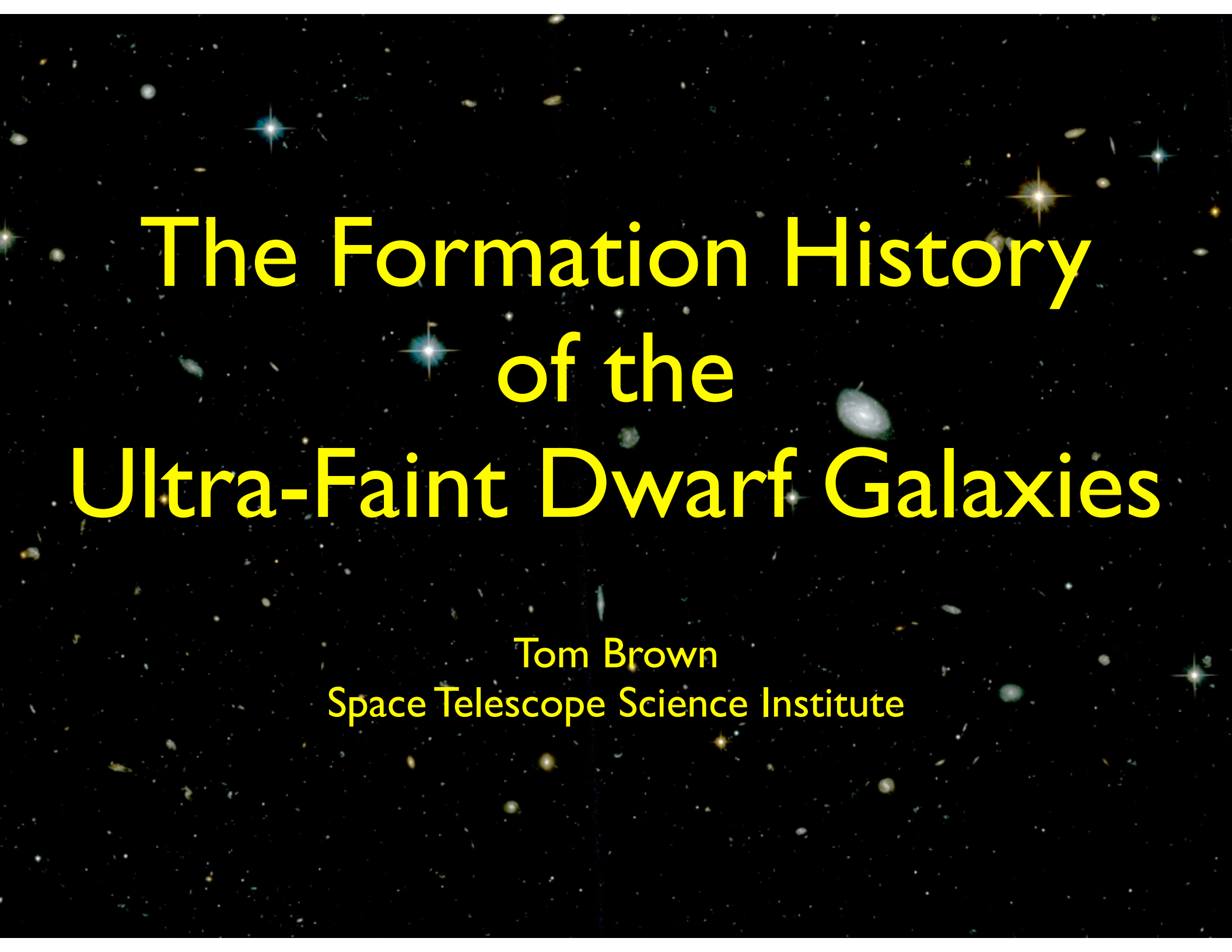


The Formation History of the Ultra-Faint Dwarf Galaxies

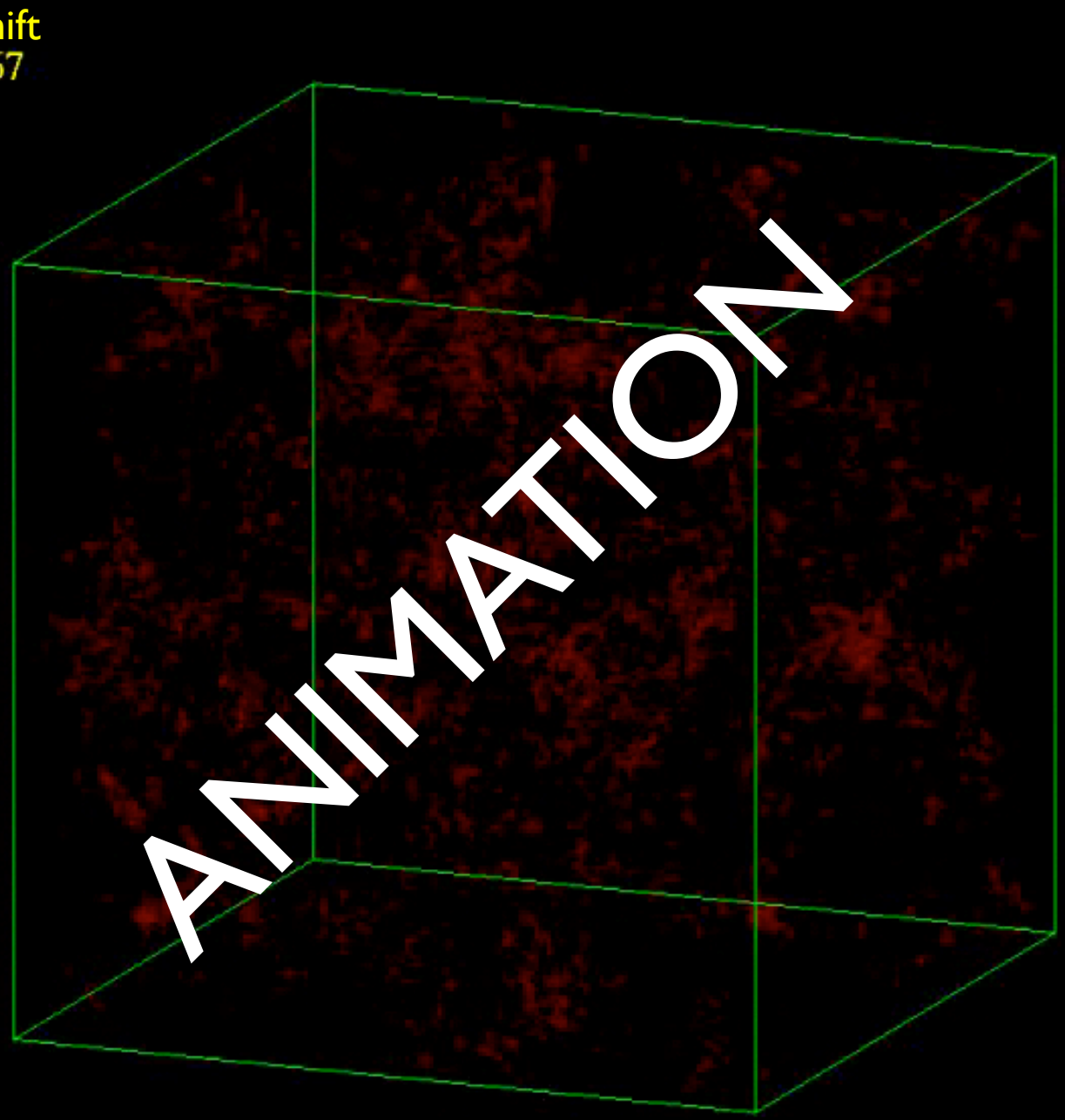
Tom Brown
Space Telescope Science Institute

The Formation History of the Ultra-Faint Dwarf Galaxies

Jason Tumlinson (STScI), Marla Geha (Yale), Josh Simon (Carnegie),
Luis Vargas (Yale), Don VandenBerg (U of Victoria),
Evan Kirby (CalTech), Jason Kalirai (STScI), Roberto J. Avila (STScI),
Mario Gennaro (STScI), Harry Ferguson (STScI),
Ricardo Munoz (U de Chile), Puragra Guhathakurta (UCO/Lick),
Alvio Renzini (INAF)

ΛCDM is consistent with:

- large-scale structure
- cosmic microwave background
- abundances of light elements
- expansion of universe



However:

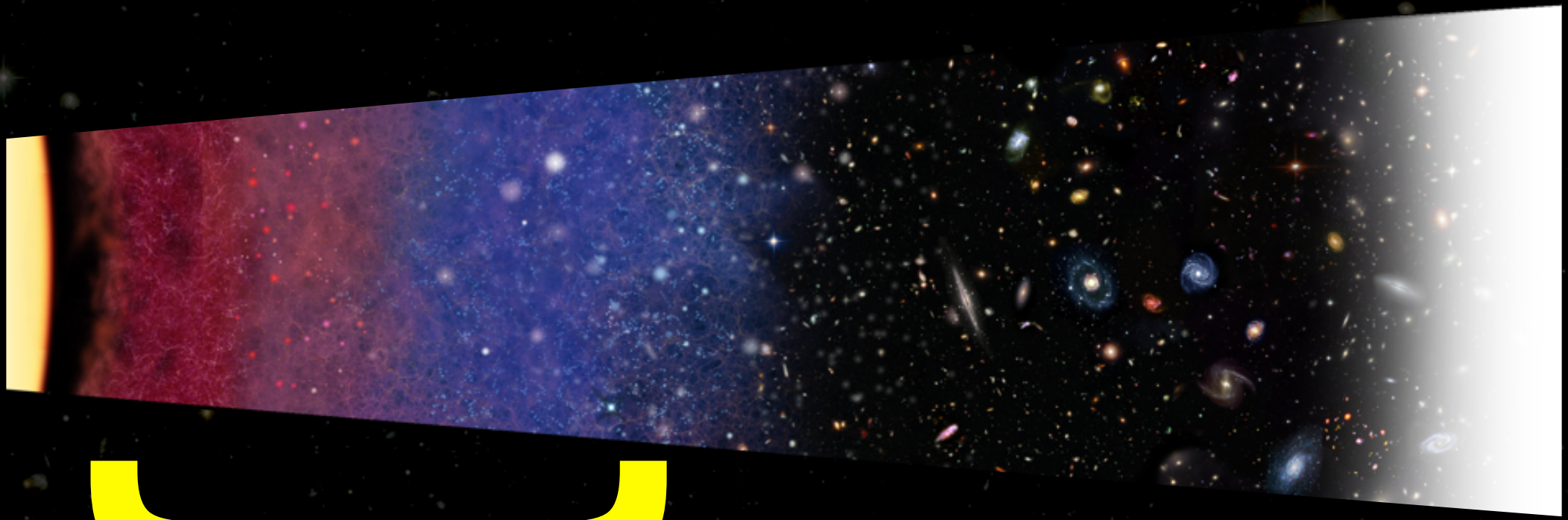
ΛCDM predicts more dark matter sub-halos than seen as visible dwarf galaxies

"missing satellite problem"

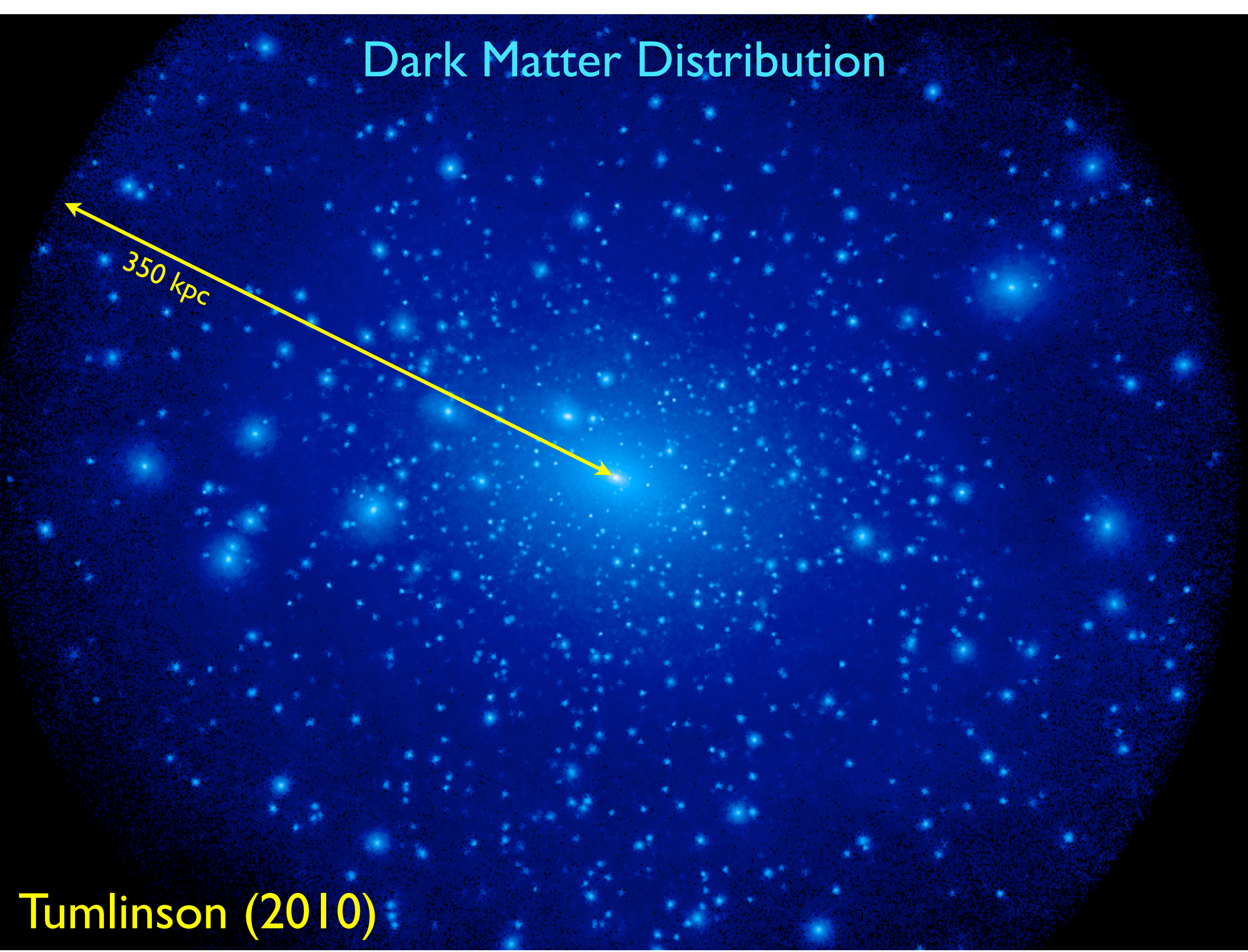
B. Moore (U. of Zurich)

