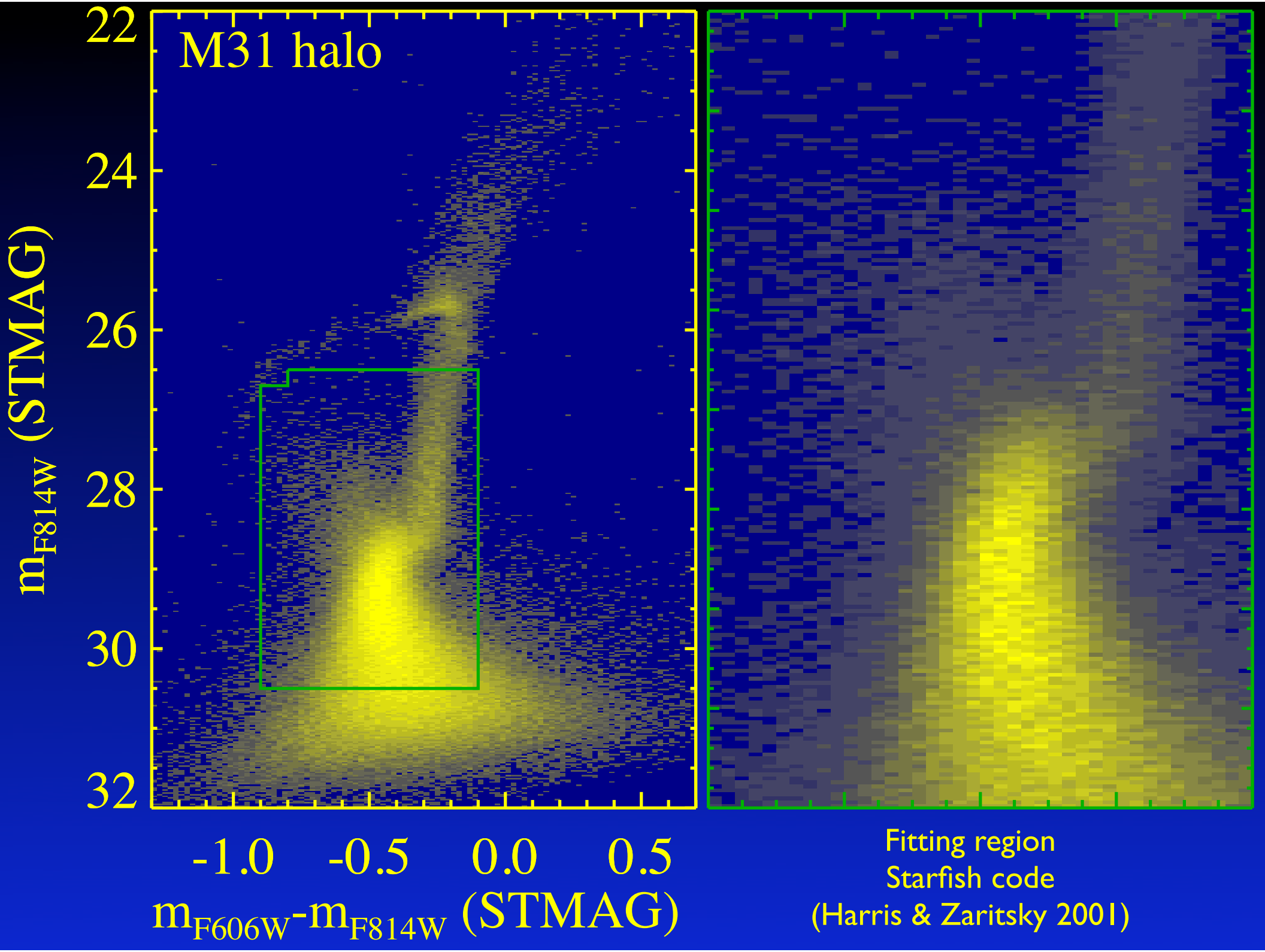

24
26
28
30
m_{F814W} (STMAG)
-0.8
-0.4
0.0
0.4
m_{F606W}-m_{F814W}

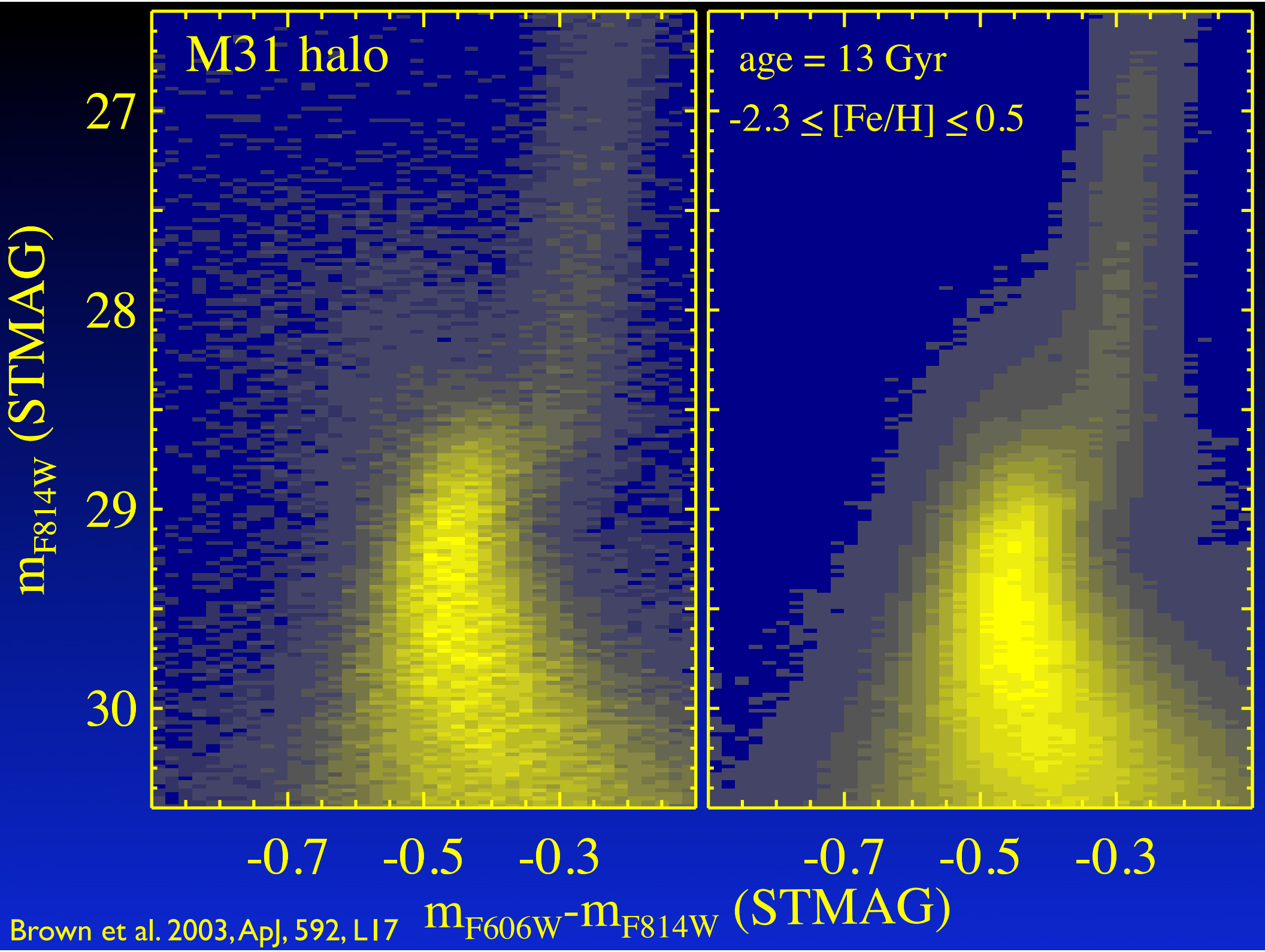


Brown et al. 2003, ApJ, 592, L17

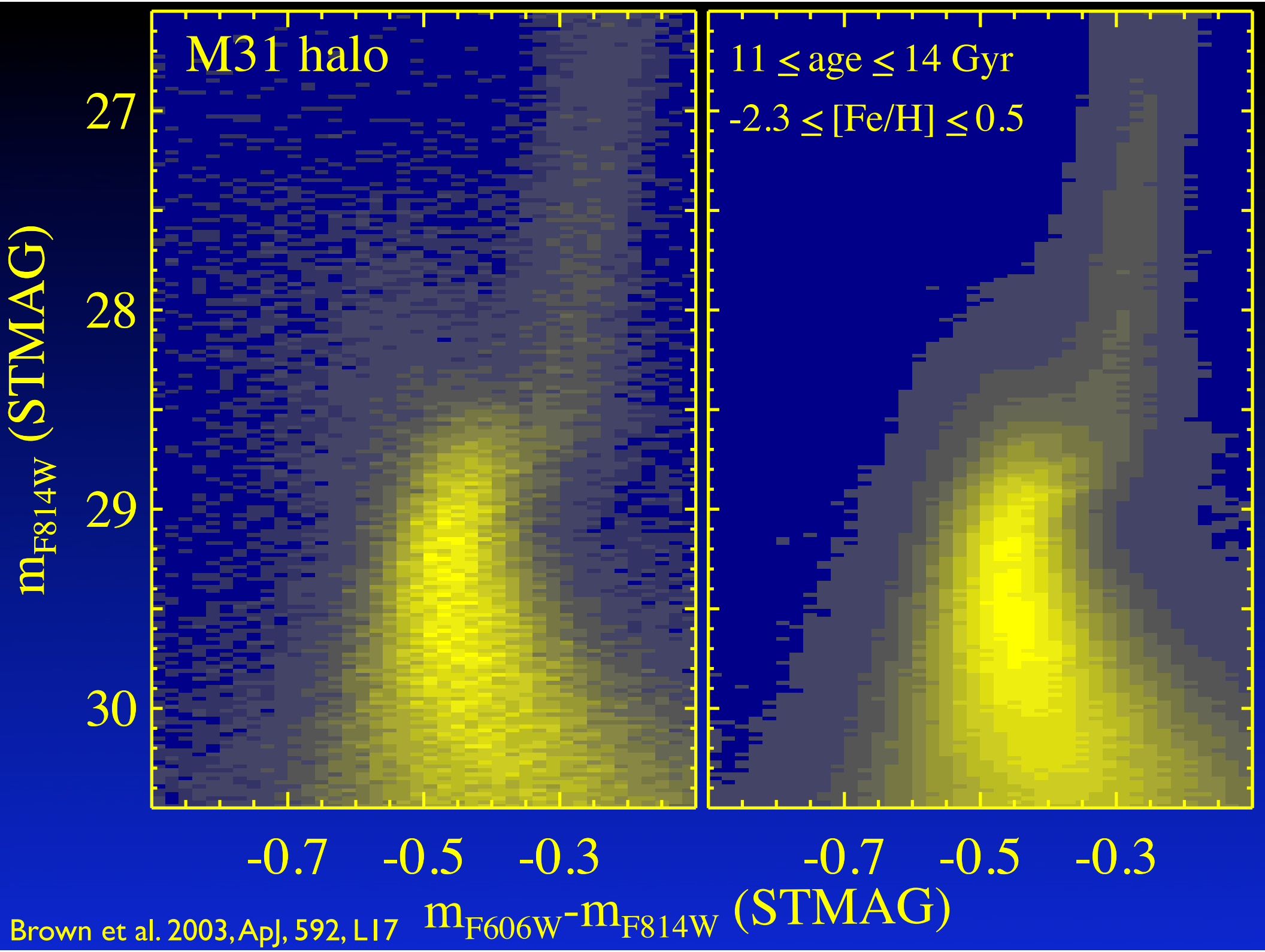


Brown et al. 2003, ApJ, 592, L17

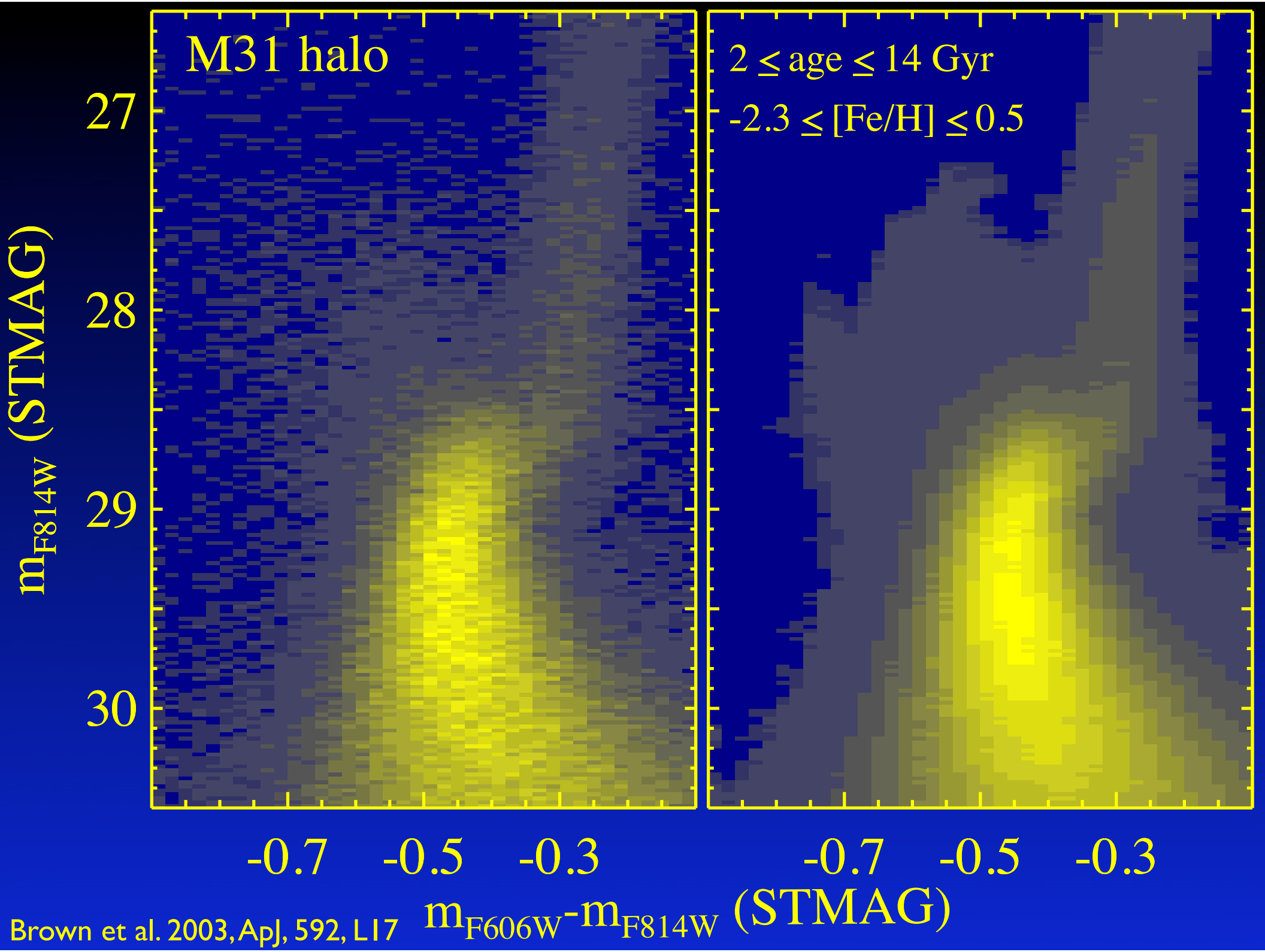

M31 halo
22
24
26
28
30
32
m_{F814W} (STMAG)
-1.0
-0.5
0.0
0.5
m_{F606W}-m_{F814W} (STMAG)
Fitting region
Starfish code
(Harris & Zaritsky 2001)