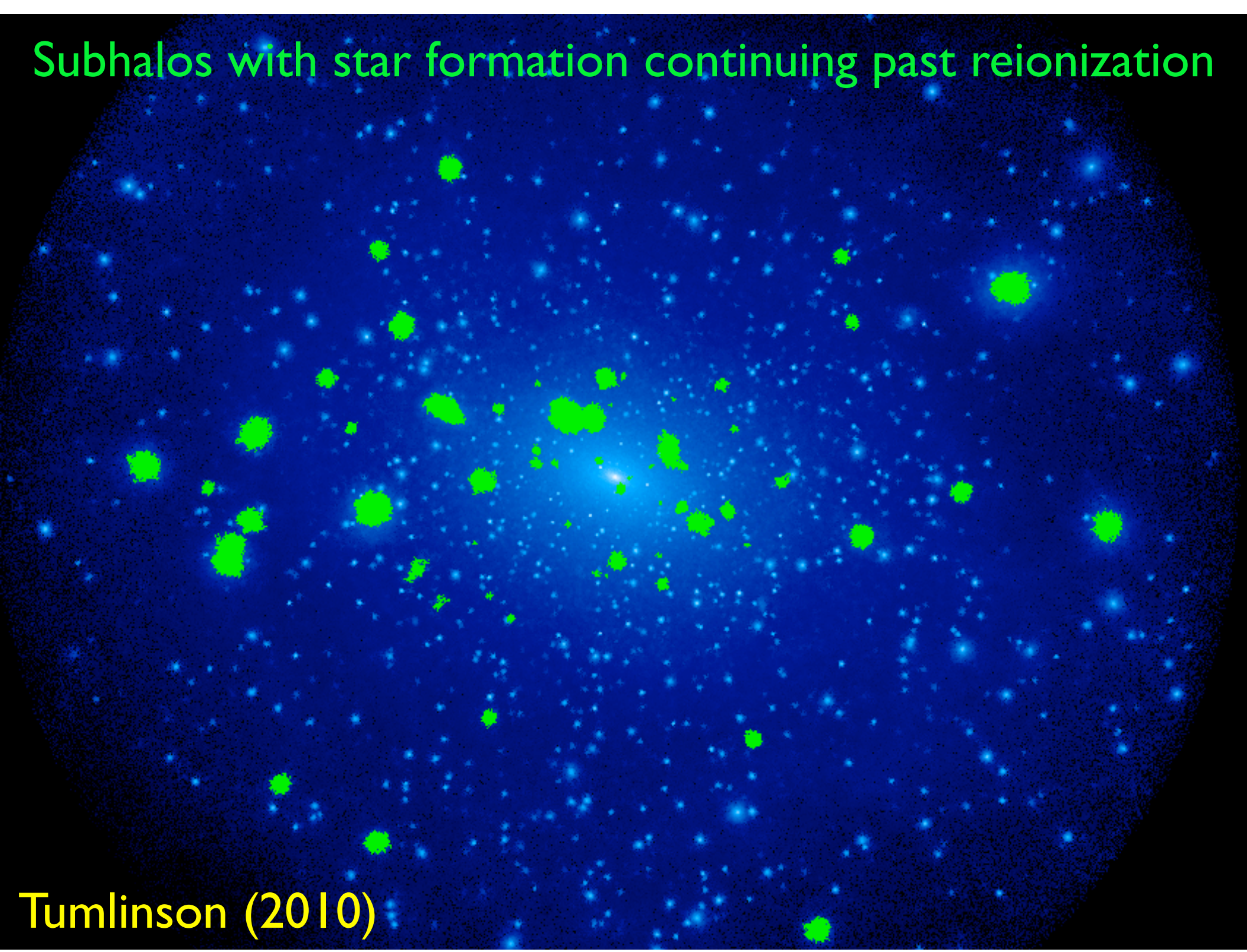
Theoretical solution - reionization

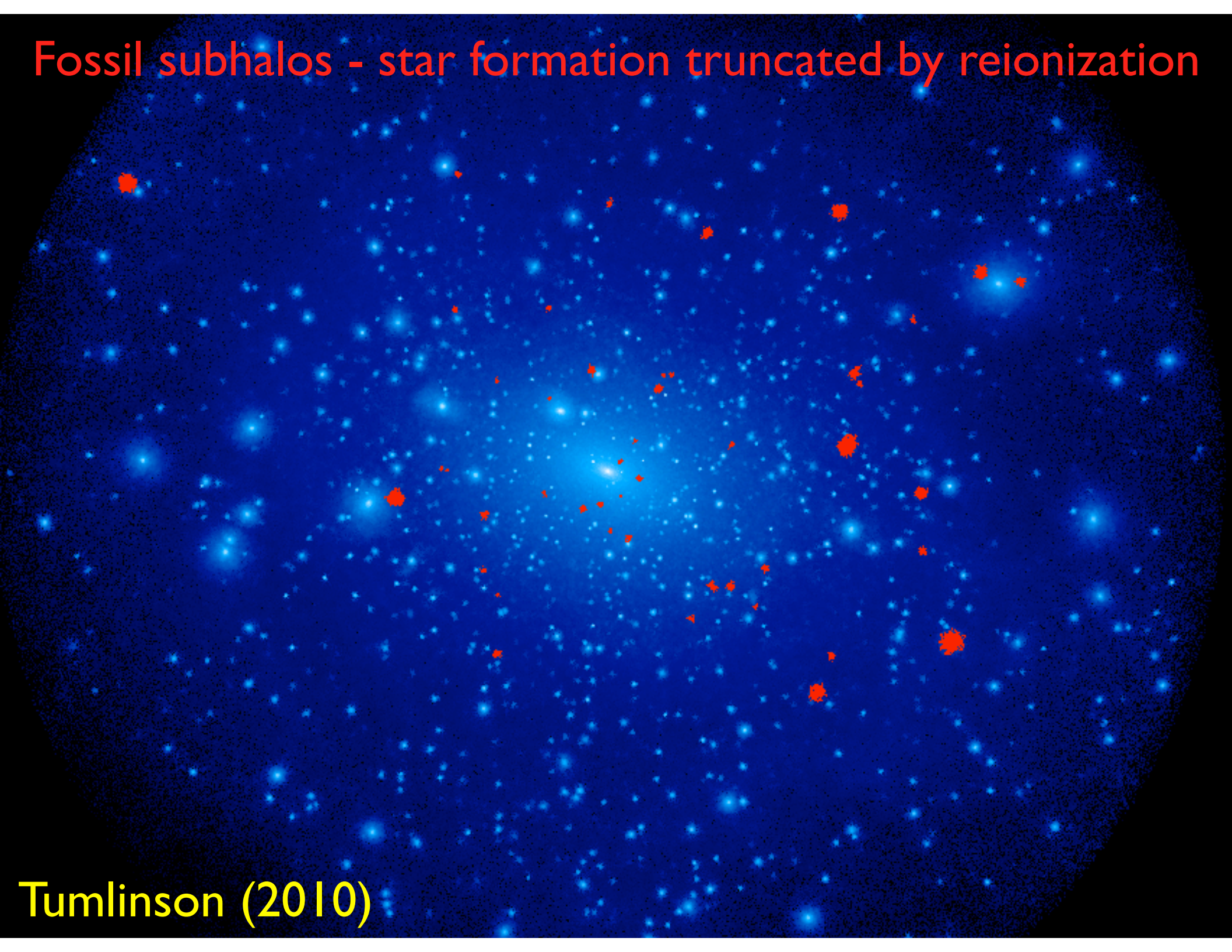
(Bullock+ 2001; Ricotti & Gnedin 2005)

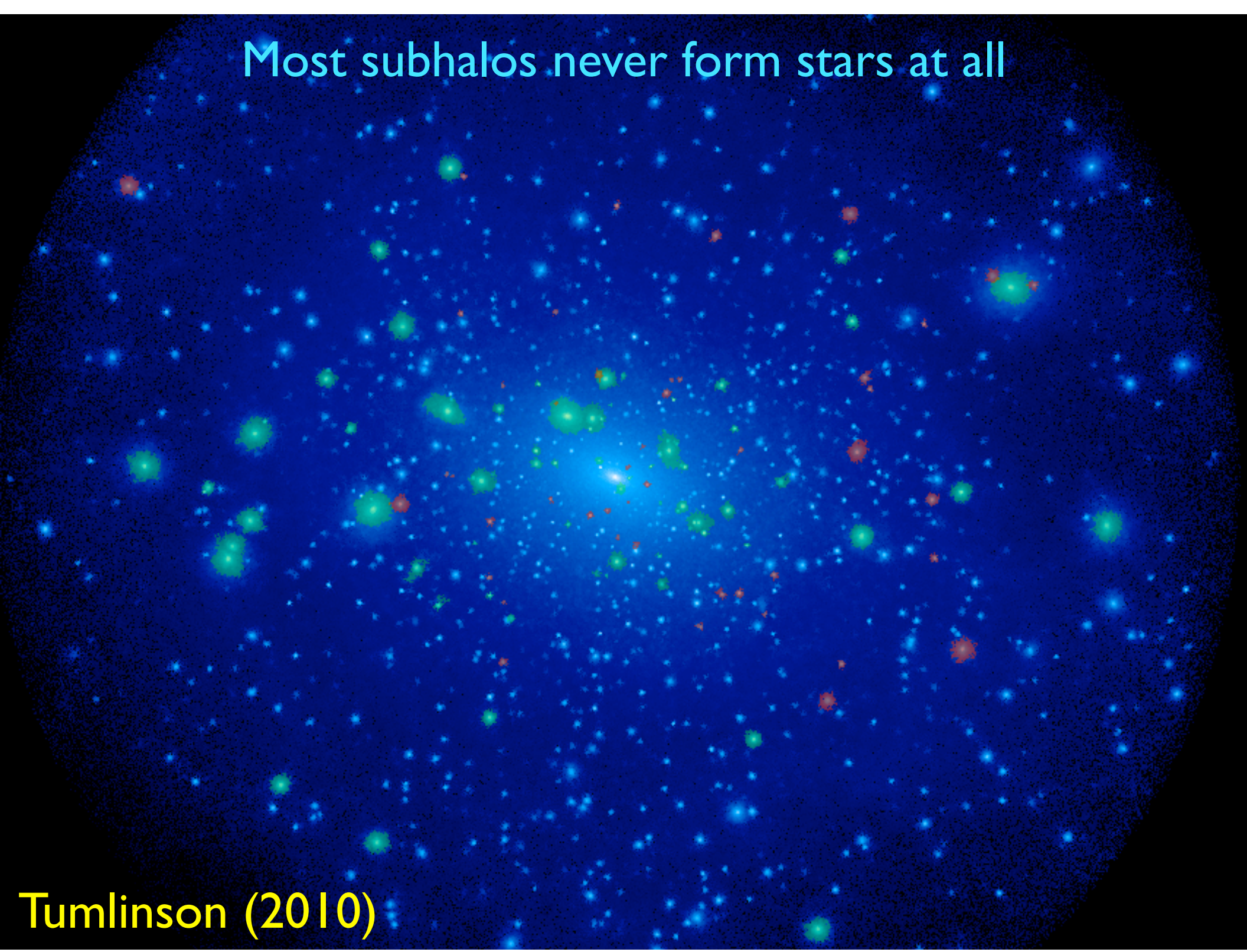


- small dark-matter halos start with little gas
- reionization of universe heats this gas
- thermal pressure boils gas out of halo
- gas is not re-accreted