Brown et al. 2003, ApJ, 592, L17

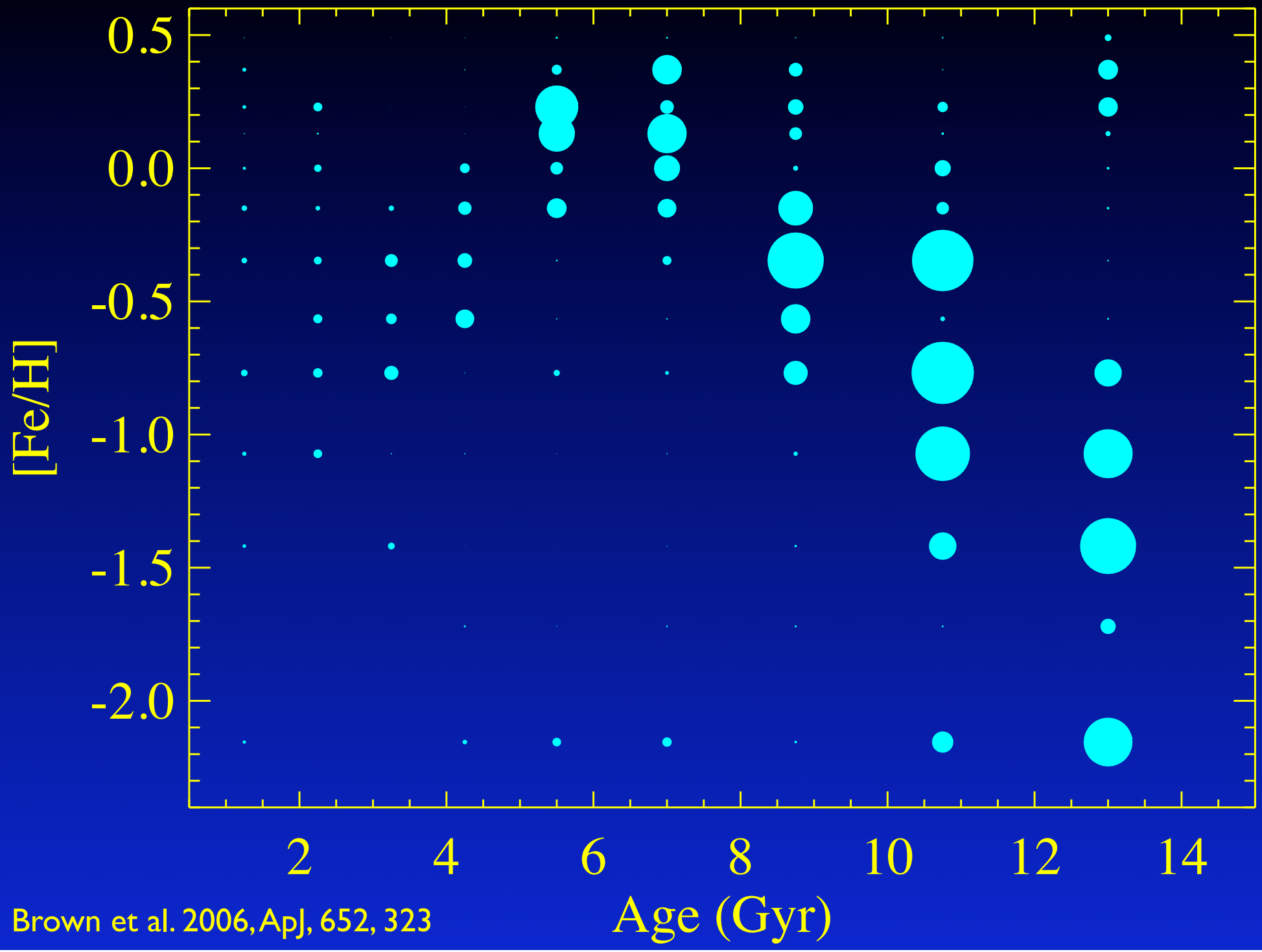


Brown et al. 2003, ApJ, 592, L17



Brown et al. 2003, ApJ, 592, L17

Halo Distribution in Age and Metallicity

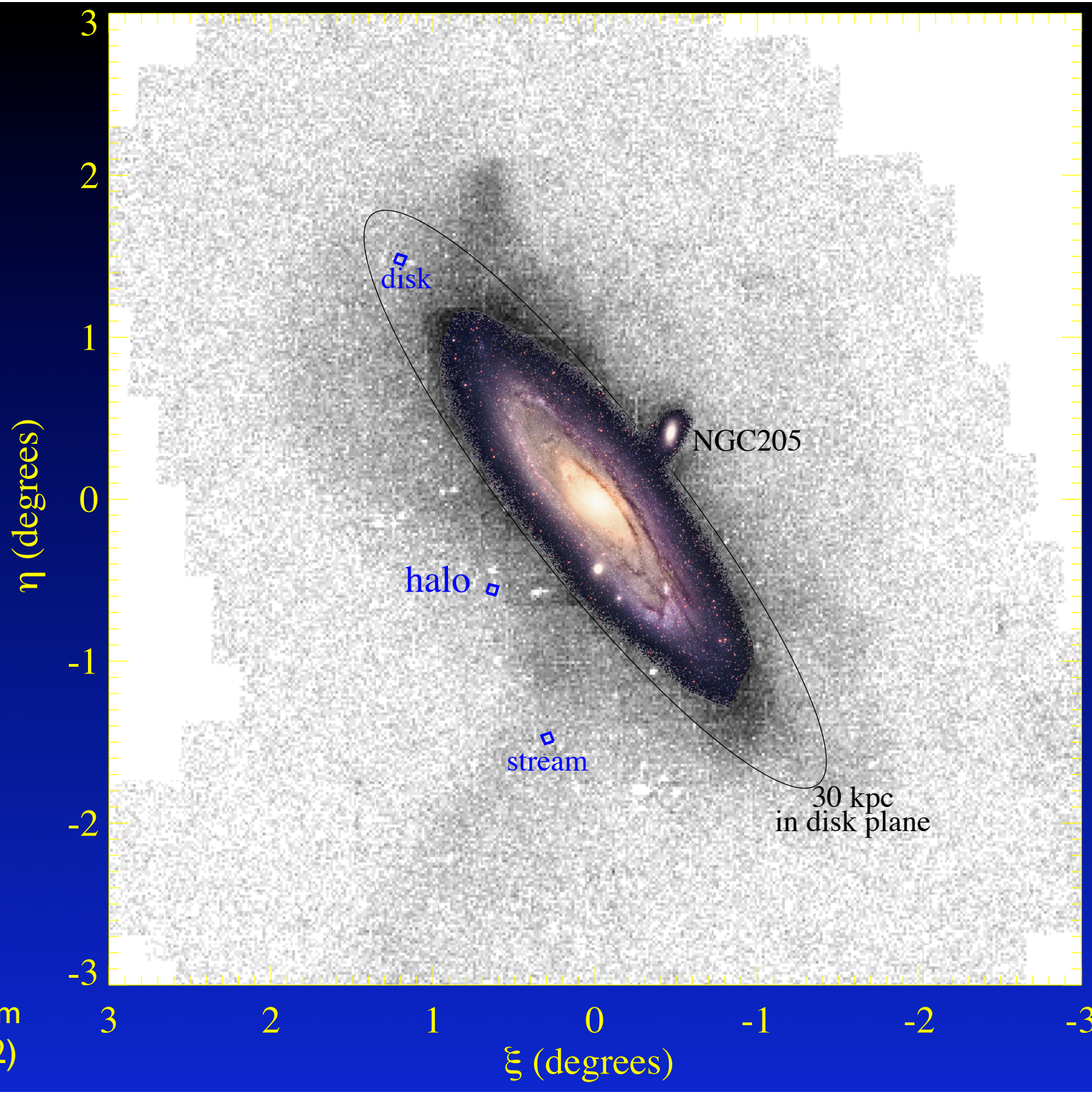


Brown et al. 2006, ApJ, 652, 323

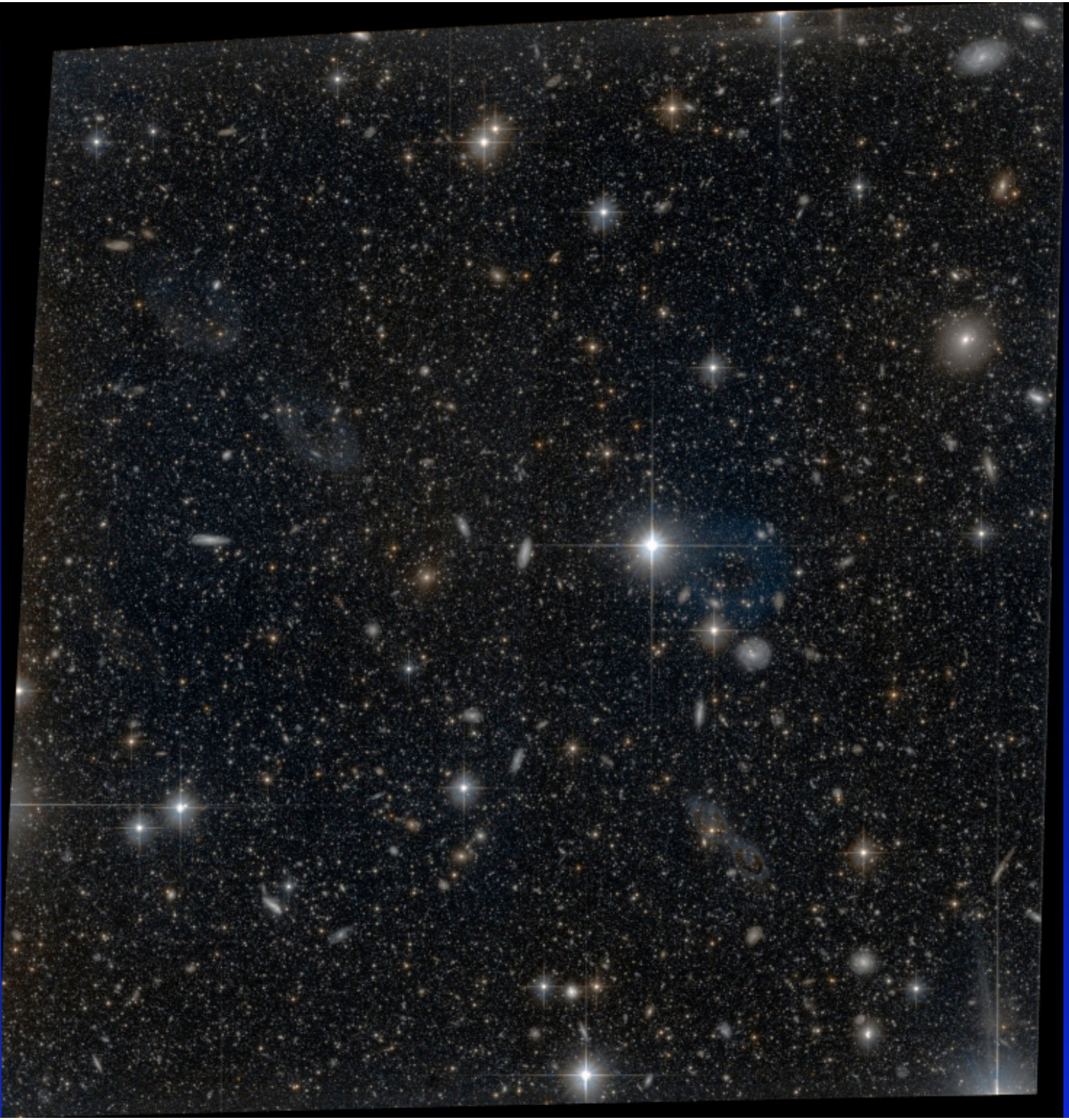
Mergers

- Best-fit model has 40% of the stellar mass younger than 10 Gyr and metal-rich
- Some of the stars belong to the textbook "old metal-poor population"
- At the time, we suggested the intermediate-age stars in the halo originated in a major merger or series of smaller mergers
- We now know what merger that was...

In 2004, we obtained deep fields in the tidal stream and outer disk



(star count map from Ferguson et al. 2002)



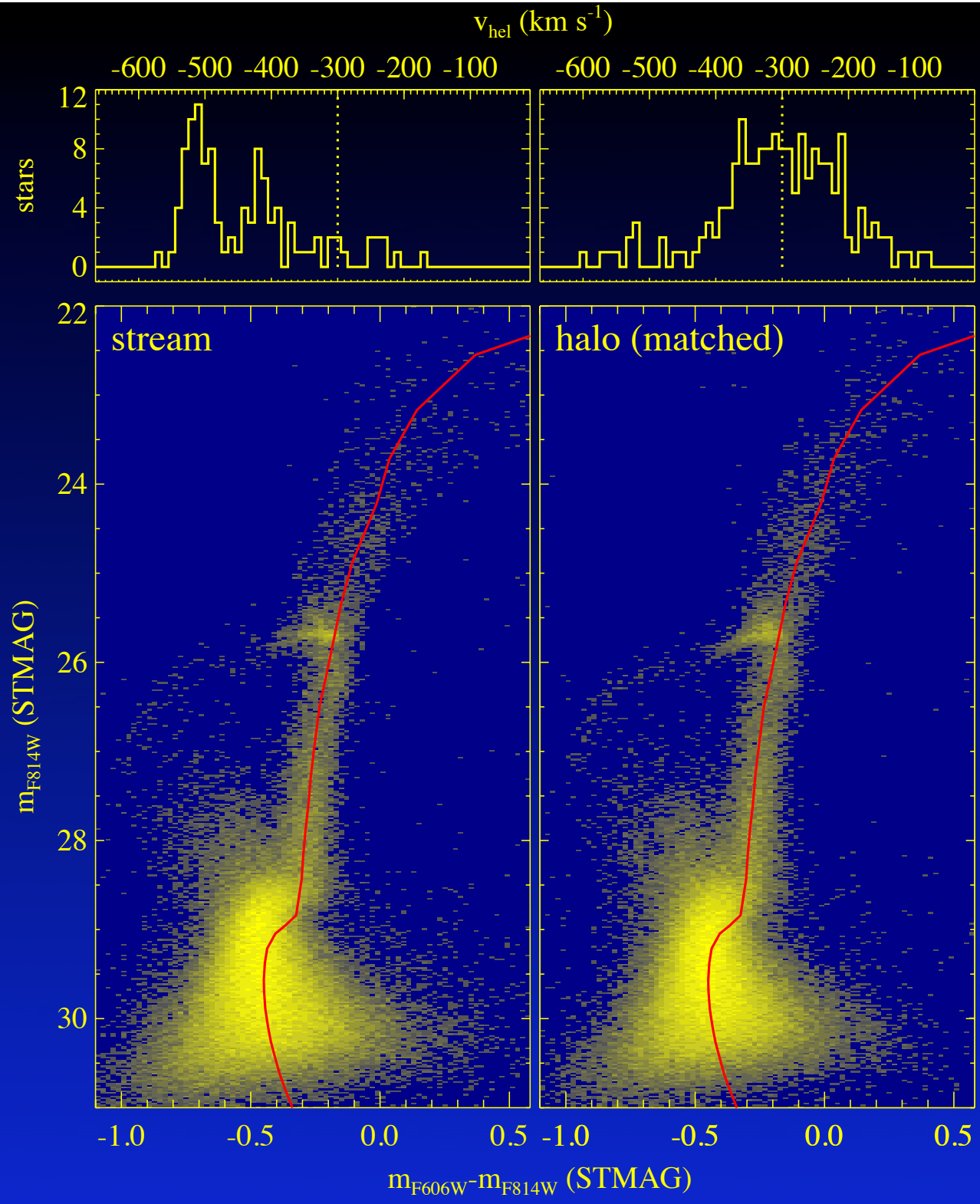
M31 stream
(20 kpc)

210 x 210
arcsec

800 x 800 pc

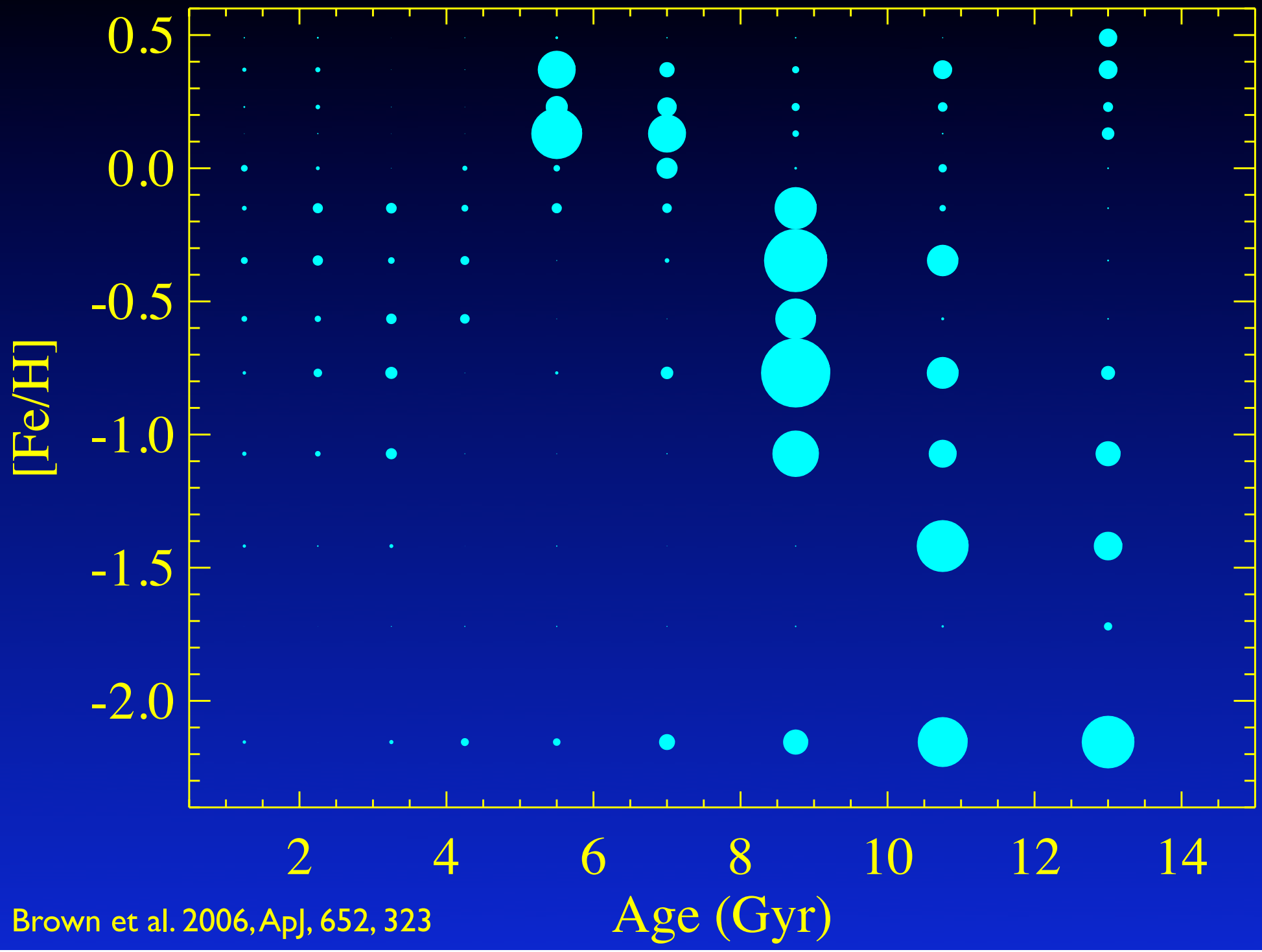
Distribution of velocities in stream and halo are distinct

Distribution of ages and metallicities in stream and halo are nearly identical



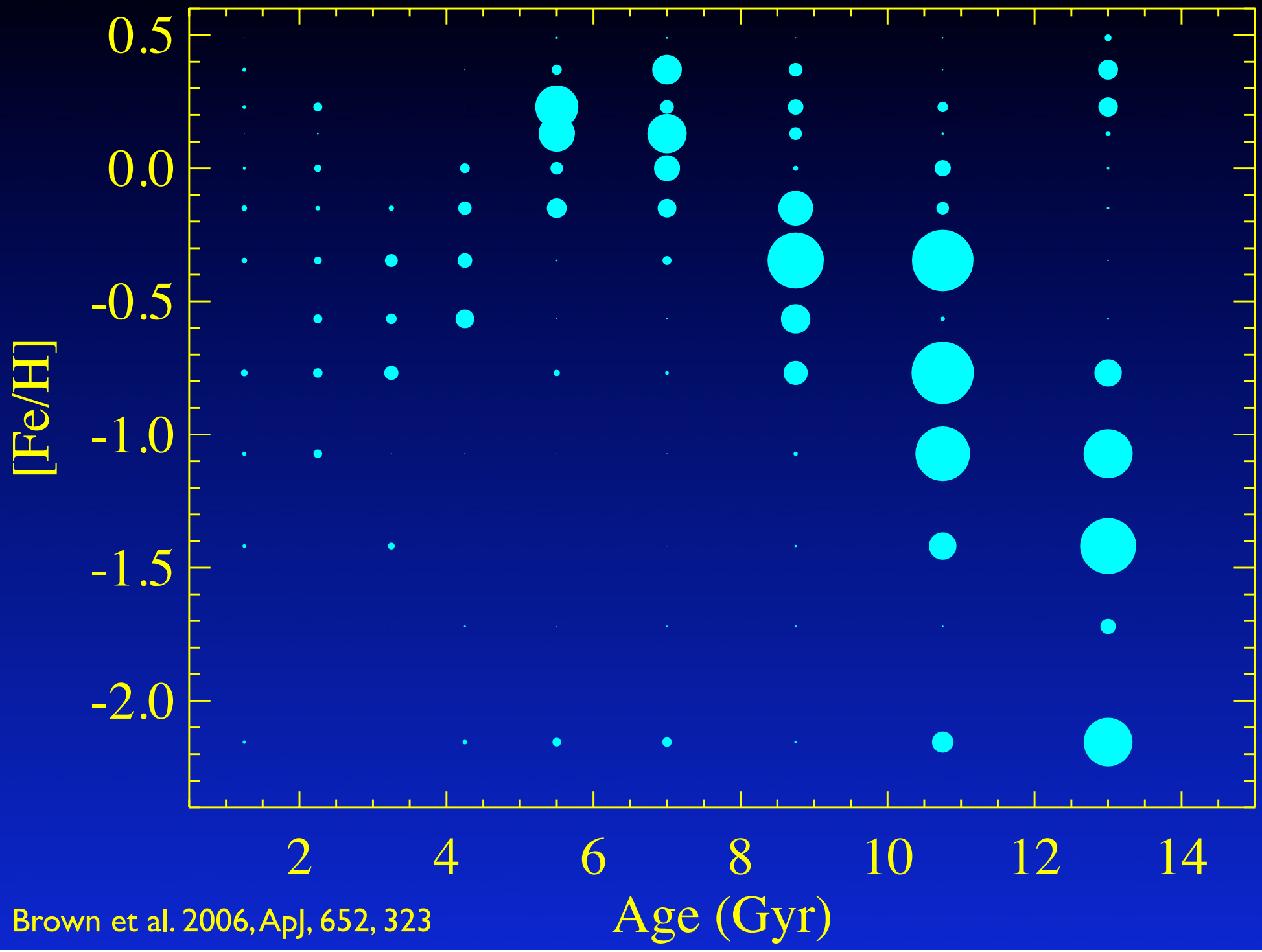
Brown et al. 2006, ApJ, 636, L89

Stream Distribution in Age and Metallicity



Brown et al. 2006, ApJ, 652, 323

Halo Distribution in Age and Metallicity

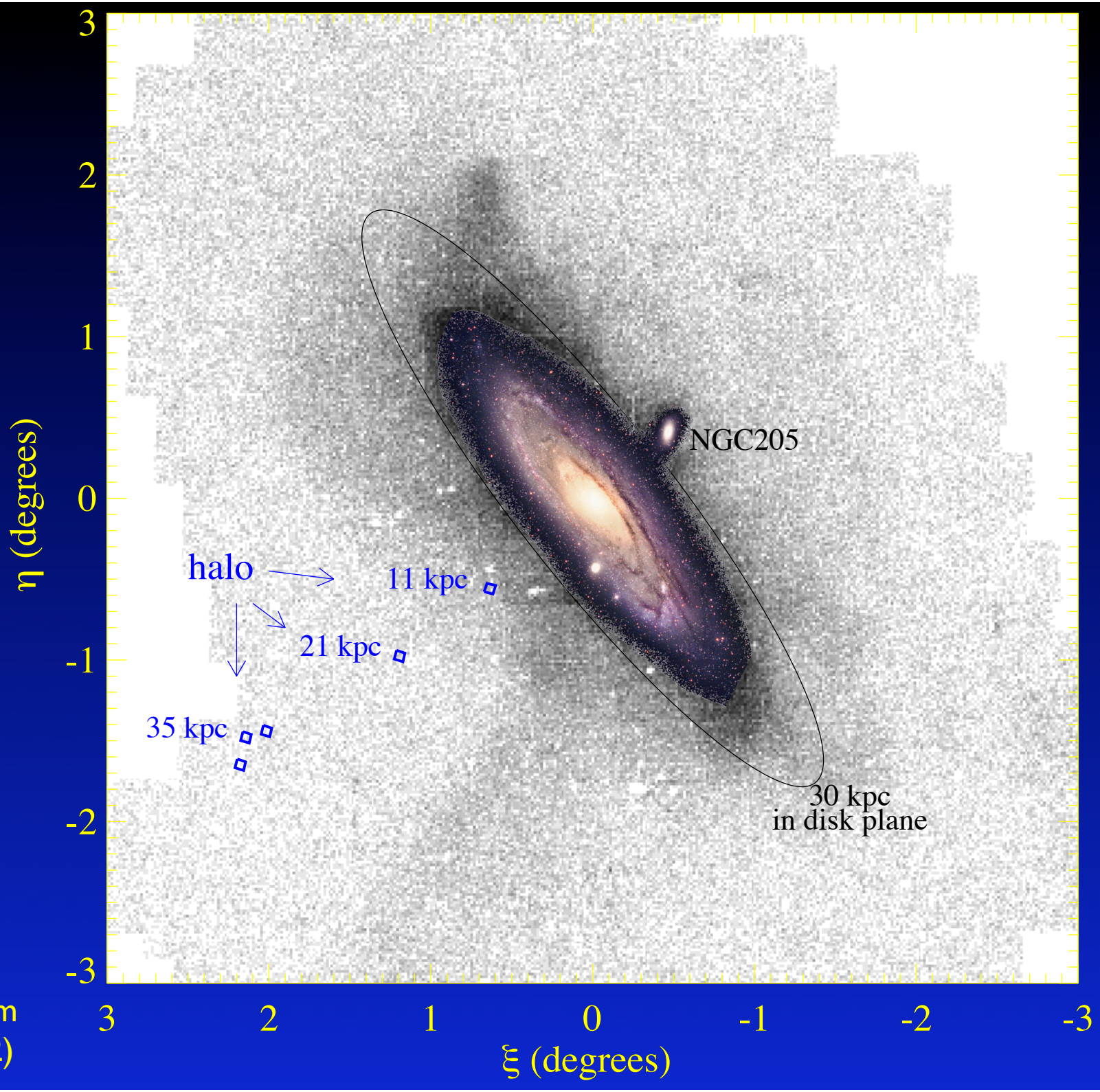


Brown et al. 2006, ApJ, 652, 323

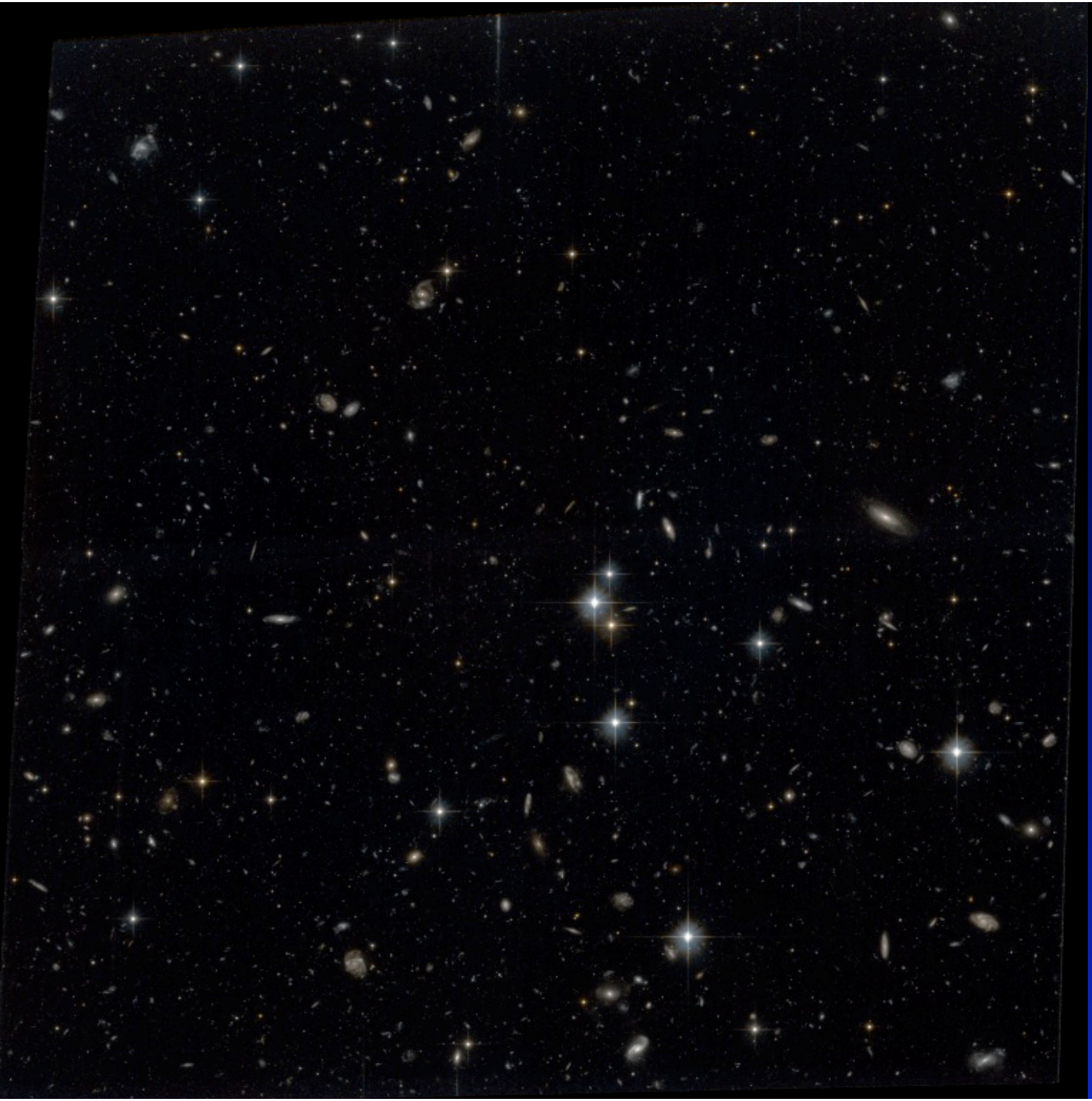
Star formation history of the stream

- Most likely explanation: the inner spheroid of Andromeda is polluted with debris from the stream's progenitor (or objects like it)
- This explanation is supported by simulations and kinematic data
(Fardal et al. 2007; Gilbert et al. 2007)
- The stream is the merger event that explains the population in our original halo field

In 2006, we obtained new images in the extended halo.
21 kpc field and two 35 kpc fields completed before ACS failure.



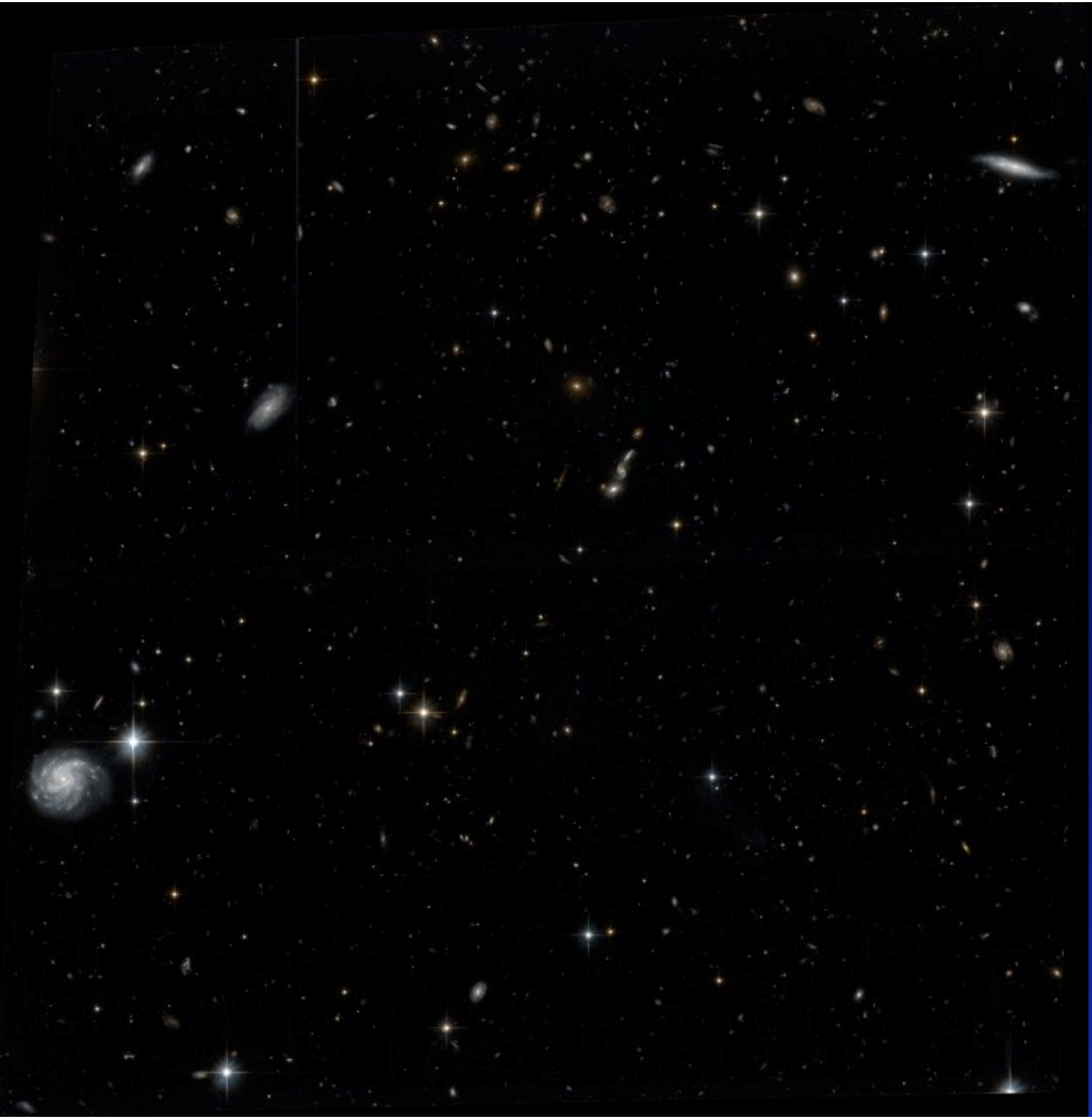
(star count map from Ferguson et al. 2002)