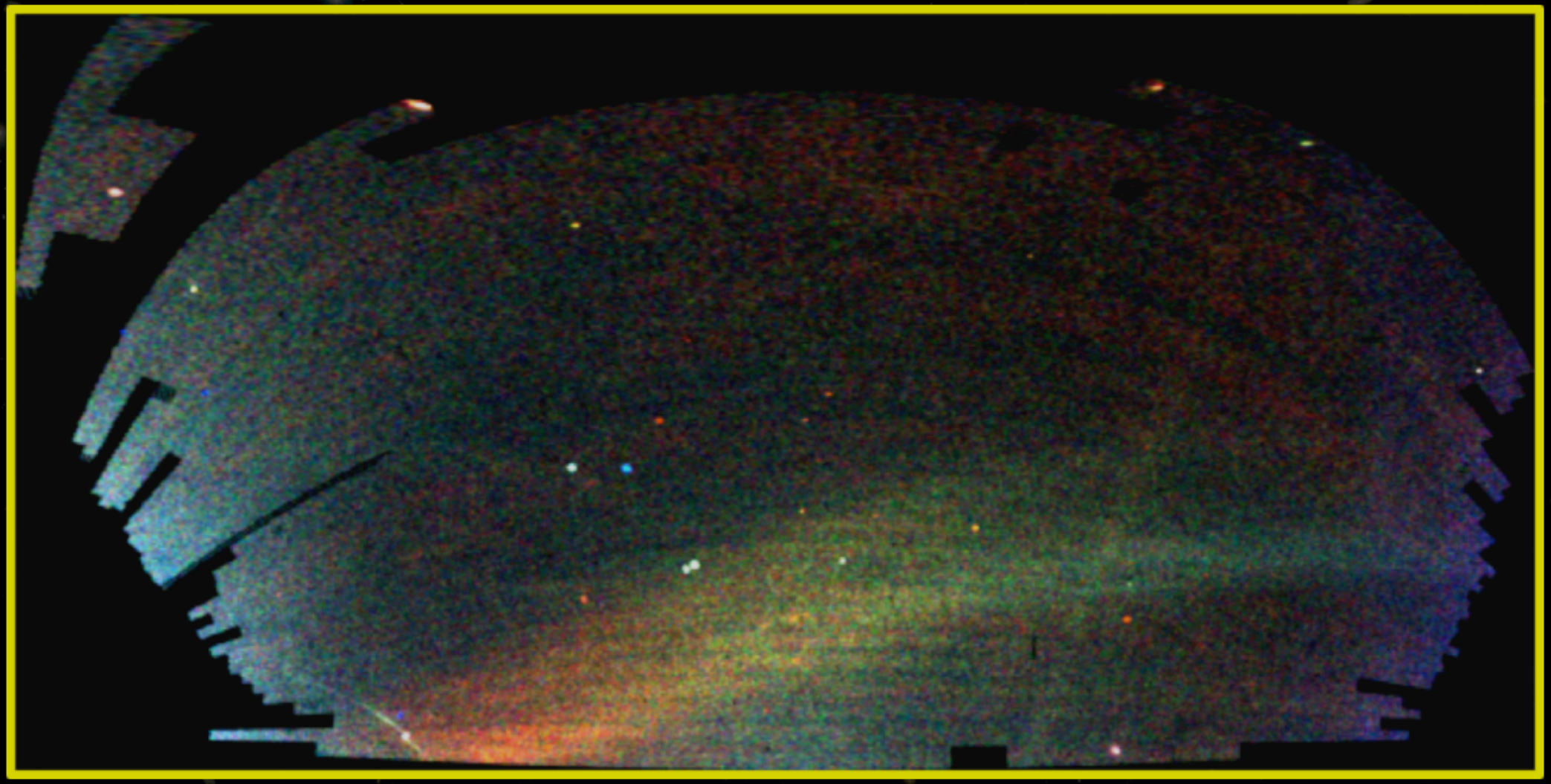

Dark Matter Distribution
350 kpc
Tumlinson (2010)


Subhalos with star formation continuing past reionization
Tumlinson (2010)


Fossil subhalos - star formation truncated by reionization
Tumlinson (2010)

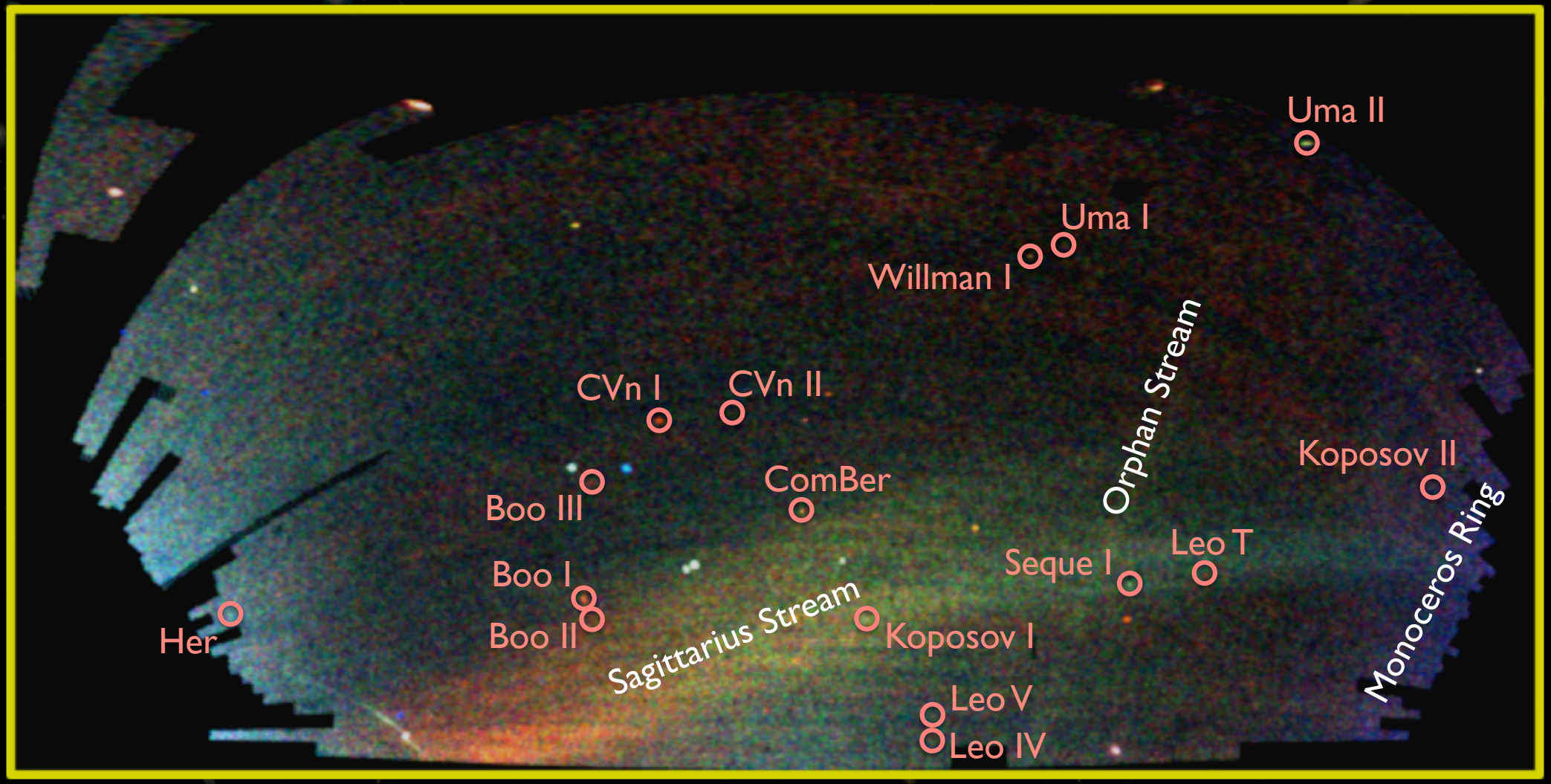

Most subhalos never form stars at all
Tumlinson (2010)

SDSS Field of Streams



Belokurov+ (2007)

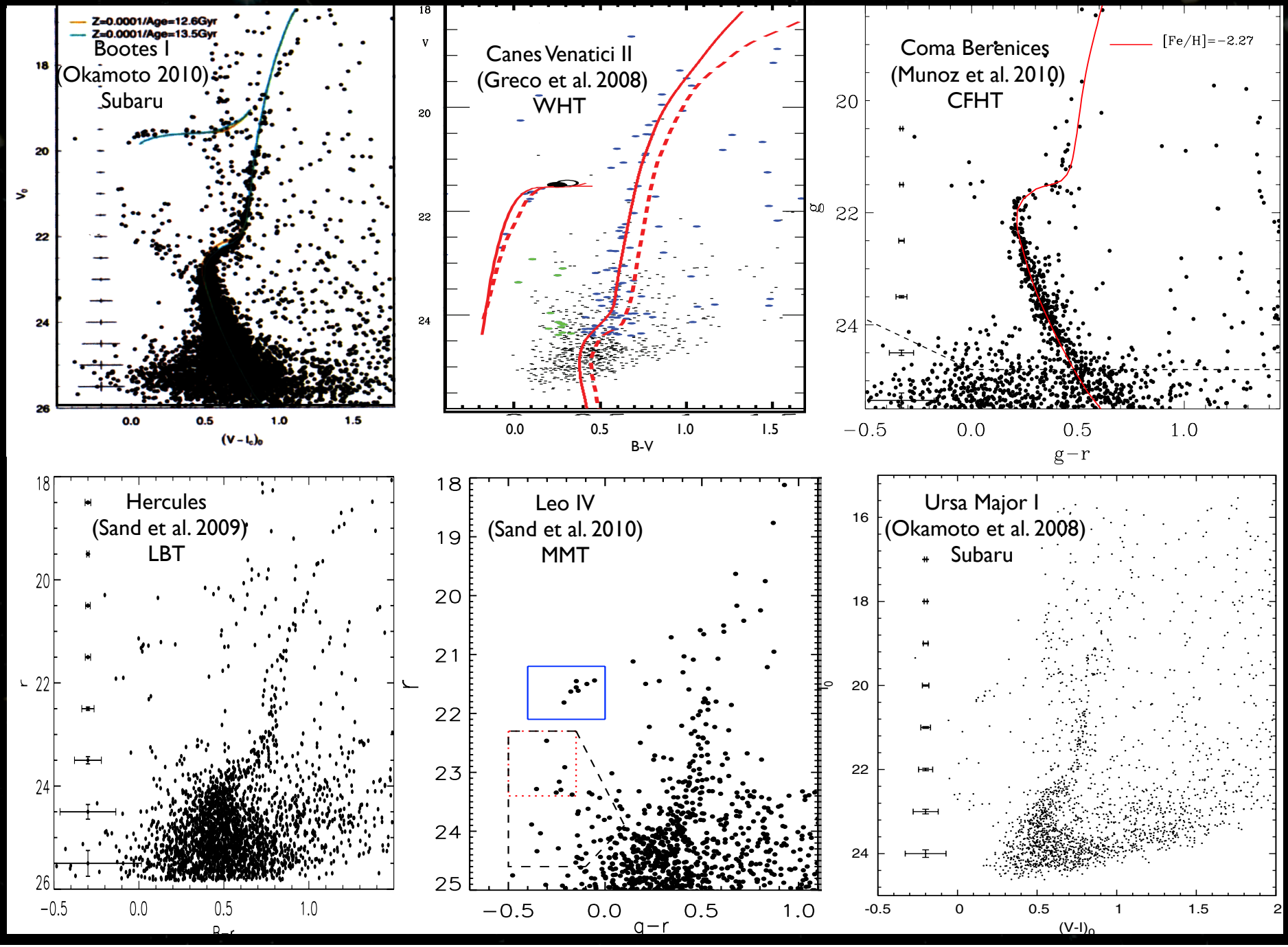
SDSS Field of Streams



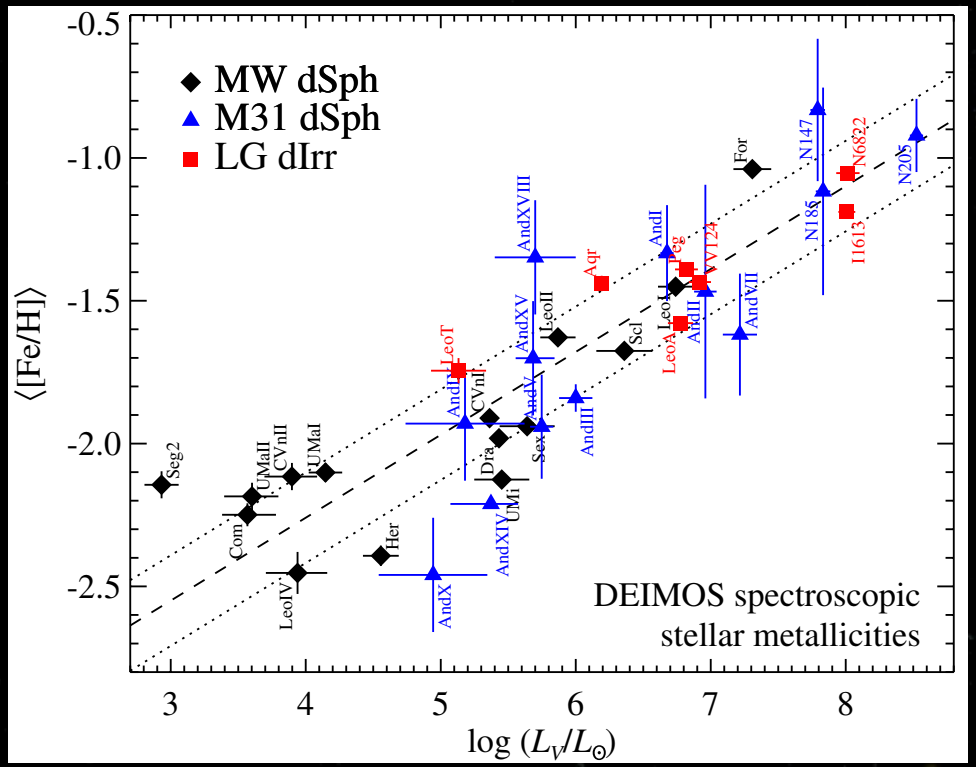
Belokurov+ (2007)

Faint satellites & streams found around MW & M31:
Willman+ 2005; Zucker+ 2004,2005,2006;
McConnachie+ 2009; Majewski+ 2007; Irwin+ 2008;
Belokurov+ 2006; Martin+ 2009; etc.