M31 halo
(21 kpc)

210 x 210
arcsec

800 x 800 pc



M31 halo
(35 kpc)

210 x 210
arcsec

800 x 800 pc

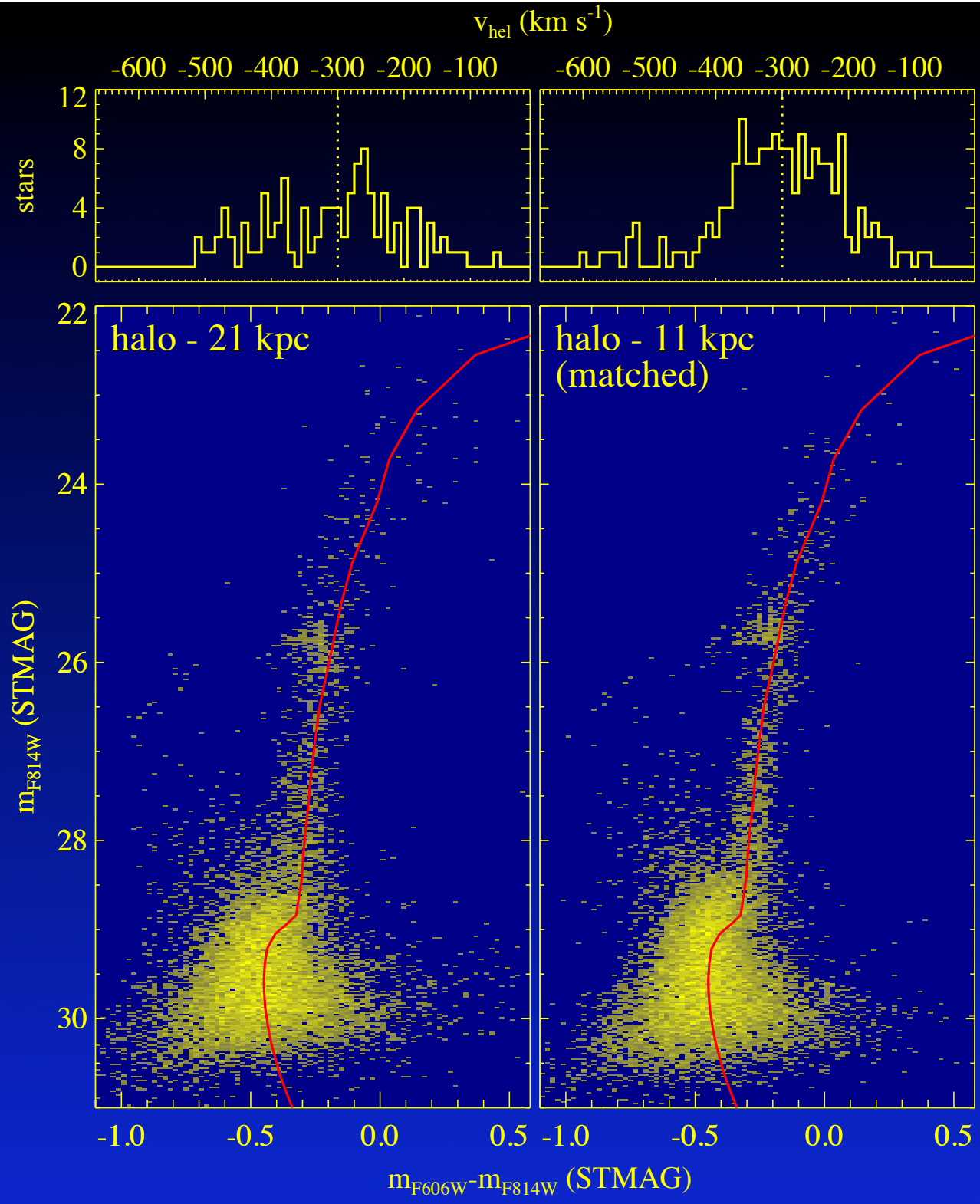
M31 halo
(35 kpc)

210 x 210
arcsec

800 x 800 pc

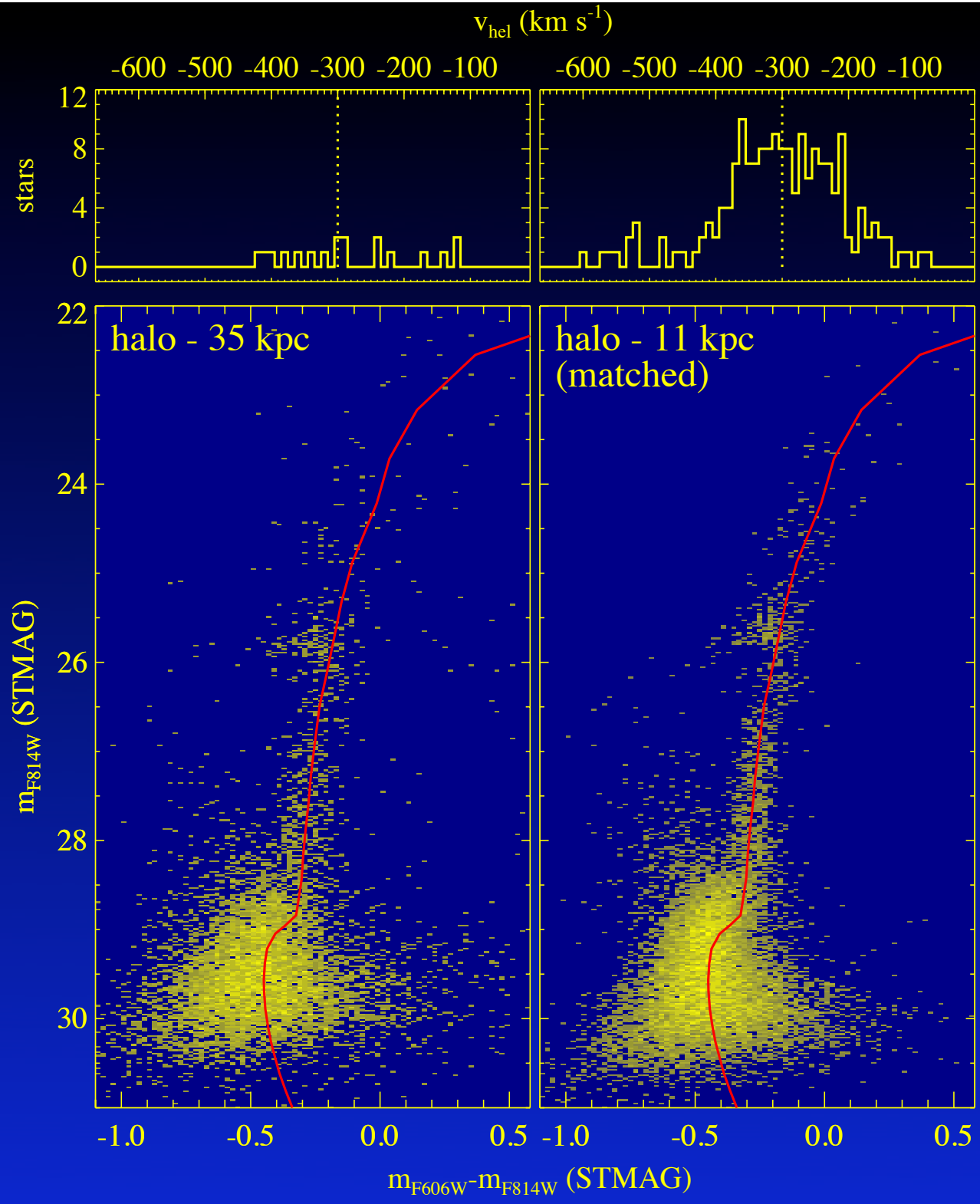
Distribution of velocities in each field is broad and centered on M31 systemic

21 kpc field is older and somewhat more metal-poor



Brown et al. 2007, ApJ, 658, L95

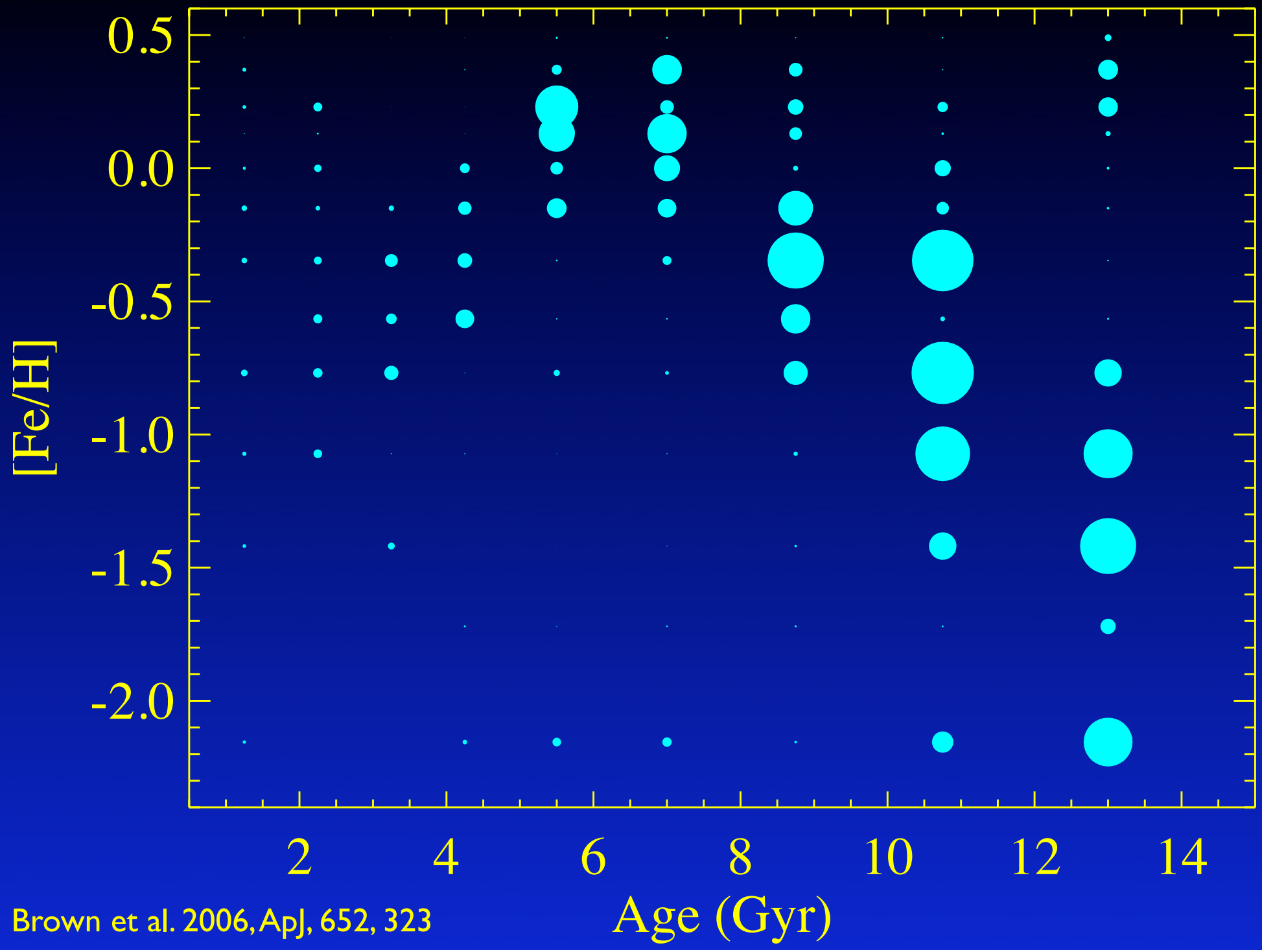
Distribution of velocities in each field is broad and centered on M31 systemic