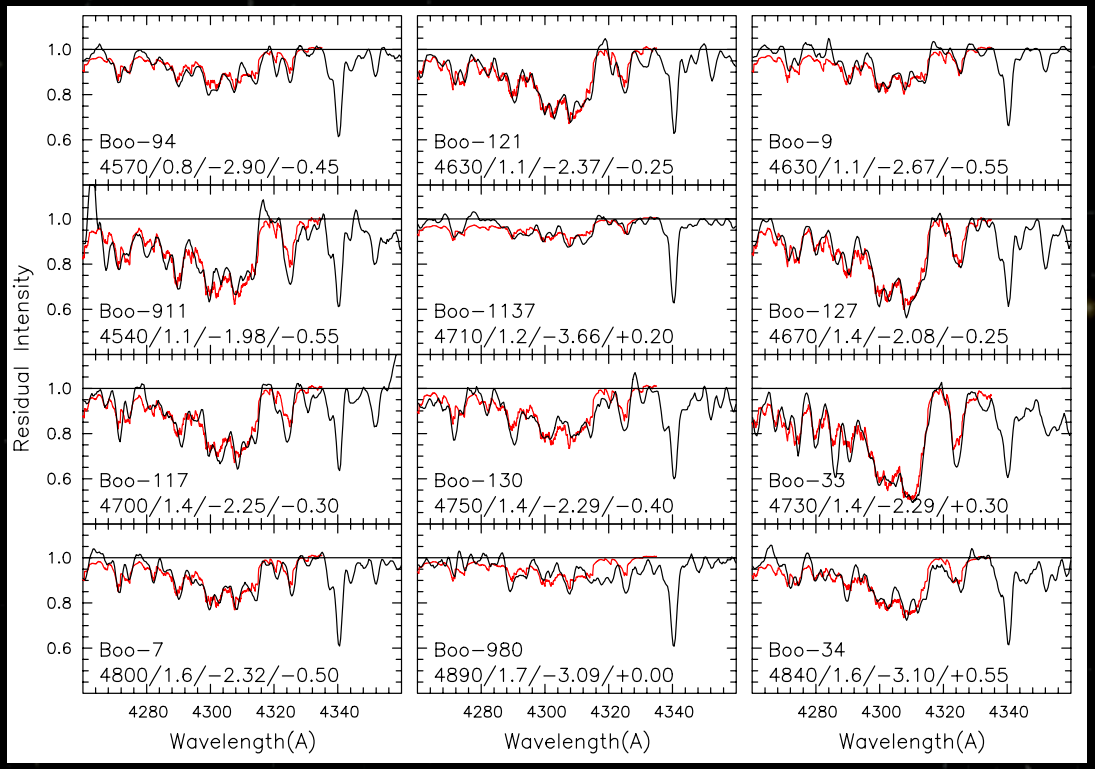
UFDs are old


Z=0.0001/Age=12.6Gyr
Z=0.0001/Age=13.5Gyr
Bootes I
(Okamoto 2010)
Subaru
Canes Venatici II
(Greco et al. 2008)
WHT
Coma Berenices
(Munoz et al. 2010)
CFHT
[Fe/H]=−2.27
Hercules
(Sand et al. 2009)
LBT
Leo IV
(Sand et al. 2010)
MMT
Ursa Major I
(Okamoto et al. 2008)
Subaru

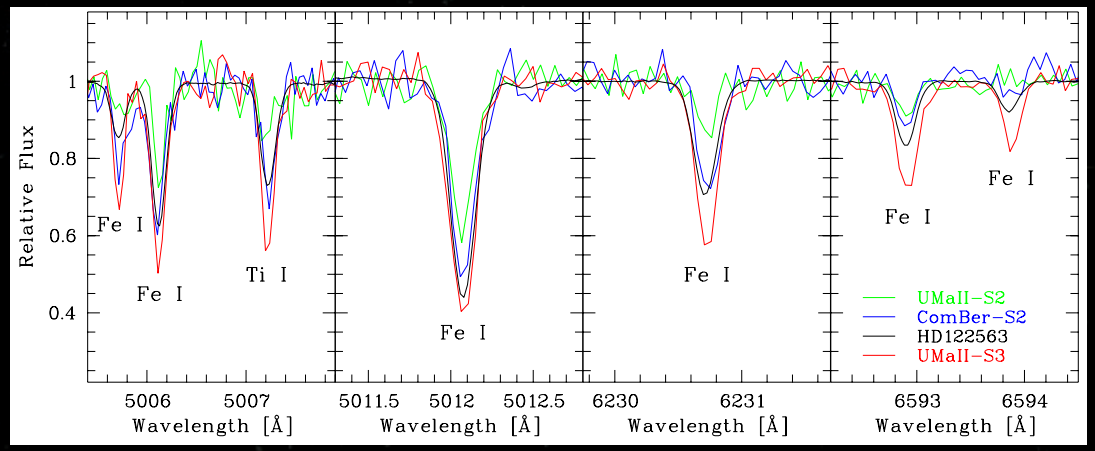
UFDs are metal poor, but with significant metallicity spread



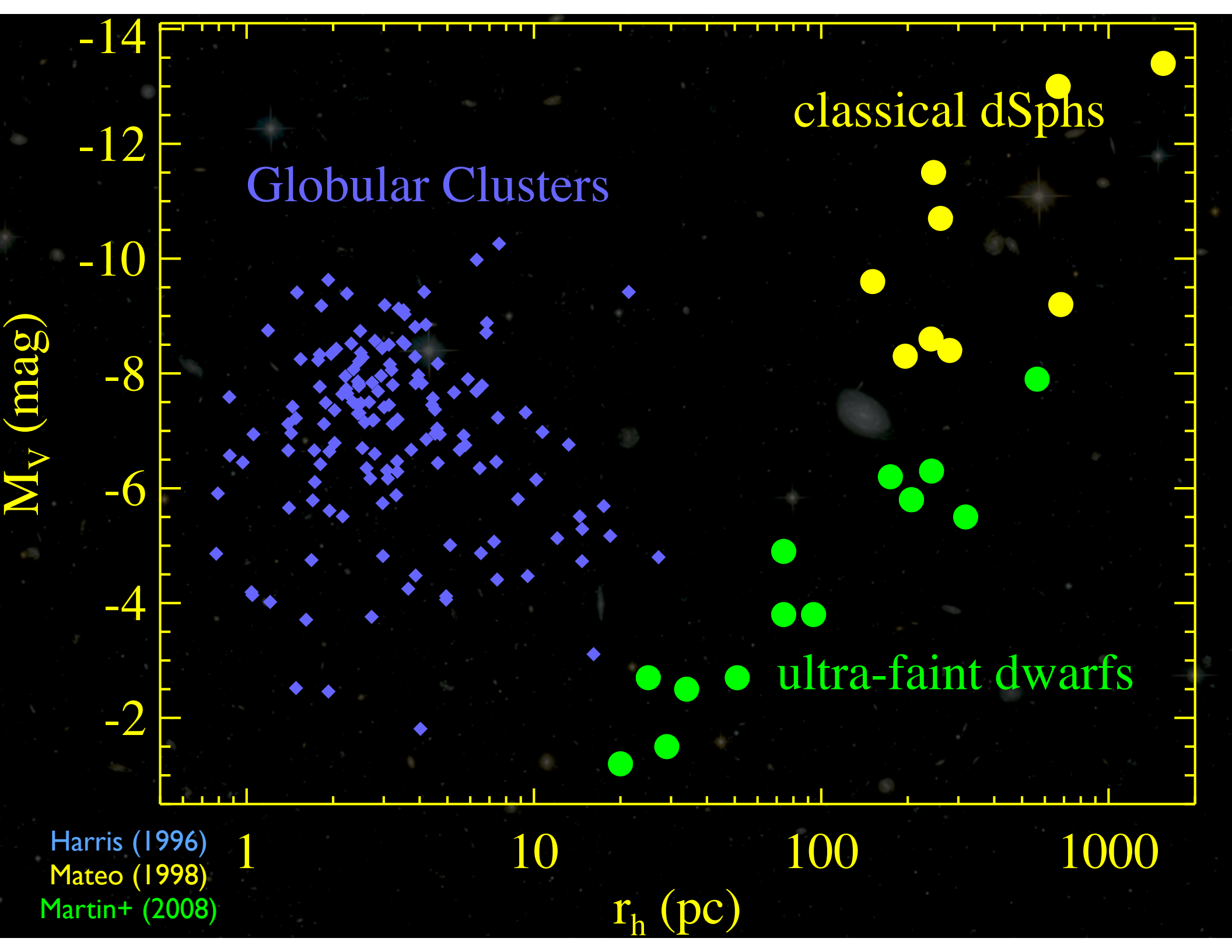
Kirby+ (2008, 2013)

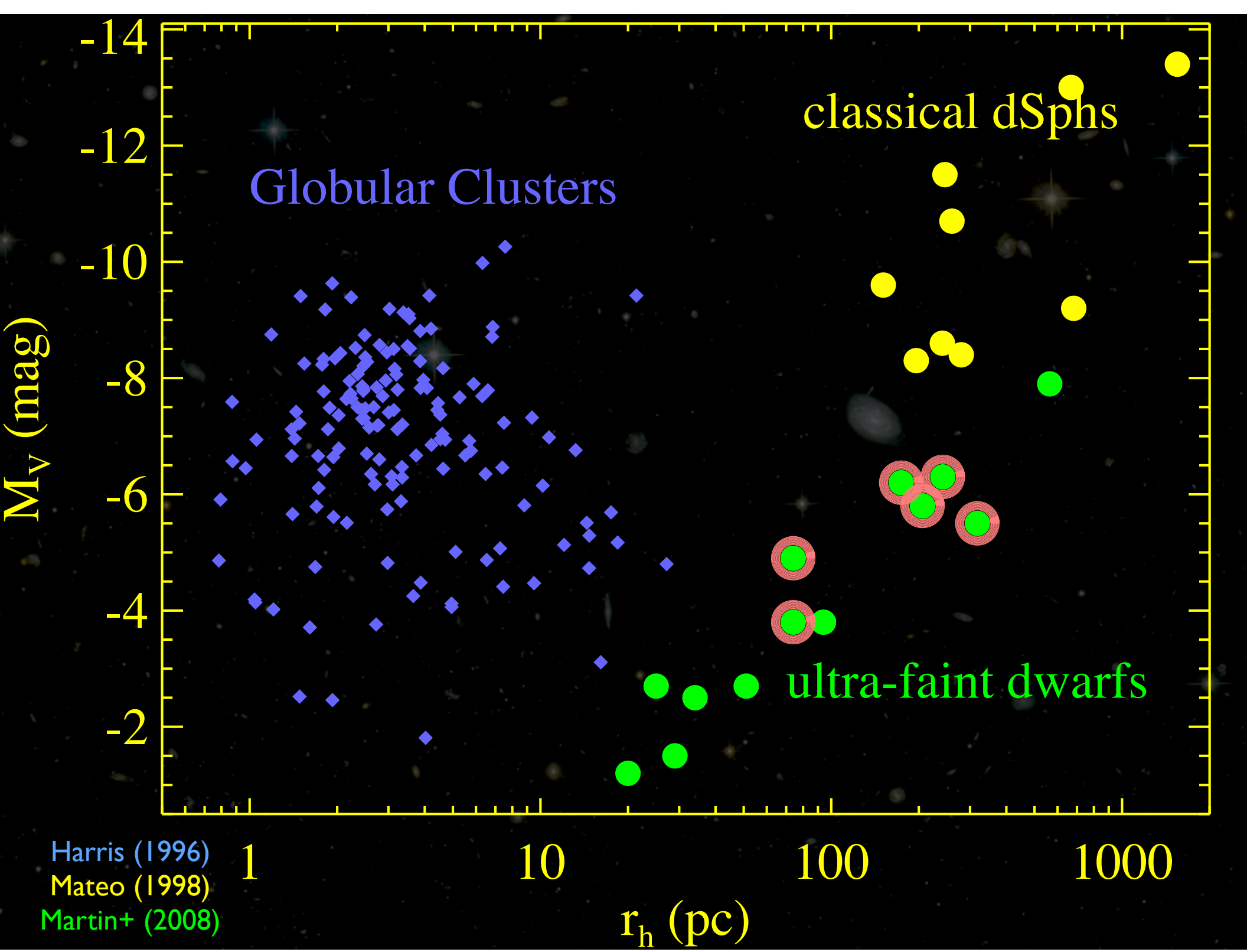


Norris+ (2010)



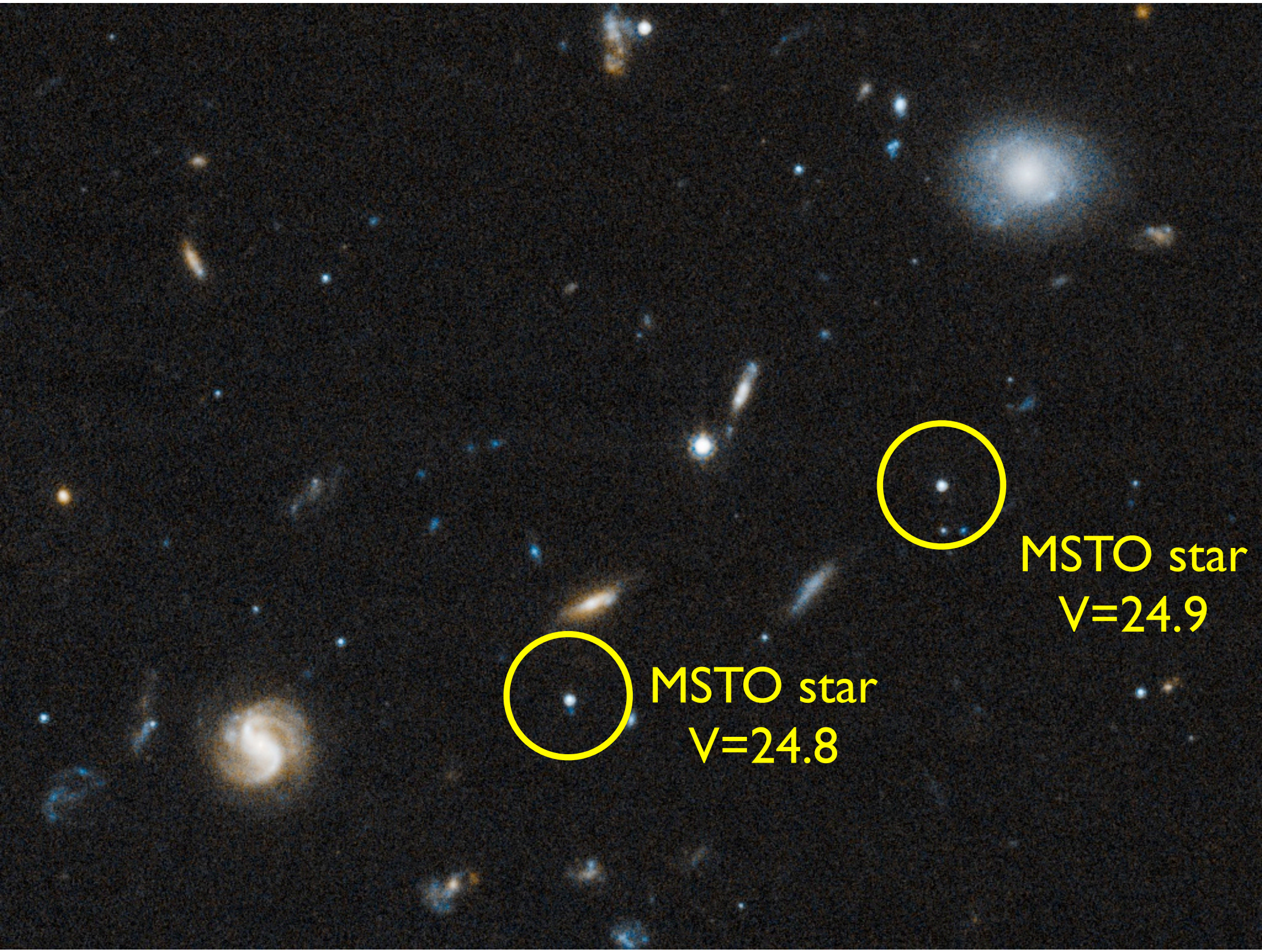
Frebel+ (2010)


-14
-12
-10
-8
-6
-4
-2
M_V (mag)
Globular Clusters
classical dSphs
ultra-faint dwarfs
1
10
100
1000
r_h (pc)
Harris (1996)
Mateo (1998)
Martin+ (2008)

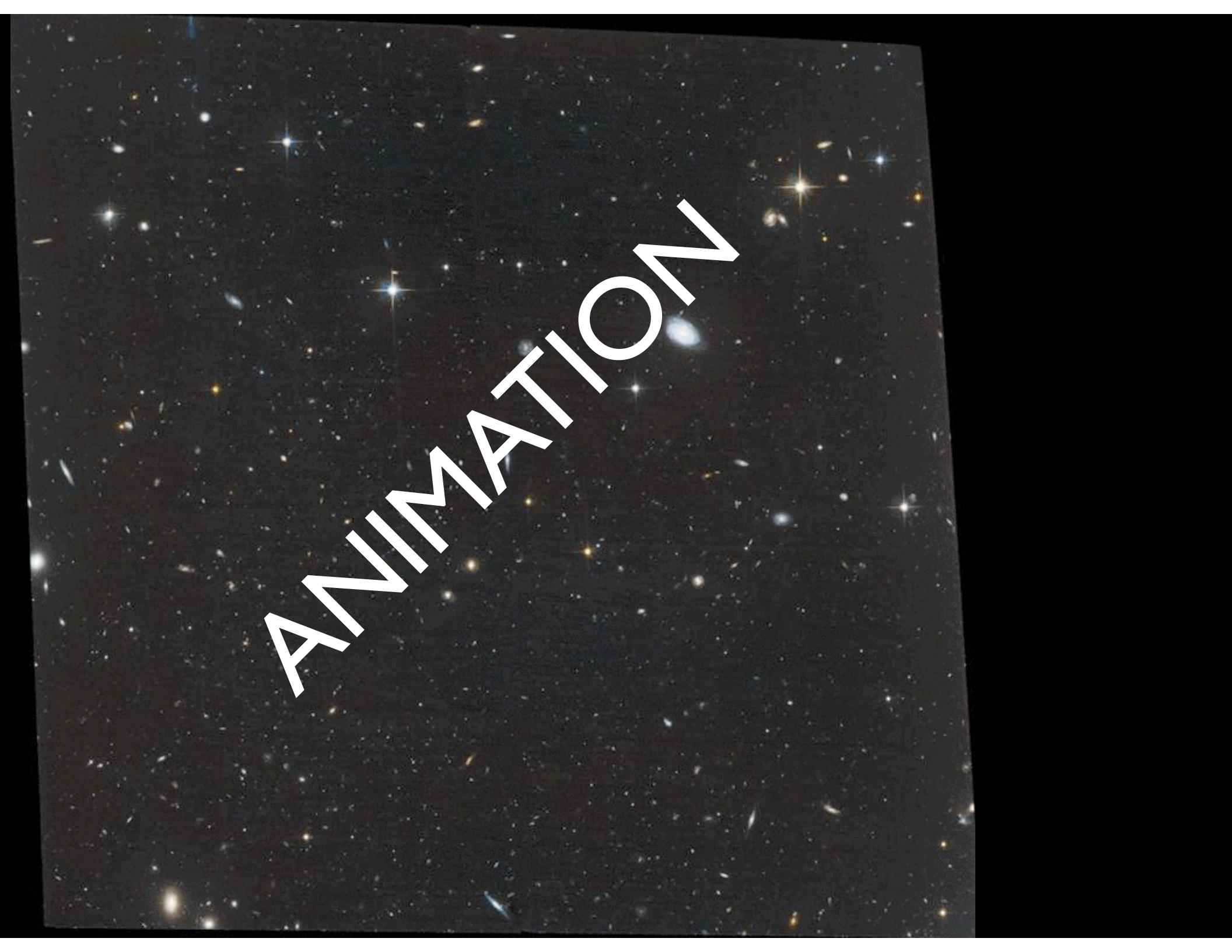

-14
-12
-10
-8
-6
-4
-2
M_V (mag)
Globular Clusters
classical dSphs
ultra-faint dwarfs
1
10
100
1000
r_h (pc)
Harris (1996)
Mateo (1998)
Martin+ (2008)