35 kpc field is older and somewhat more metal-poor

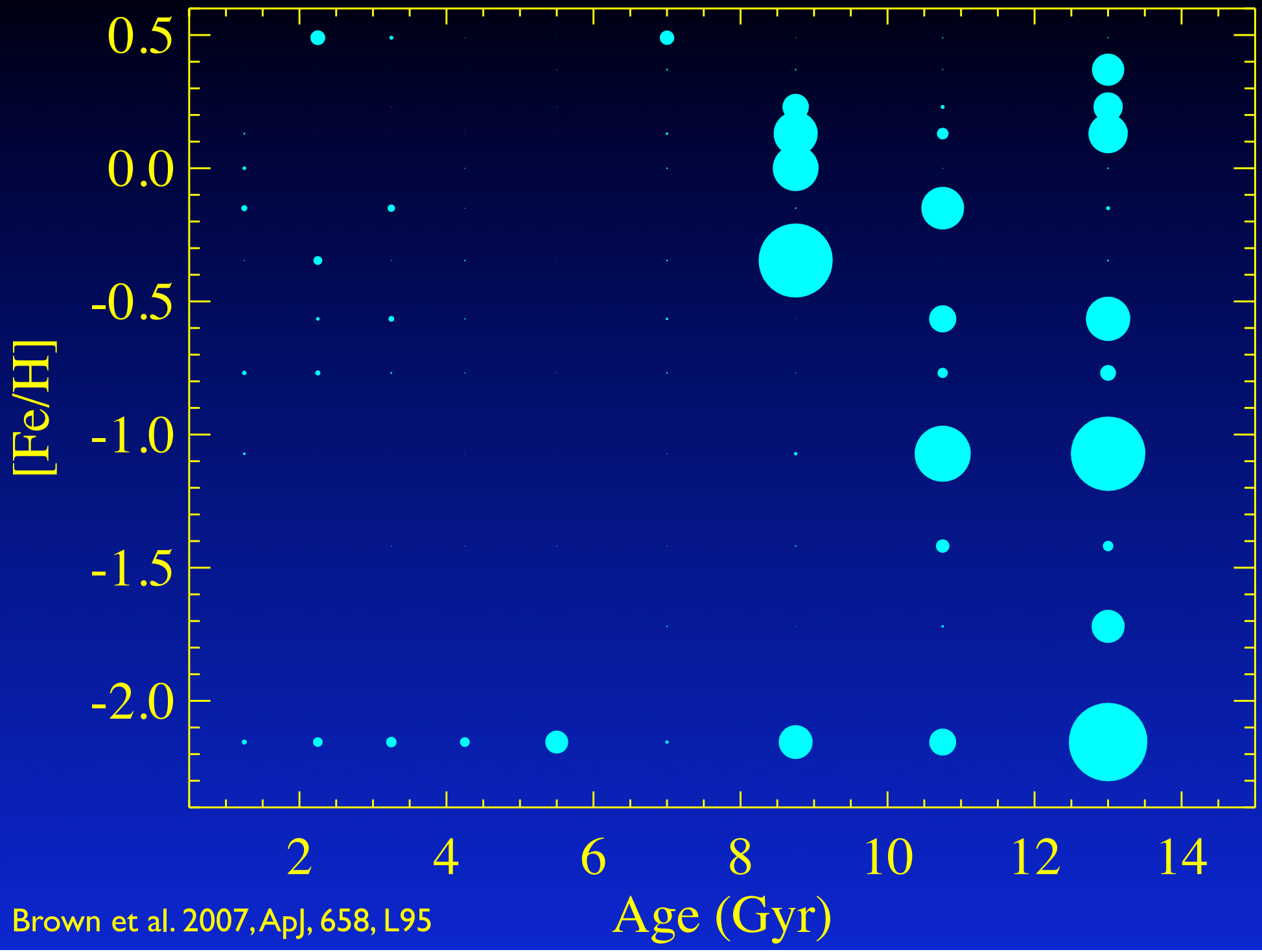
Brown et al. 2008, ApJ, 658, L121

Age & Metallicity Distribution in 11 kpc Field



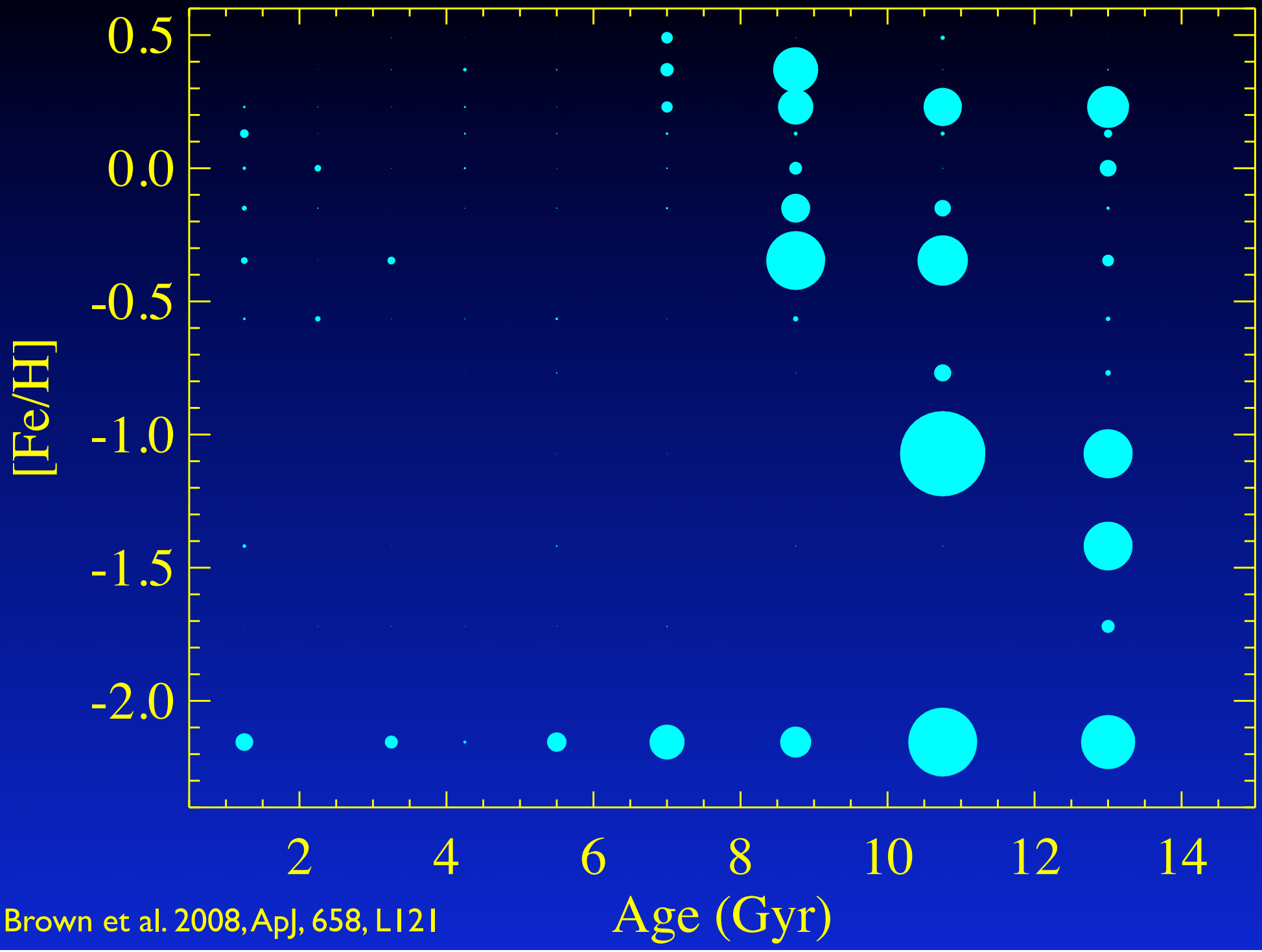
Brown et al. 2006, ApJ, 652, 323

Age & Metallicity Distribution in 21 kpc Field



Brown et al. 2007, ApJ, 658, L95

Age & Metallicity Distribution in 35 kpc Field

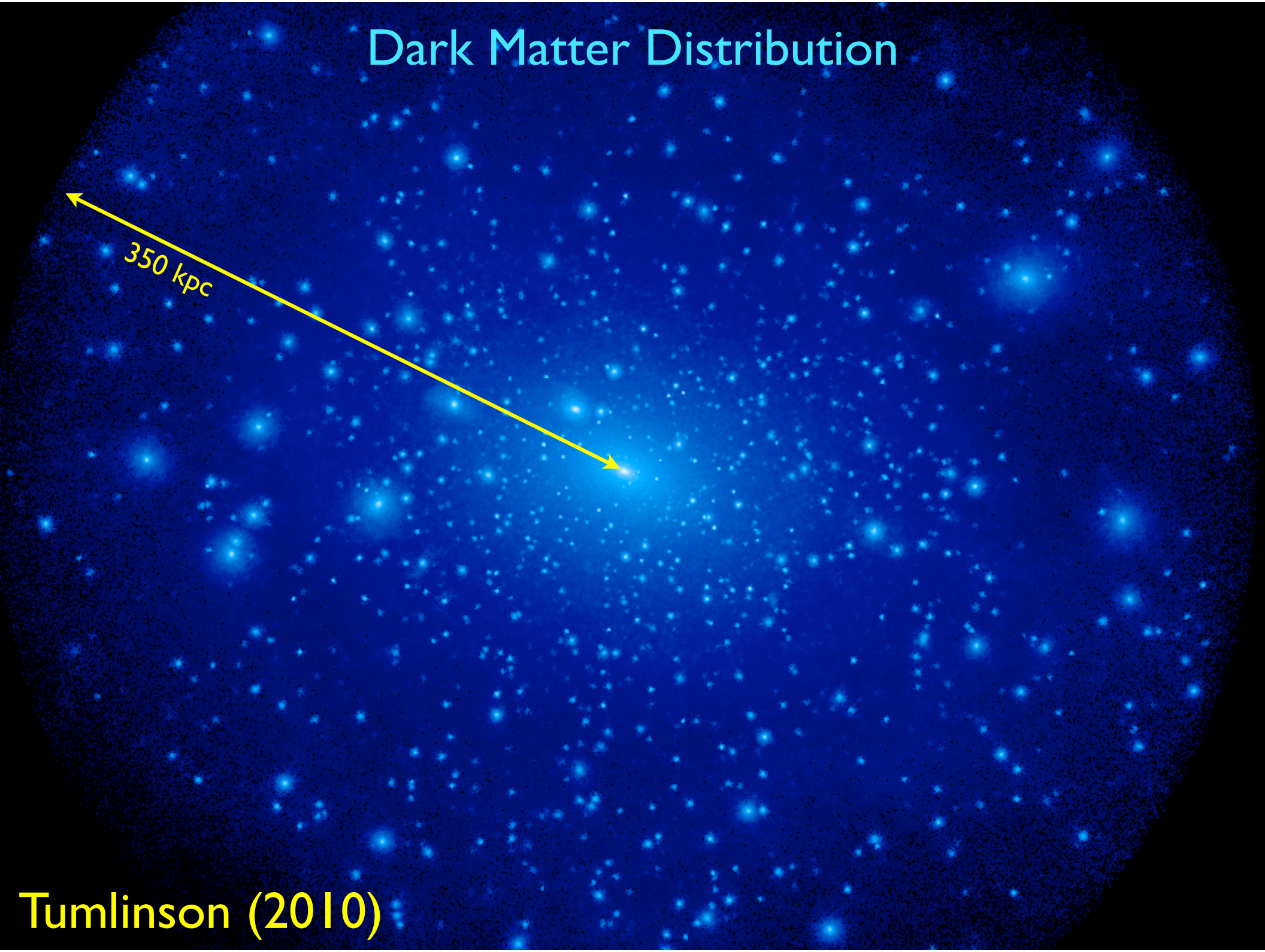


Brown et al. 2008, ApJ, 658, L121

Star Formation Histories at 21 kpc and 35 kpc

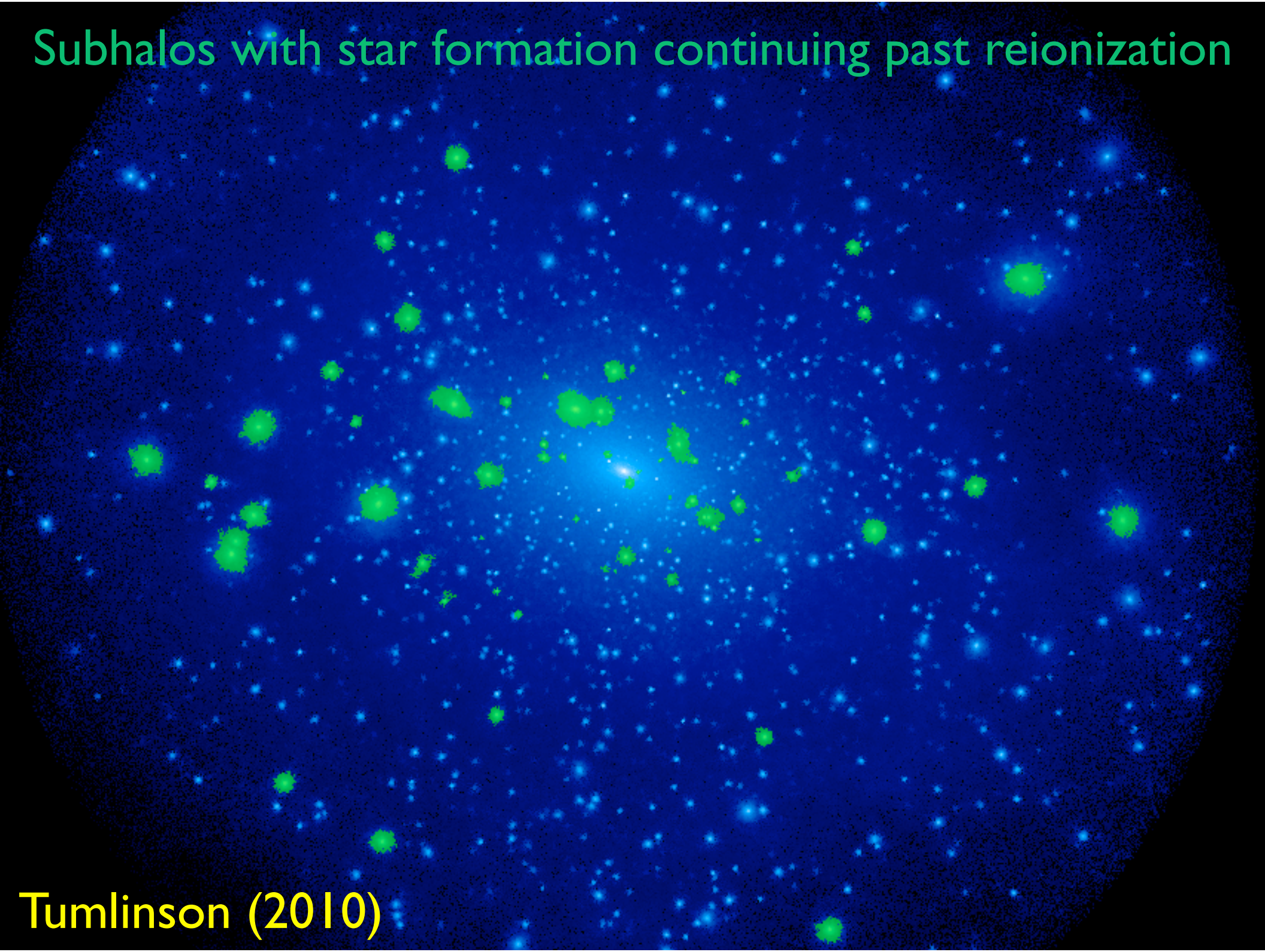
- These fields span the transition between inner "bulge-like" halo and outer "classical" halo
- The halo fields at 21 and 35 kpc exhibit lower metallicities and older ages, but are not purely ancient
  - A population entirely >10 Gyr ruled out at >8 sigma
- Intermediate-age stars are not surprising, given the myriad streams criss-crossing the halo in wide-field star count maps (McConnachie et al. 2009, Ibata et al. 2007)
- Dwarf galaxies of the Local Group exhibit extended star formation histories (Orban et al. 2008, Weisz et al. 2011)

Dark Matter Distribution



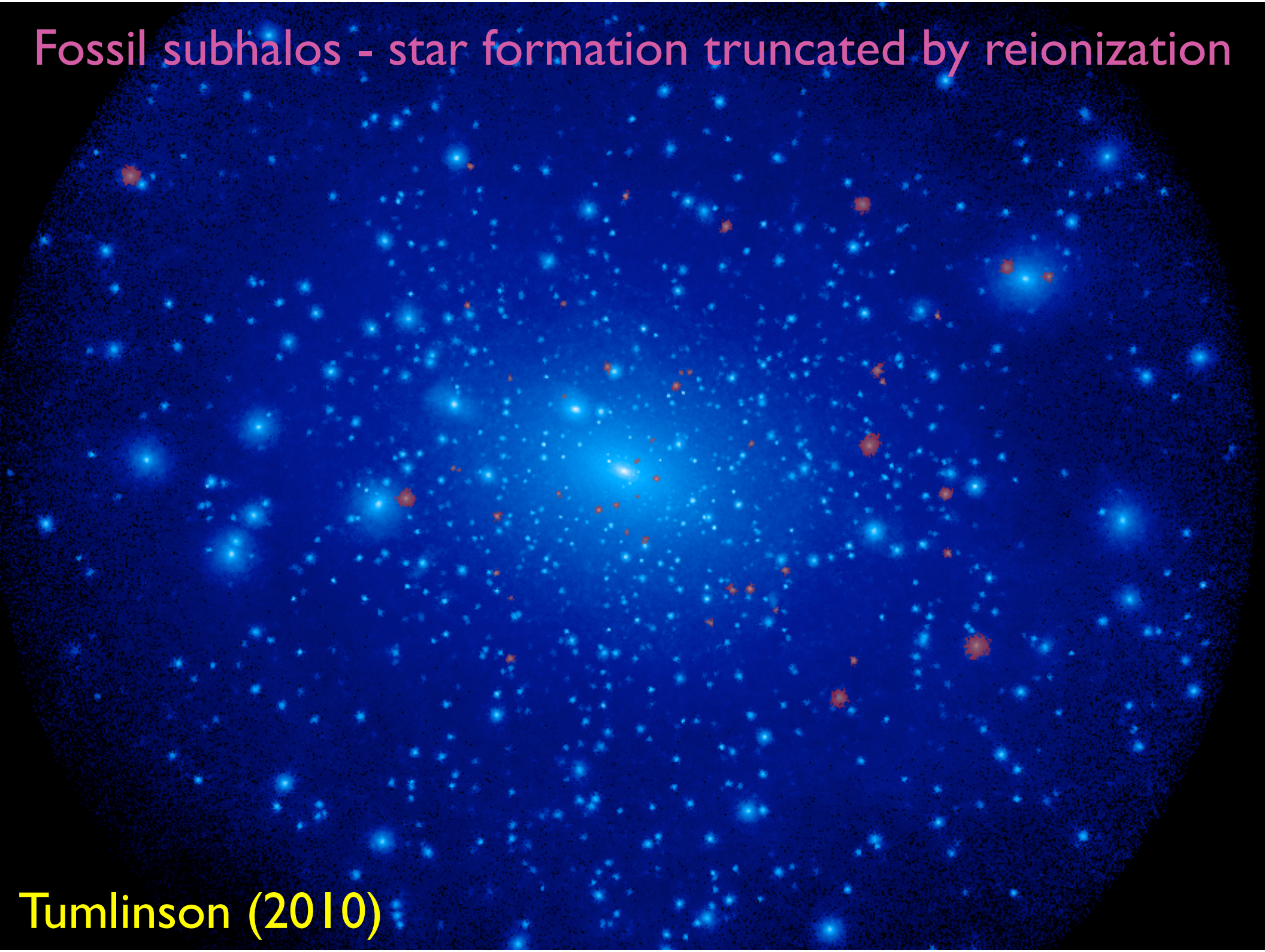
Tumlinson (2010)