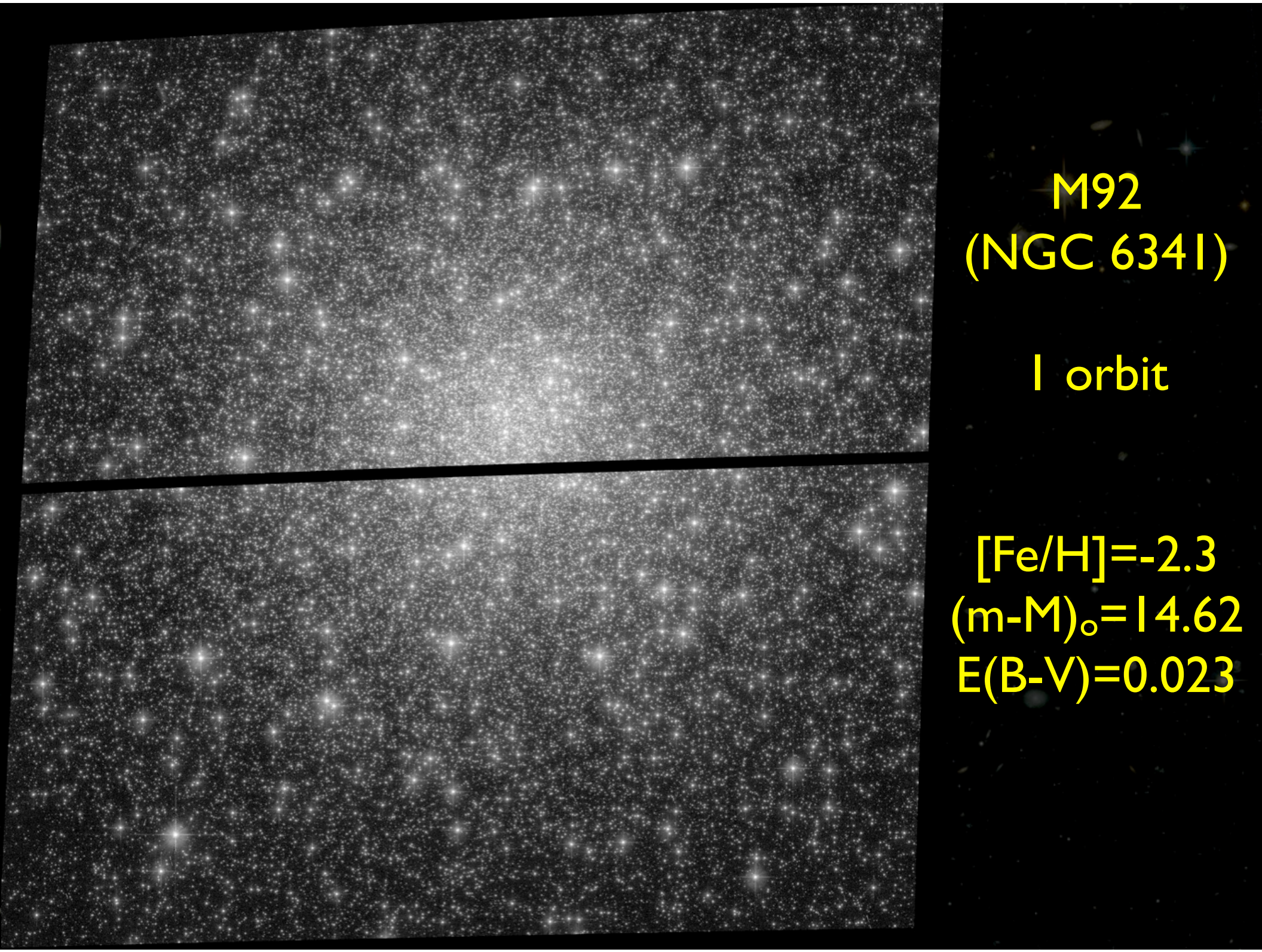

Leo IV
16 orbits
SNR~100
at MSTO
faint limit
V~28.5

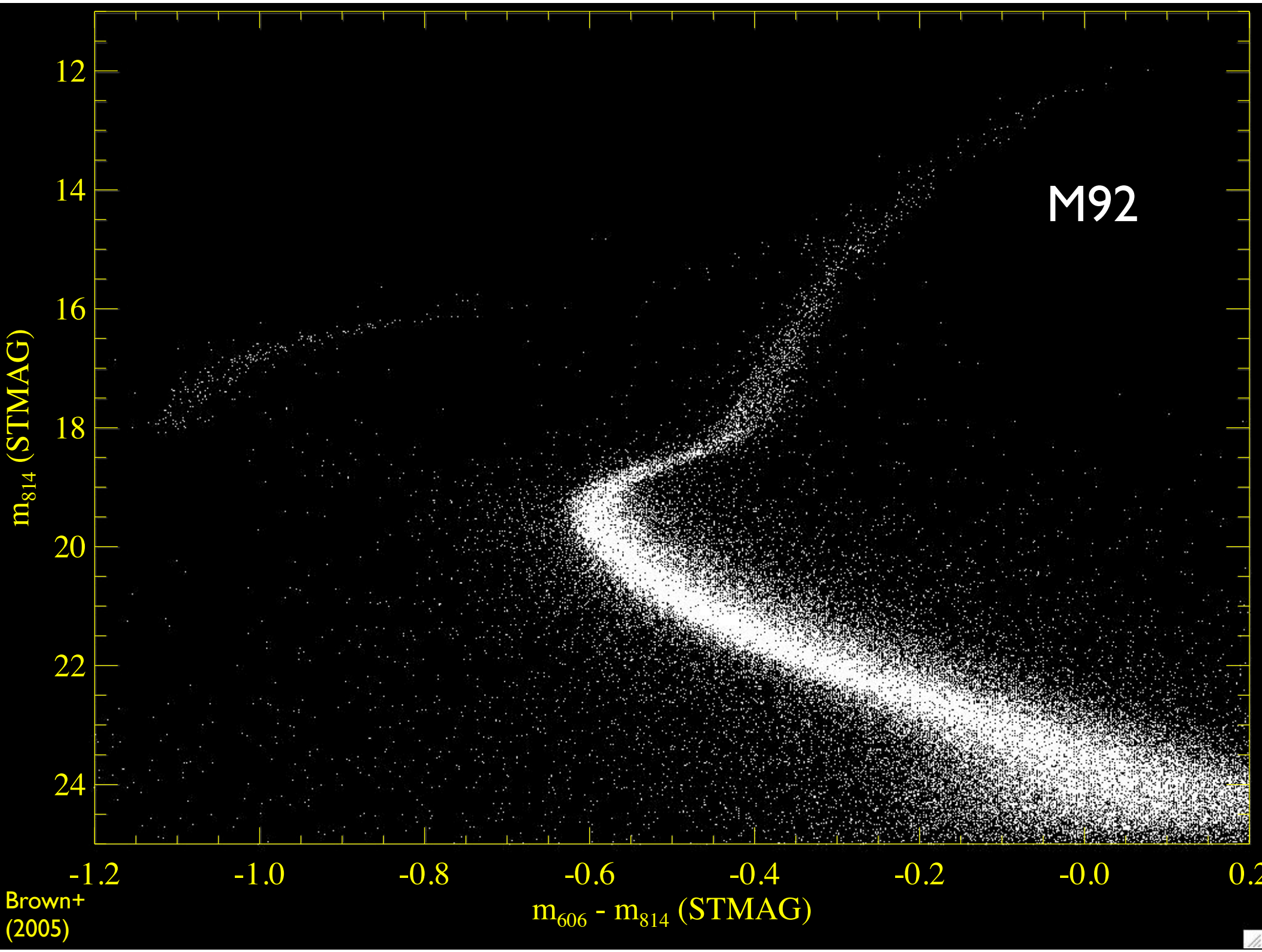

Leo IV
16 orbits
SNR~100
at MSTO
faint limit
V~28.5

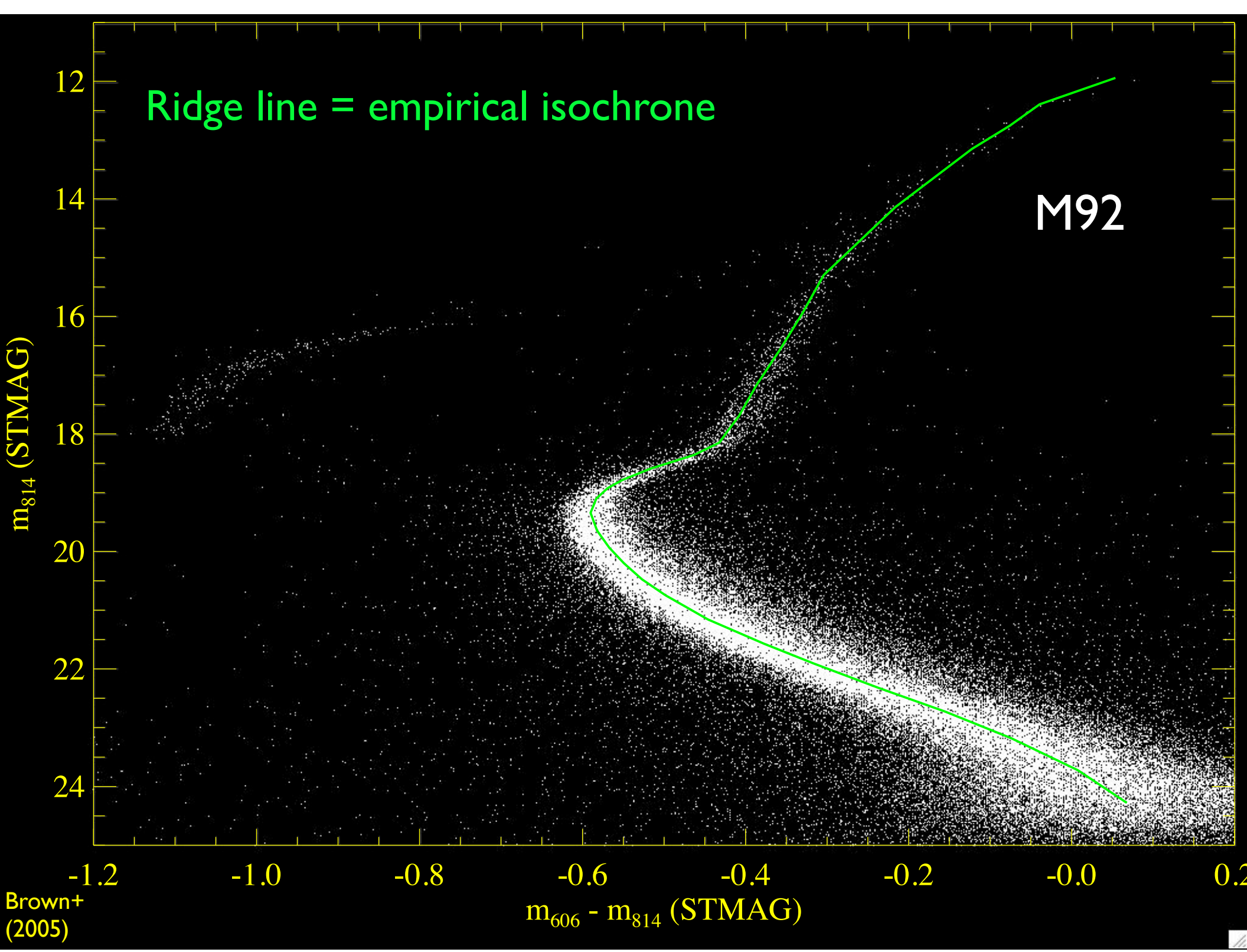

MSTO star
V=24.9
MSTO star
V=24.8

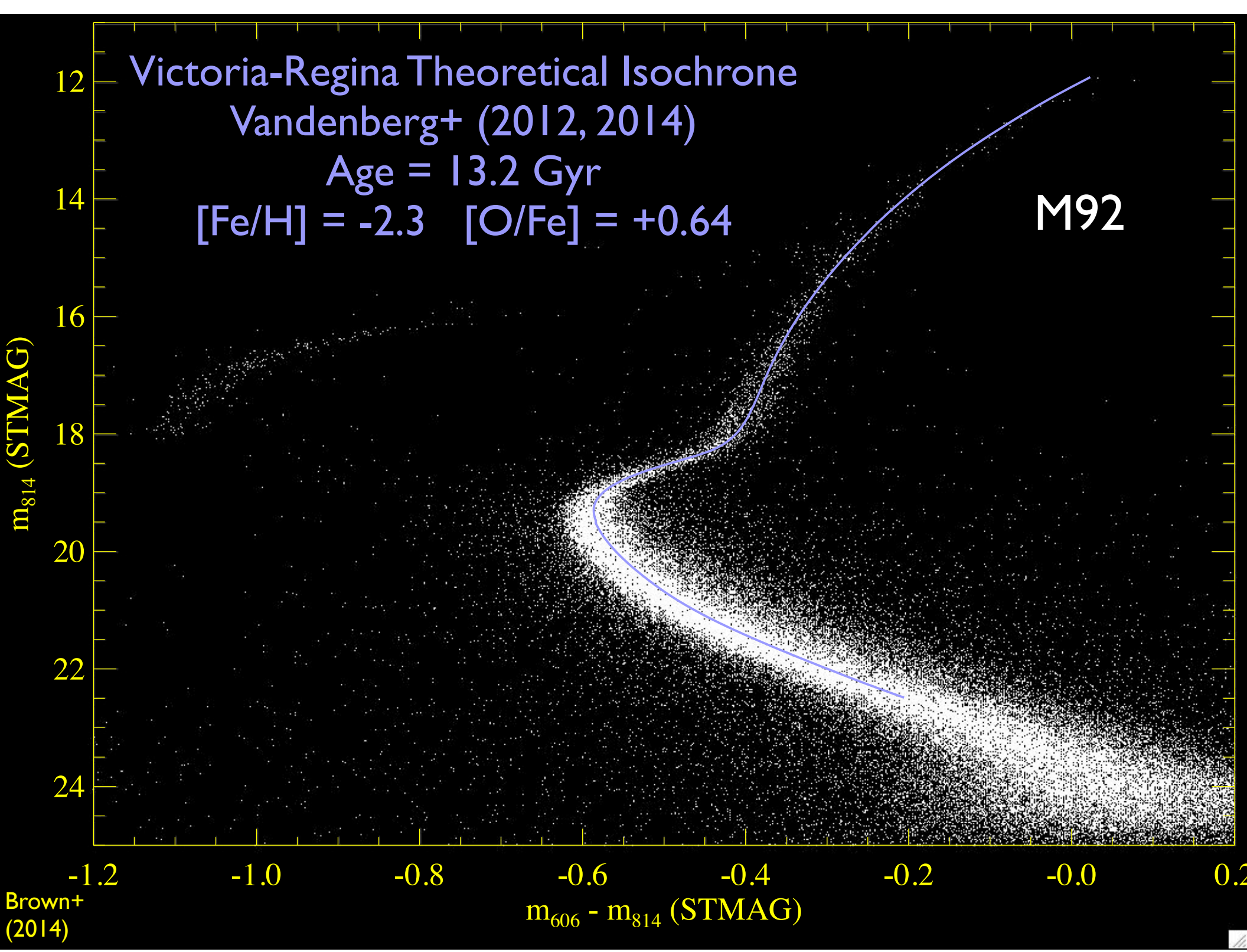

Leo IV
16 orbits
SNR~100
at MSTO
faint limit
V~28.5

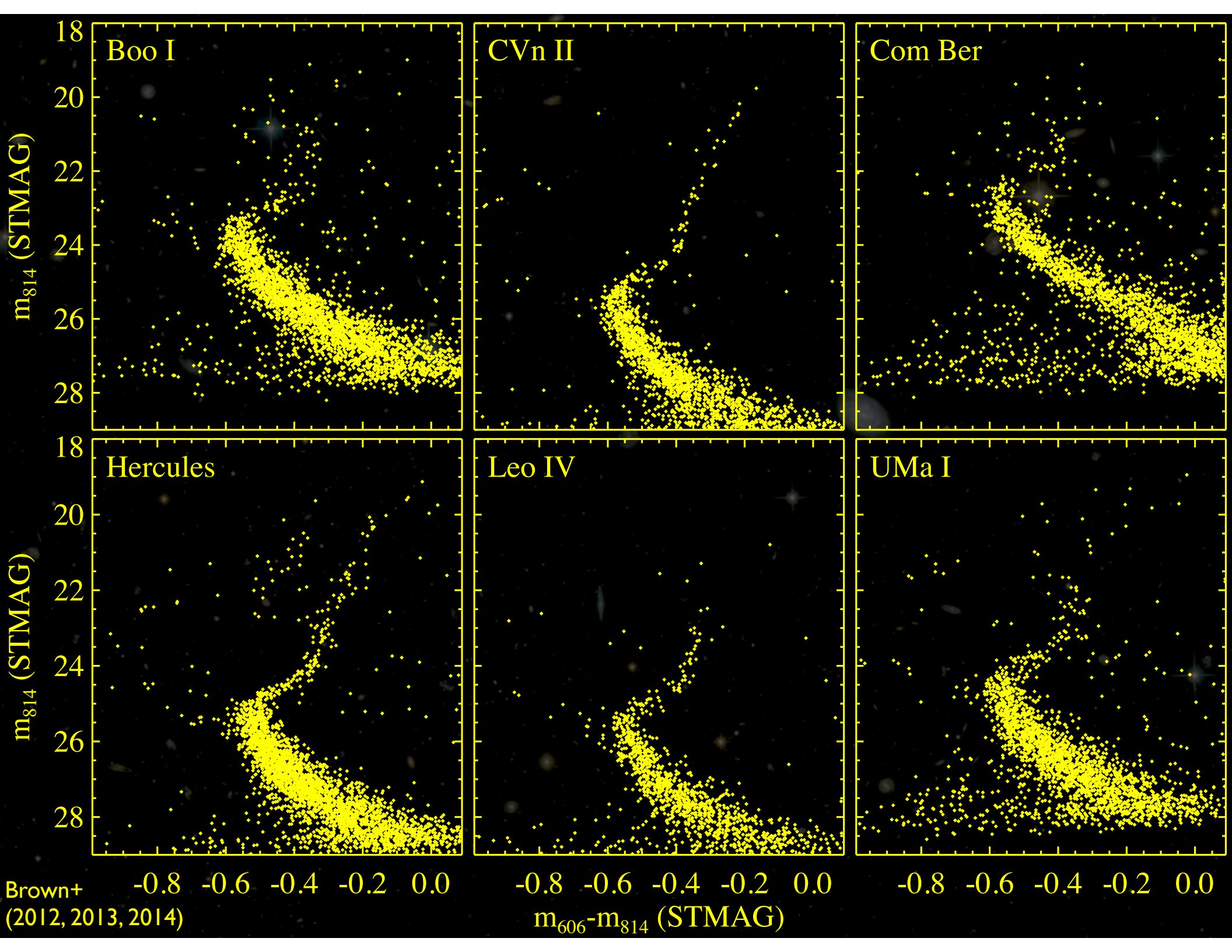

ANIMATION

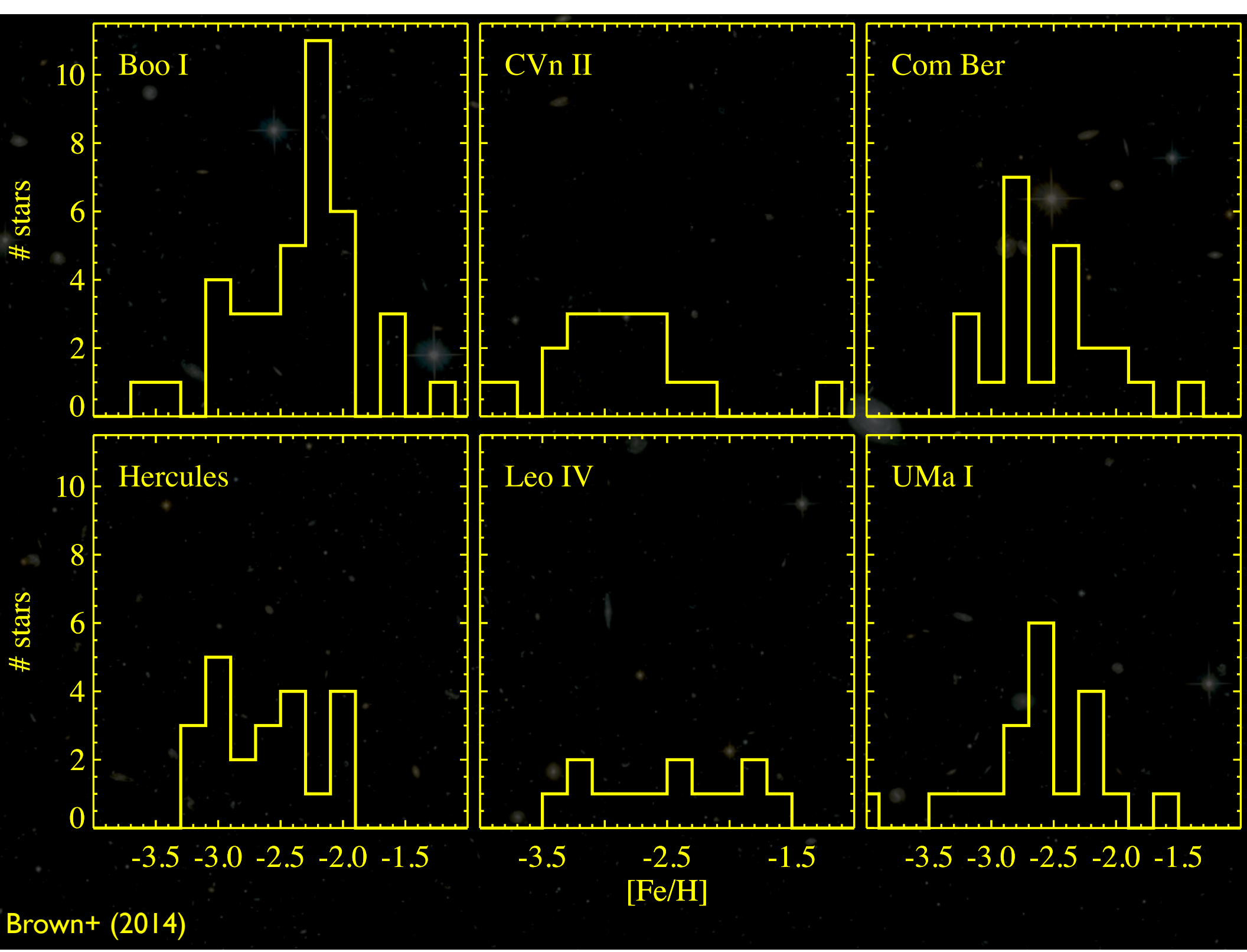

M92
(NGC 6341)
1 orbit
[Fe/H]=-2.3
$(m-M)_o$=14.62
E(B-V)=0.023

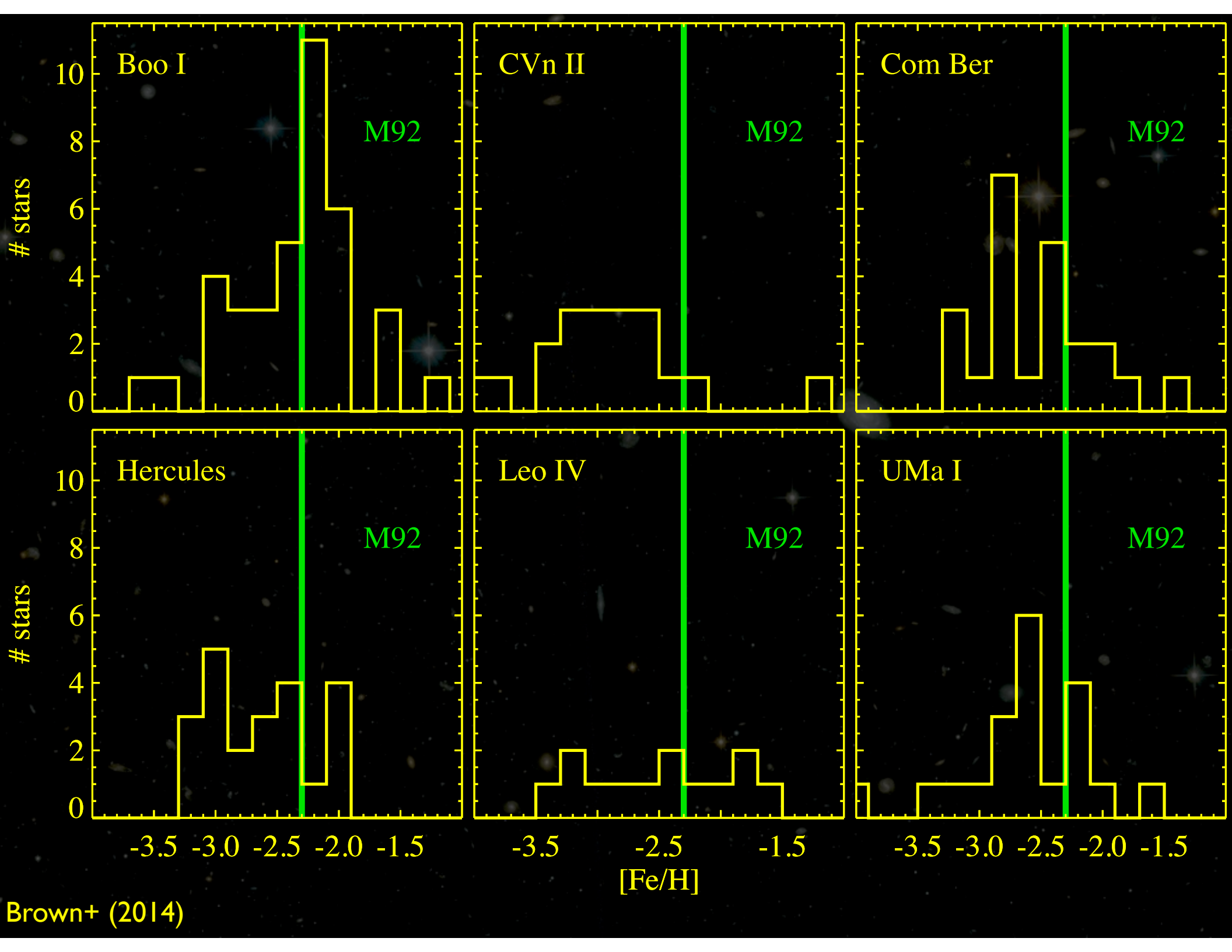

M92
12
14