Subhalos with star formation continuing past reionization



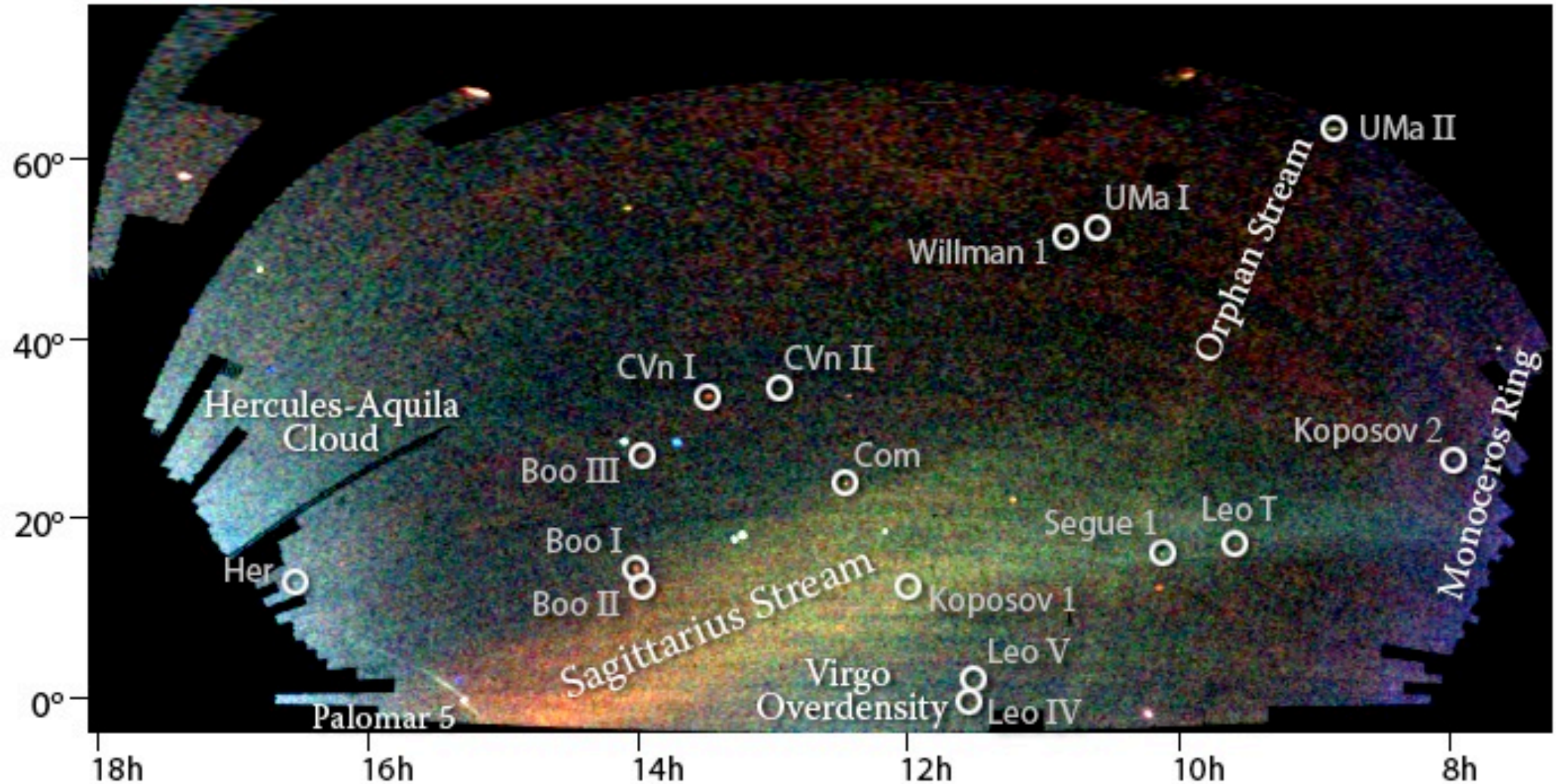
Tumlinson (2010)

Fossil subhalos - star formation truncated by reionization



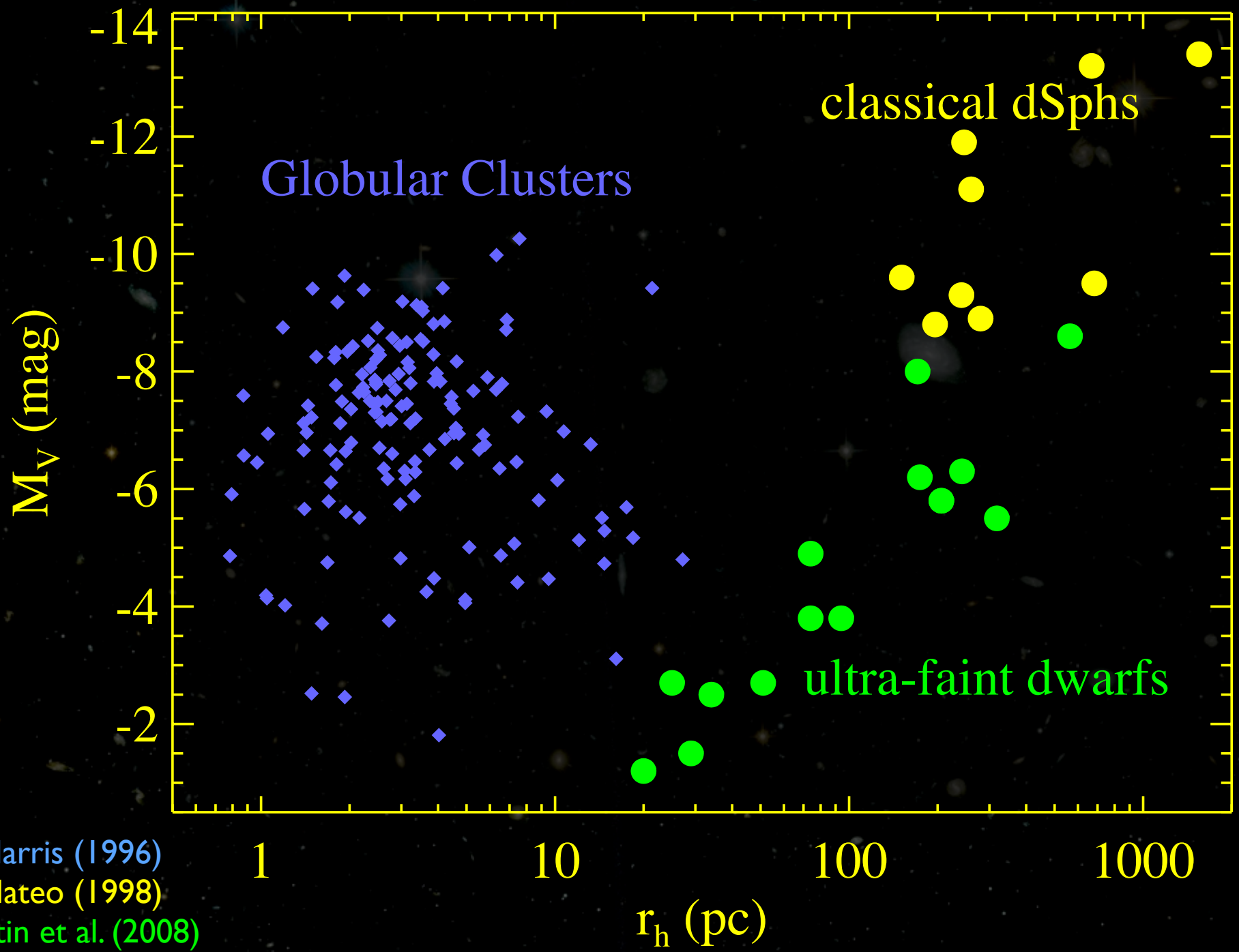
Tumlinson (2010)


Most subhalos never form stars at all
Tumlinson (2010)



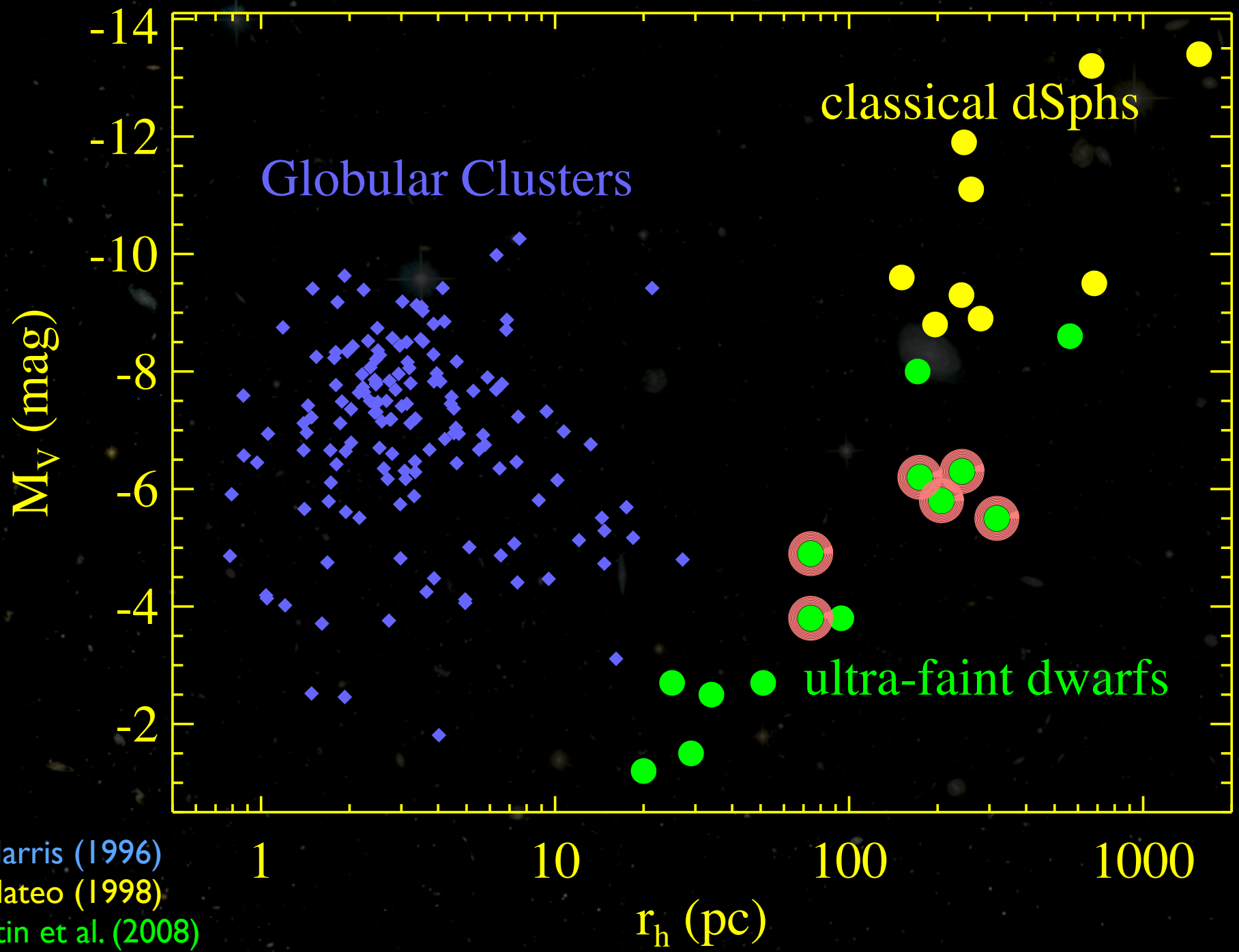
Belokurov et al. (2007)

Luminosity vs Size

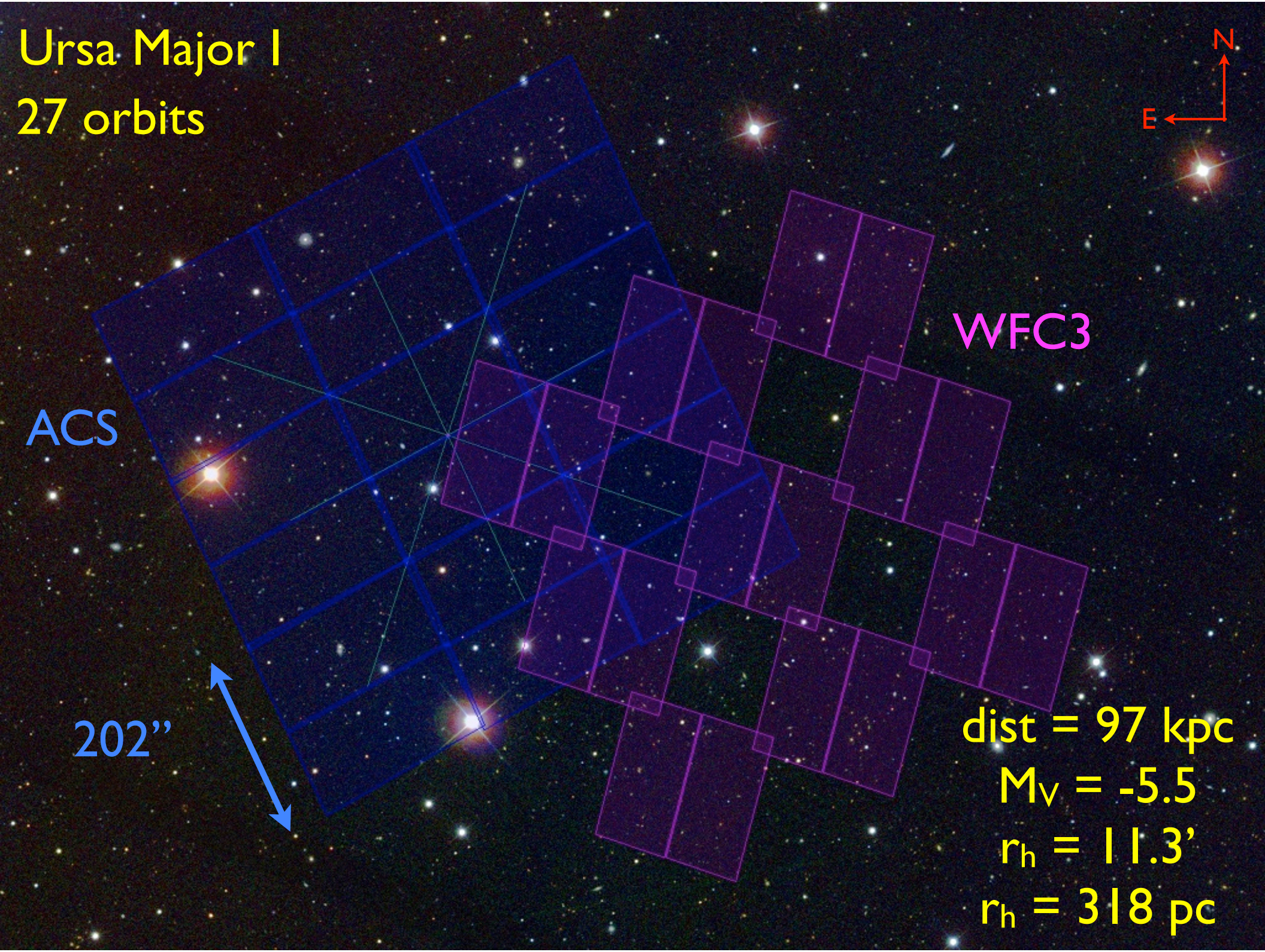


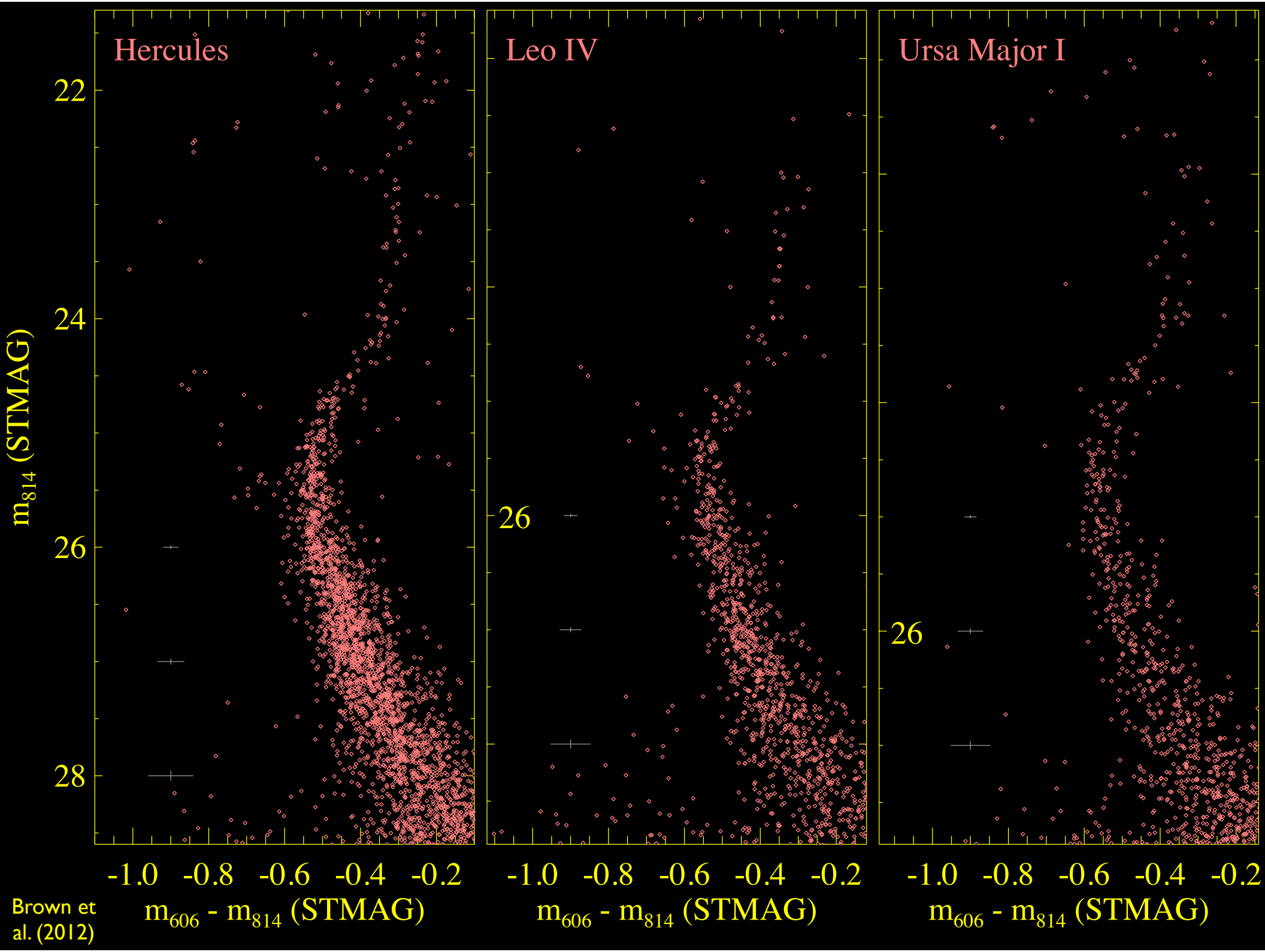
Harris (1996)
Mateo (1998)
Martin et al. (2008)