16
18
20
22
24
m_{814} (STMAG)
-1.2
-1.0
-0.8
-0.6
-0.4
-0.2
-0.0
0.2
m_{606} - m_{814} (STMAG)
Brown+
(2005)

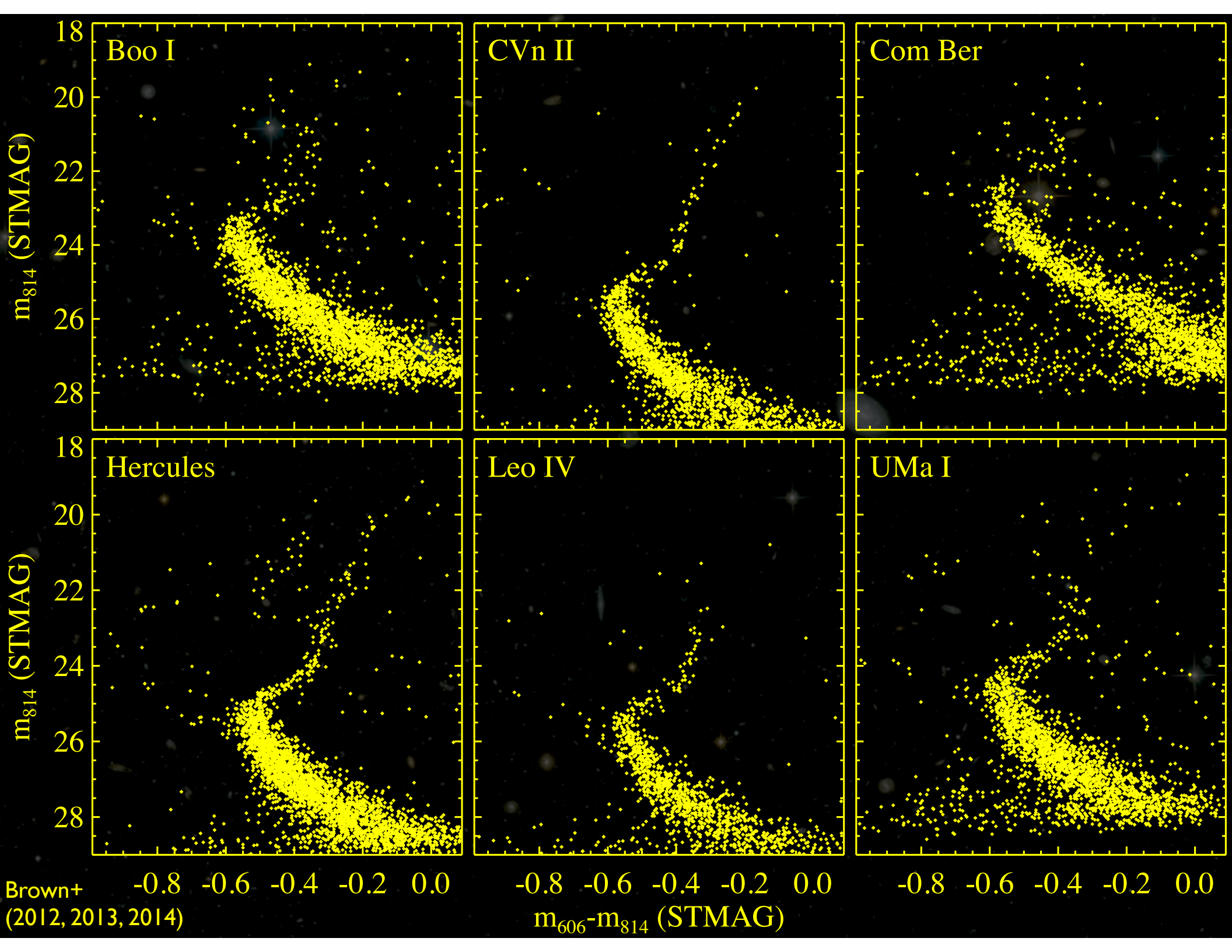

Ridge line = empirical isochrone
M92
12
14
16
18
20
22
24
m_{814} (STMAG)
-1.2
-1.0
-0.8
-0.6
-0.4
-0.2
-0.0
0.2
m_{606} - m_{814} (STMAG)
Brown+
(2005)

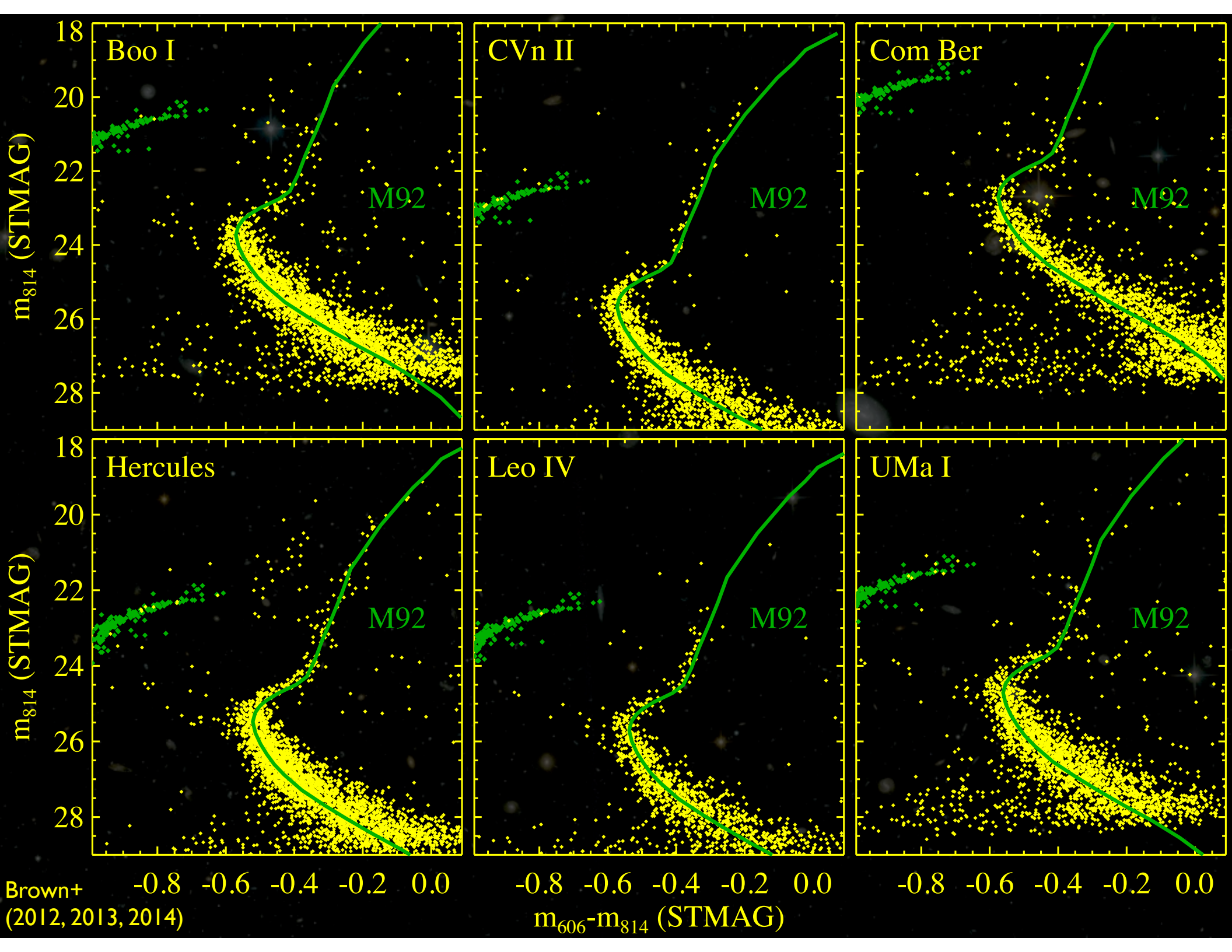

Victoria-Regina Theoretical Isochrone
Vandenberg+ (2012, 2014)
Age = 13.2 Gyr
[Fe/H] = -2.3 [O/Fe] = +0.64
M92
12
14
16
18
20
22
24
m_{814} (STMAG)
-1.2
-1.0
-0.8
-0.6
-0.4
-0.2
-0.0
0.2
m_{606} - m_{814} (STMAG)
Brown+ (2014)