Luminosity vs Size

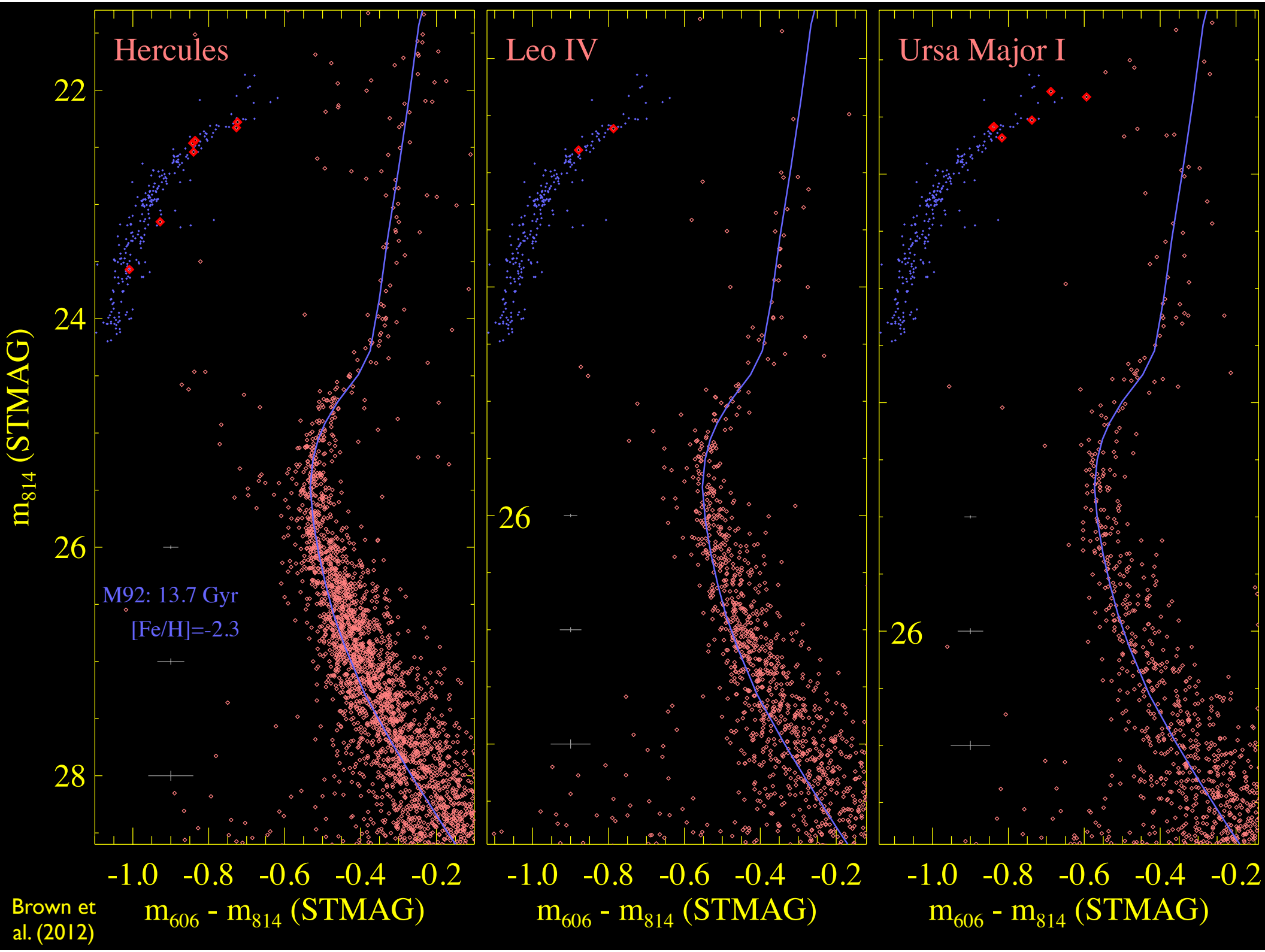


Harris (1996)
Mateo (1998)
Martin et al. (2008)

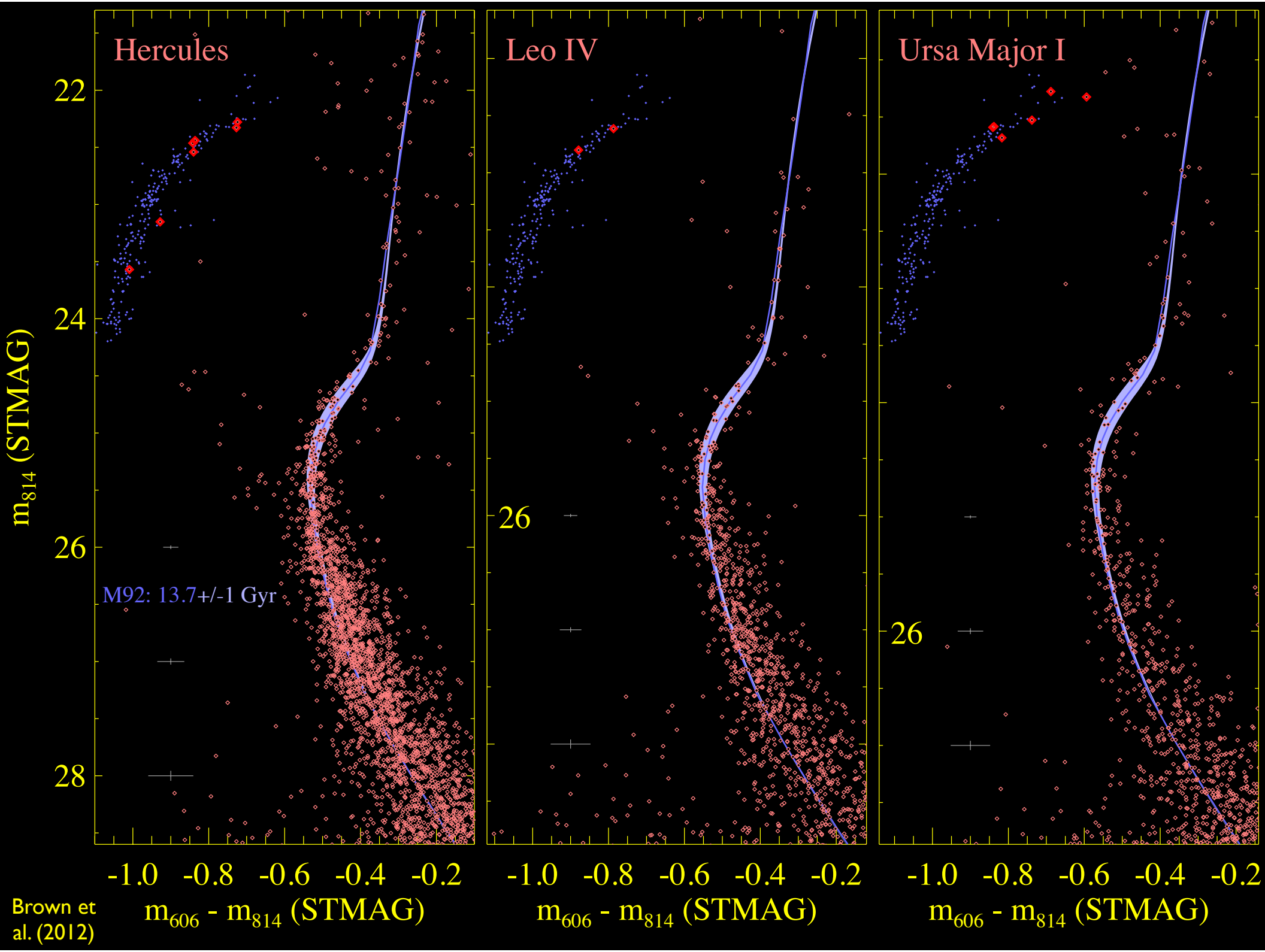

Ursa Major I
27 orbits
N
E
WFC3
ACS
202”
dist = 97 kpc
M_V = -5.5
r_h = 11.3’
r_h = 318 pc



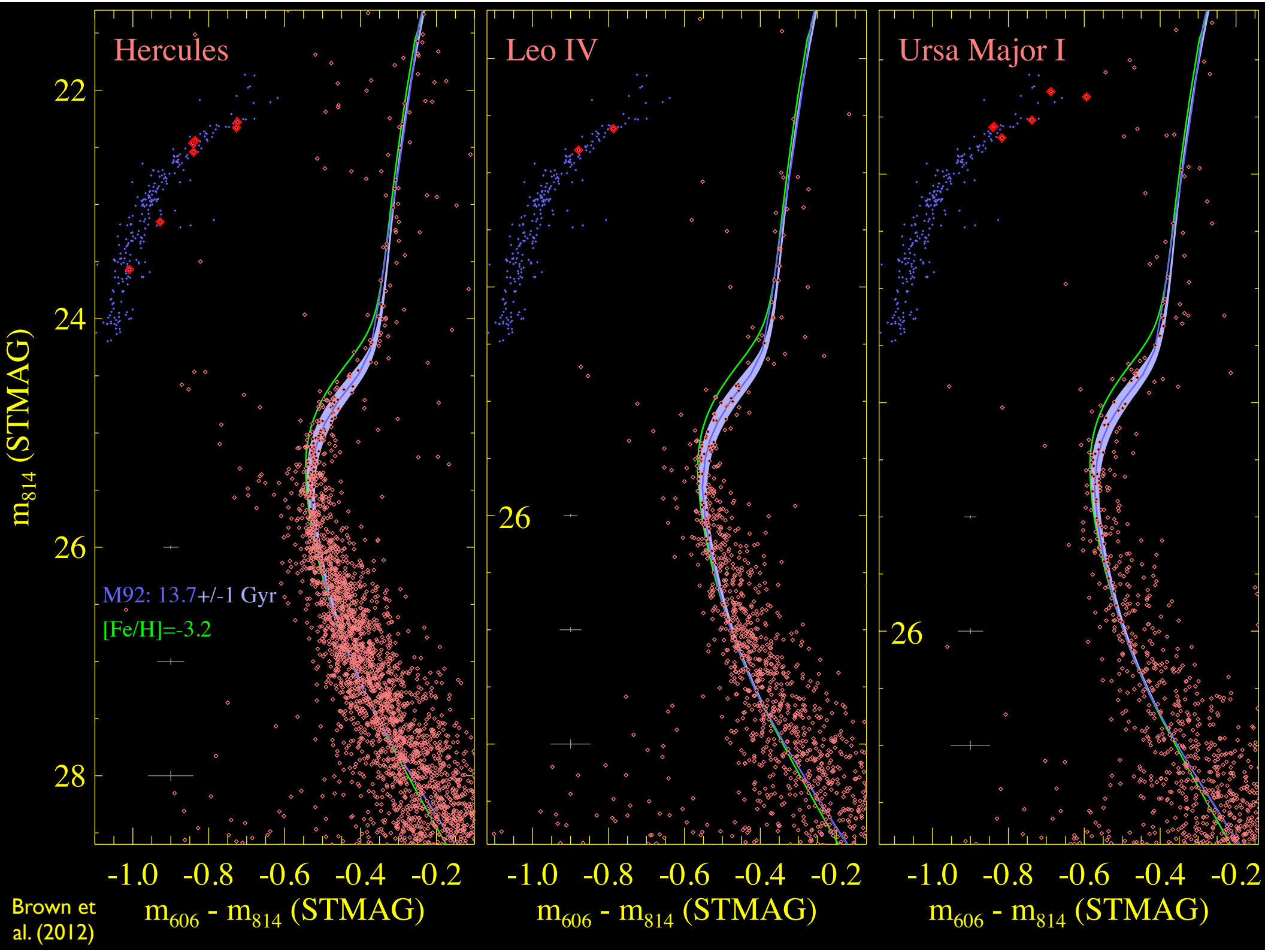
Brown et al. (2012)



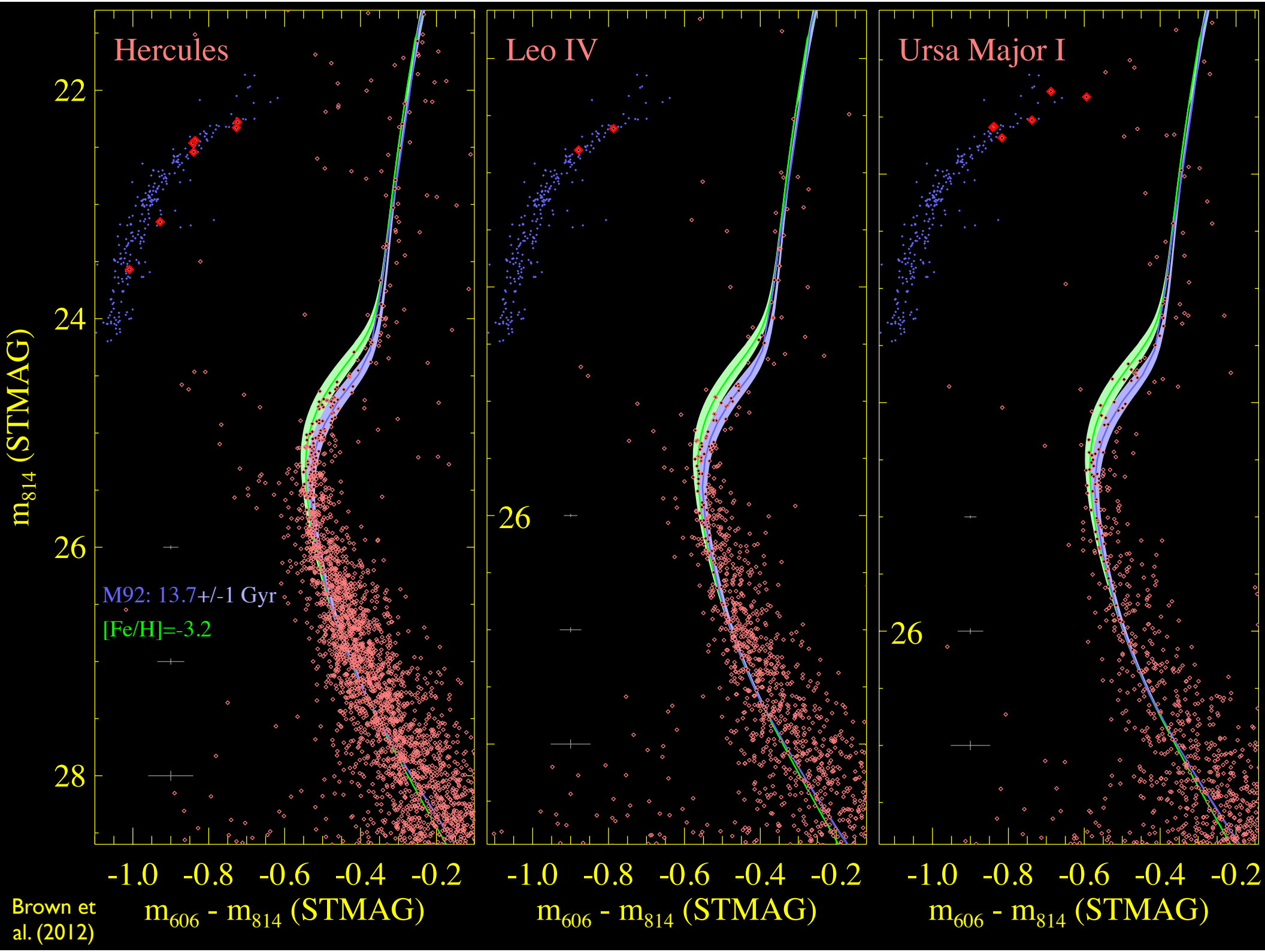
Brown et al. (2012)



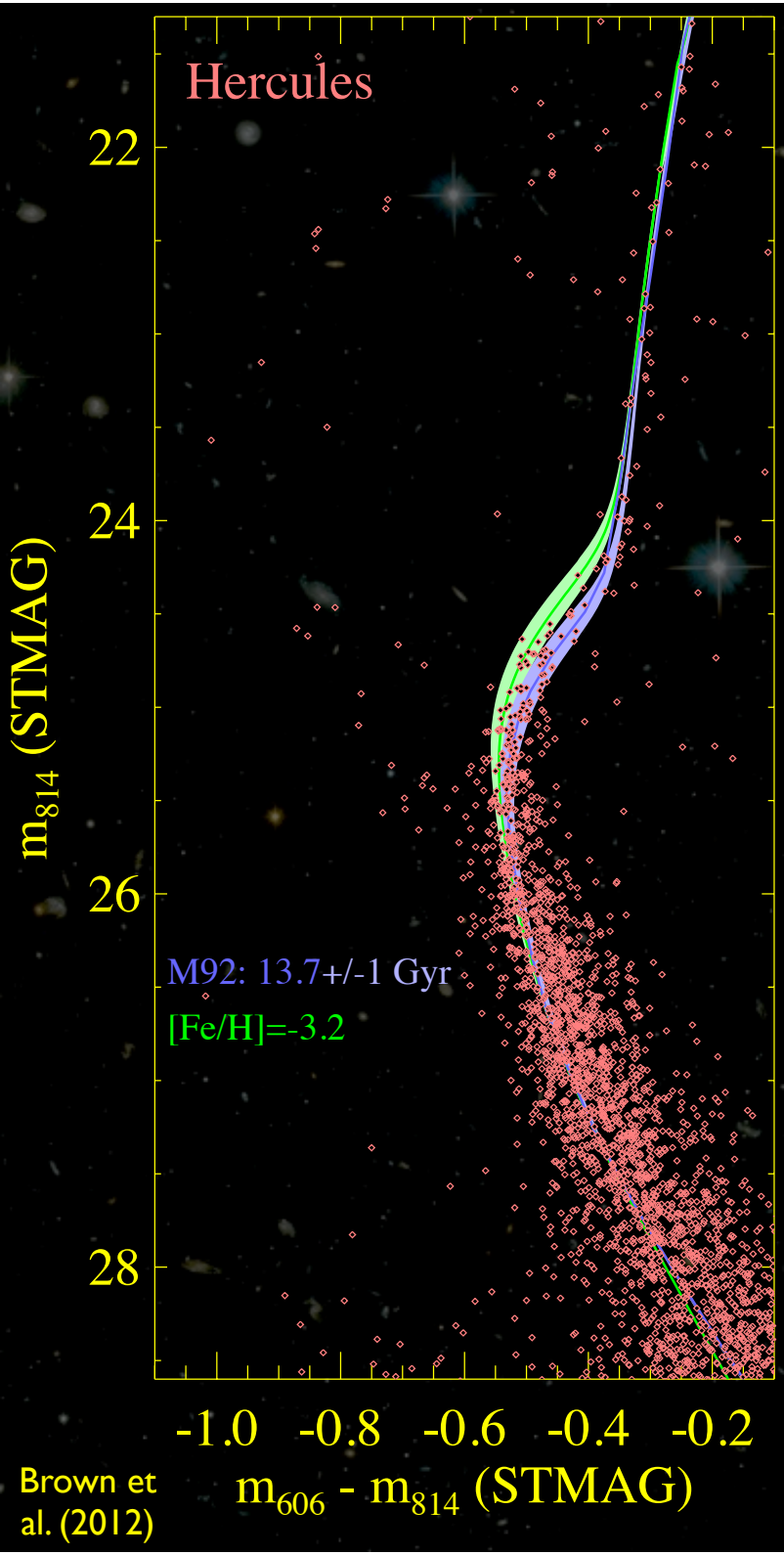
Brown et al. (2012)



Brown et al. (2012)

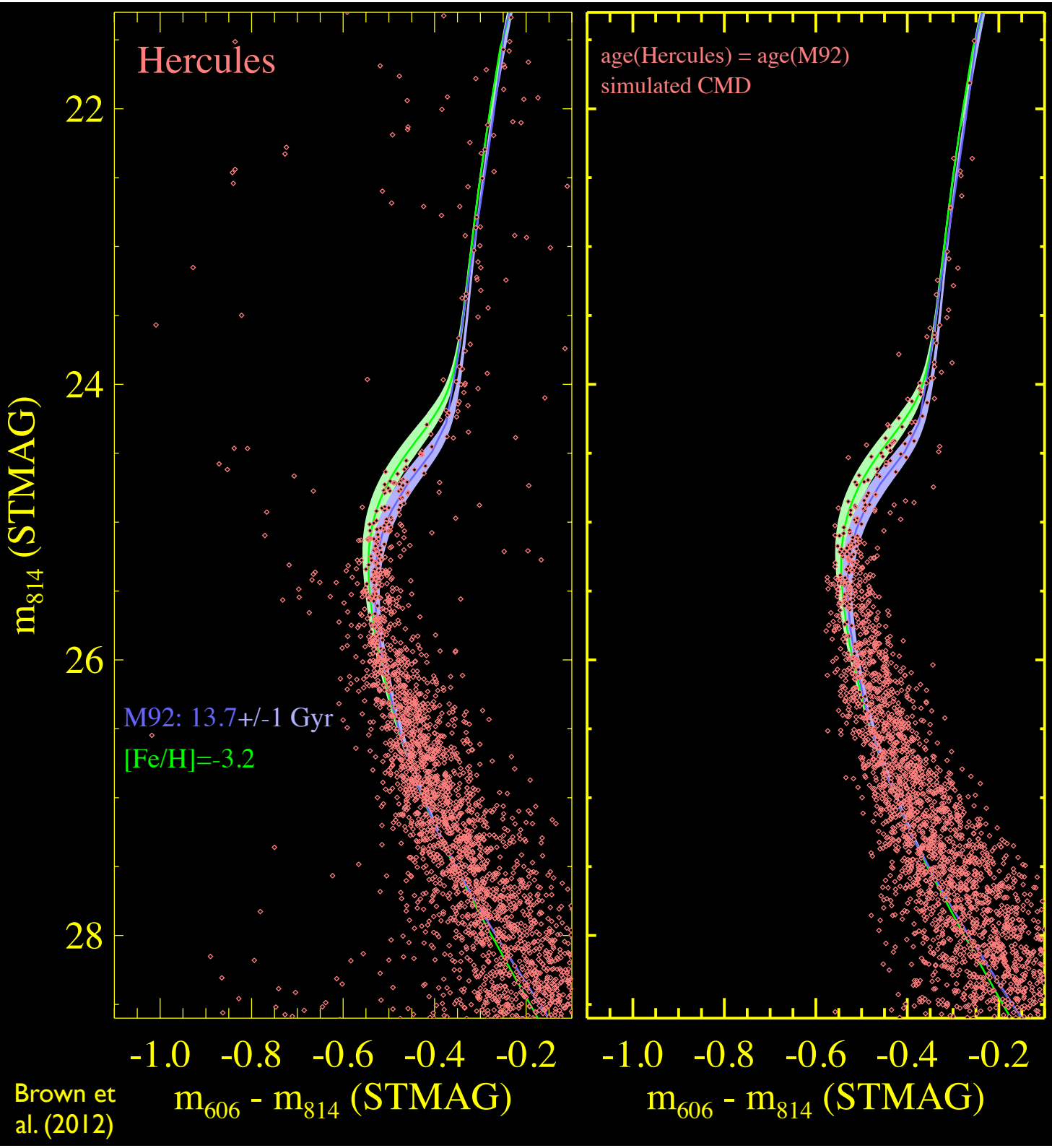


Brown et al. (2012)

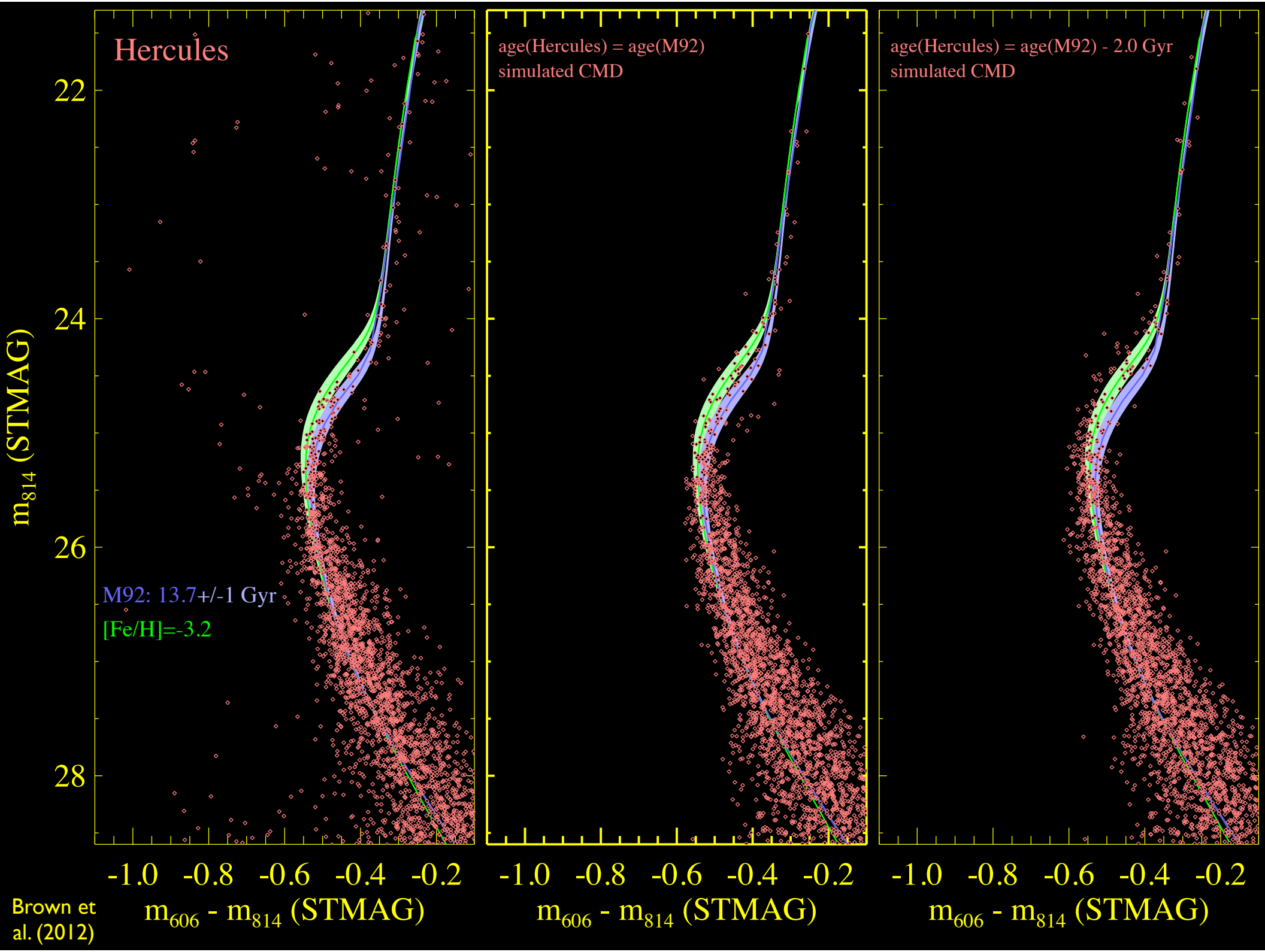


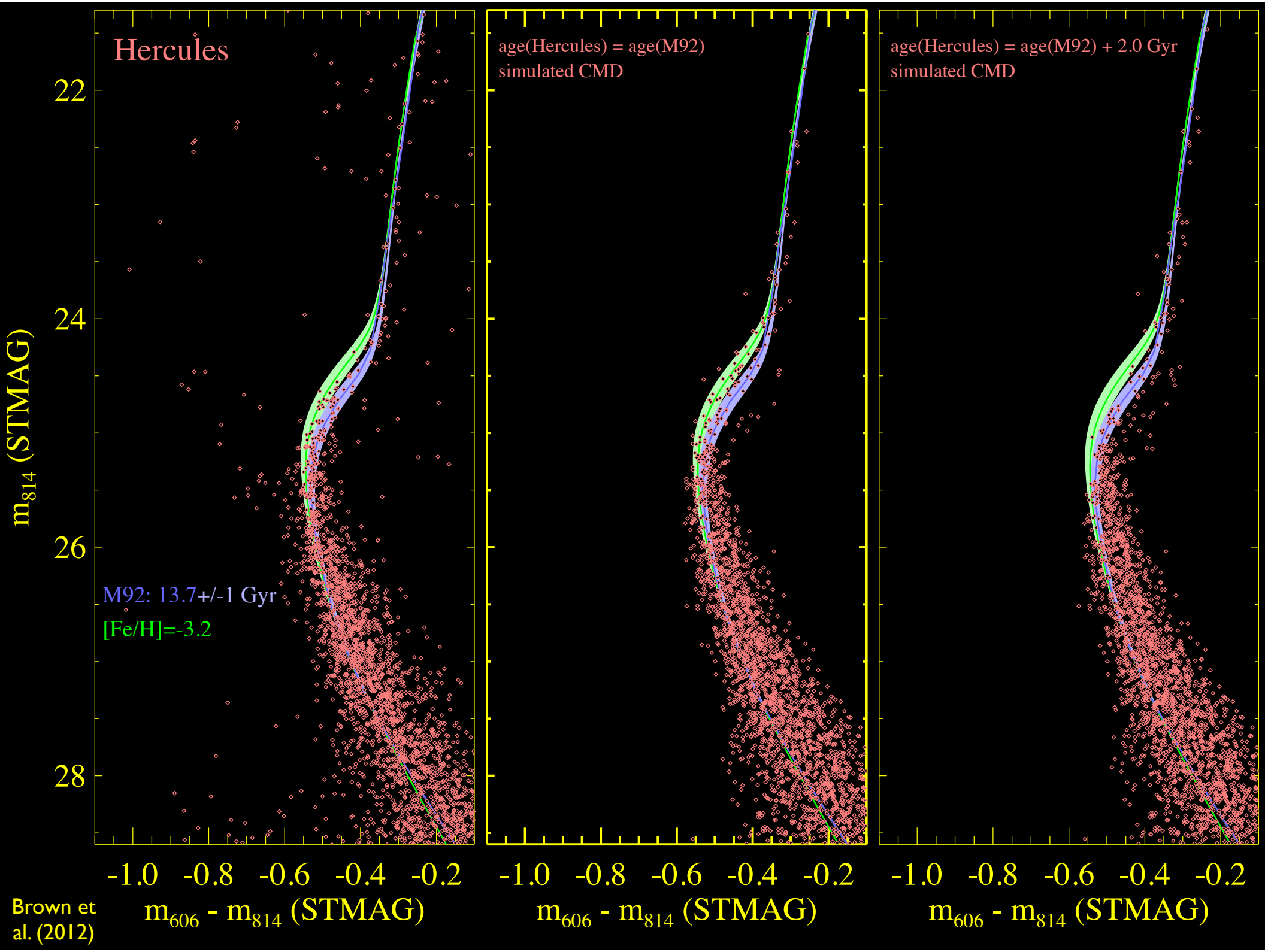
Brown et al. (2012)

- Assume spectroscopic metallicity distribution (Kirby et al. 2008; Simon & Geha 2007)
- Allow ages in fine grid of isochrones to float
- Maximum-Likelihood fit to main sequence turnoff and subgiant branch
- Mean age = 13.6 Gyr
  +/-0.2 Gyr statistical
  +/-0.6 Gyr systematic ([O/Fe])
  +/-0.6 Gyr systematic (distance)



Brown et al. (2012)


Hercules
age(Hercules) = age(M92)
simulated CMD
age(Hercules) = age(M92) - 2.0 Gyr
simulated CMD
M92: 13.7+/-1 Gyr
[Fe/H]=-3.2
22
24
26
28
m_{814} (STMAG)
-1.0 -0.8 -0.6 -0.4 -0.2
m_{606} - m_{814} (STMAG)
Brown et al. (2012)


Hercules
age(Hercules) = age(M92)
simulated CMD
age(Hercules) = age(M92) + 2.0 Gyr
simulated CMD
M92: 13.7+/-1 Gyr
[Fe/H]=-3.2
22
24
26
28
m_{814} (STMAG)
-1.0 -0.8 -0.6 -0.4 -0.2
m_{606} - m_{814} (STMAG)
Brown et al. (2012)

Summary

- All sightlines through the Andromeda halo exhibit intermediate-age stars, indicating an active merger history
- The Giant Stellar Stream looks remarkably similar to the inner halo, implying the inner halo of Andromeda is polluted by stars stripped from the stream's progenitor
- Most dwarf galaxies exhibit extended star formation histories, and the remnants of past mergers can be seen criss-crossing the Andromeda halo
- New observations of the ultra-faint dwarf galaxies demonstrate they that they are purely ancient, suggesting the faintest galaxies were truncated by reionization
- All of our Andromeda data (coadded & resampled images, artificial star tests, photometric catalogs) available at MAST