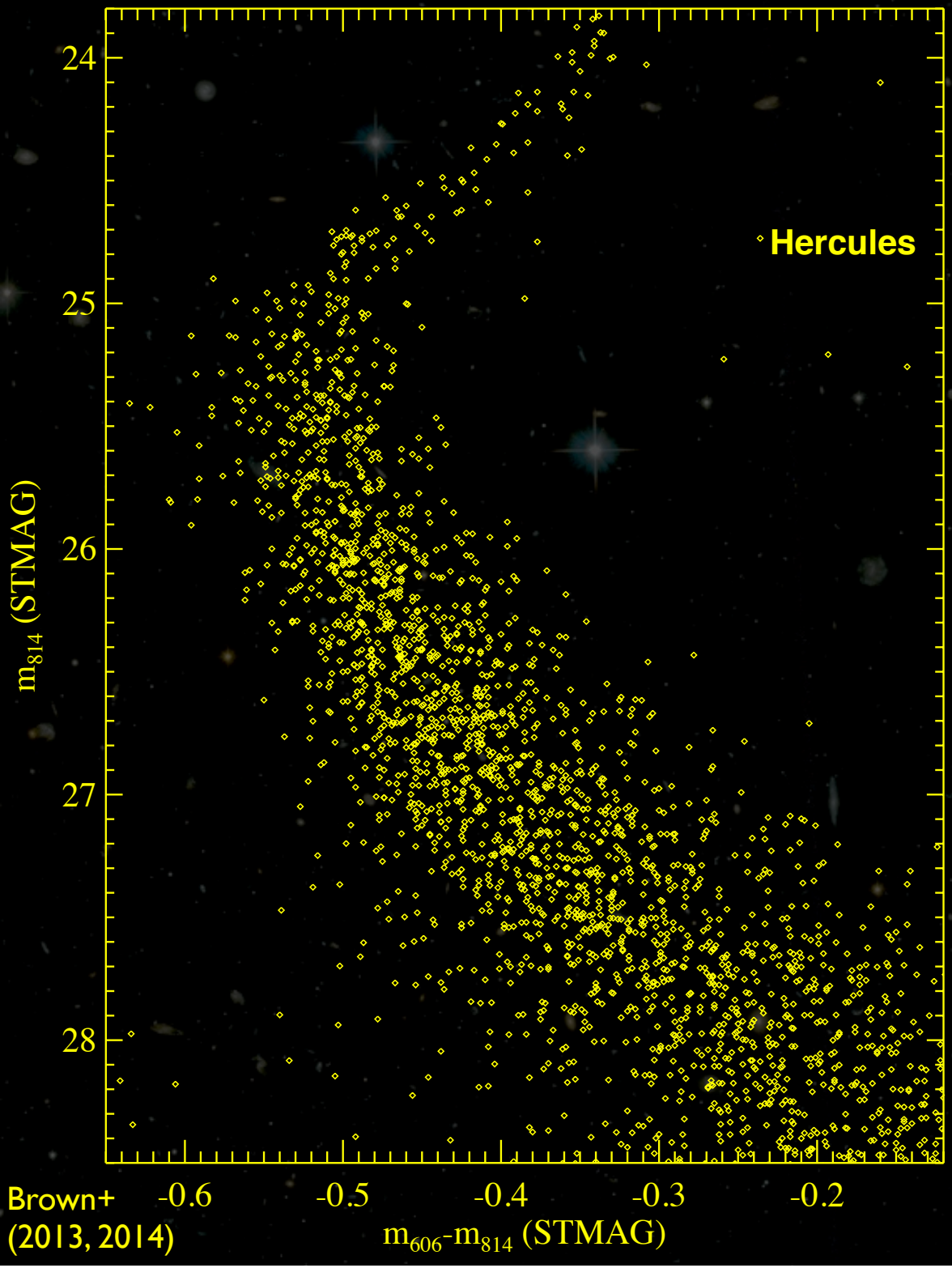

Boo I
CVn II
Com Ber
Hercules
Leo IV
UMa I
18
20
22
24
26
28
m_{814} (STMAG)
-0.8
-0.6
-0.4
-0.2
0.0
m_{606}-m_{814} (STMAG)
Brown+
(2012, 2013, 2014)


Boo I
CVn II
Com Ber
Hercules
Leo IV
UMa I
stars
stars
0
2
4
6
8
10
-3.5
-3.0
-2.5
-2.0
-1.5
[Fe/H]
Brown+ (2014)


Boo I
CVn II
Com Ber
Hercules
Leo IV
UMa I
M92
stars
[Fe/H]
0
2
4
6
8
10
-3.5
-3.0
-2.5
-2.0
-1.5
Brown+ (2014)

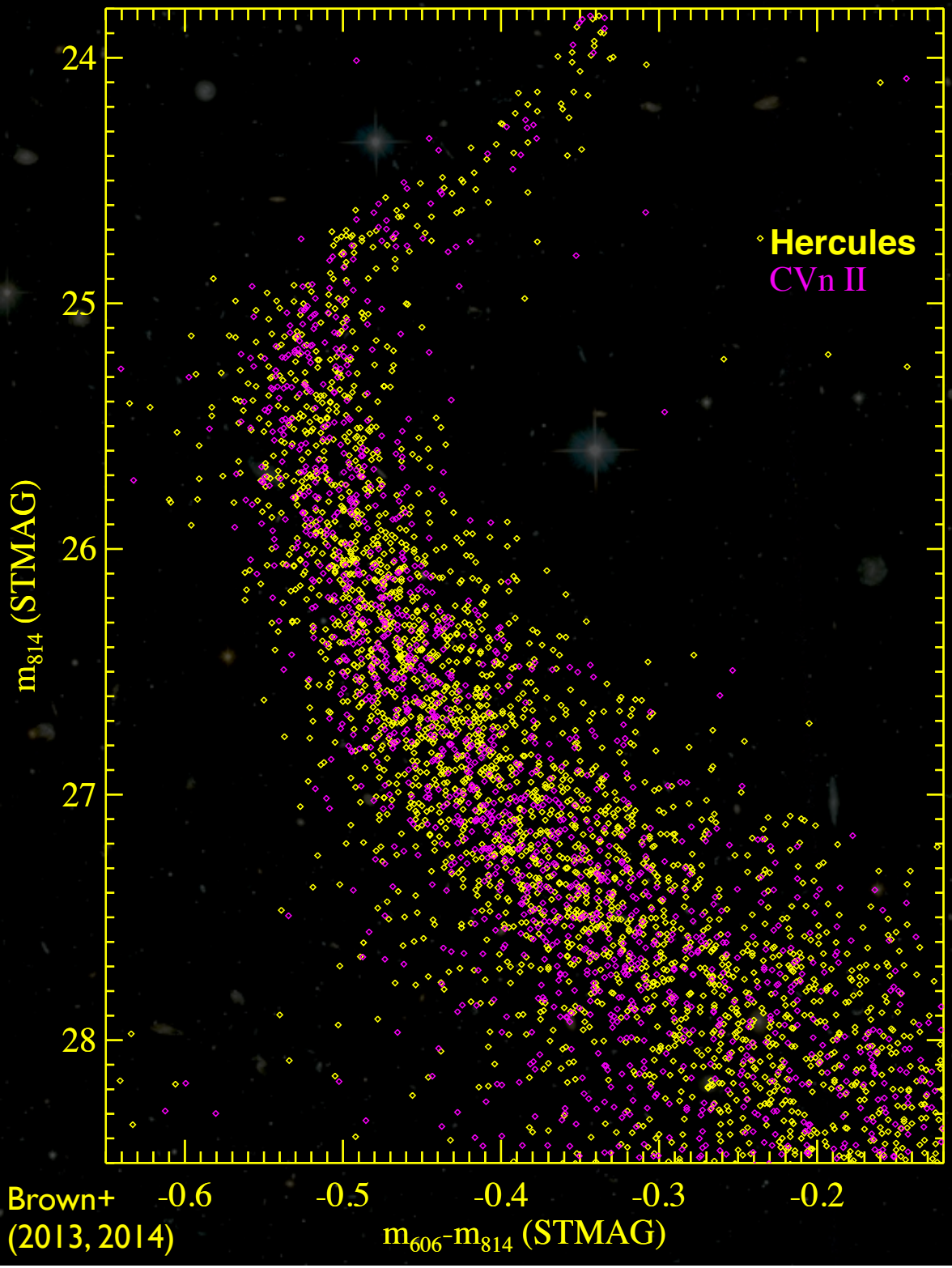

Boo I
CVn II
Com Ber
Hercules
Leo IV
UMa I
18
20
22
24
26
28
m_{814} (STMAG)
-0.8
-0.6
-0.4
-0.2
0.0
m_{606}-m_{814} (STMAG)
Brown+
(2012, 2013, 2014)


Boo I
CVn II
Com Ber
Hercules
Leo IV
UMa I
M92
18
20
22
24
26
28
m_{814} (STMAG)
-0.8
-0.6
-0.4
-0.2
0.0
m_{606}-m_{814} (STMAG)
Brown+
(2012, 2013, 2014)



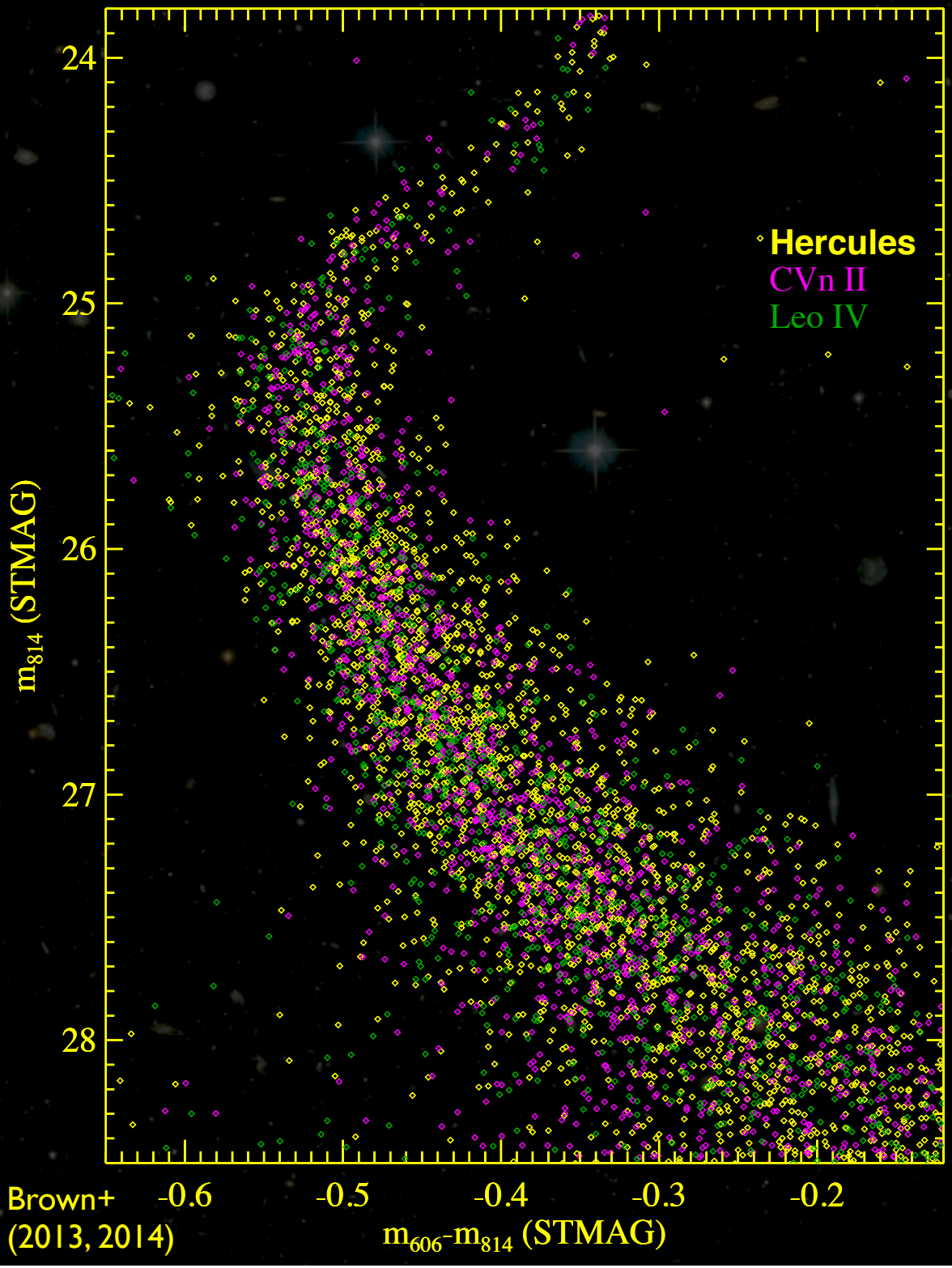
CMDs of the UFDs, all look very similar

Composite UFD CMD looks like a single-age population (to first order)



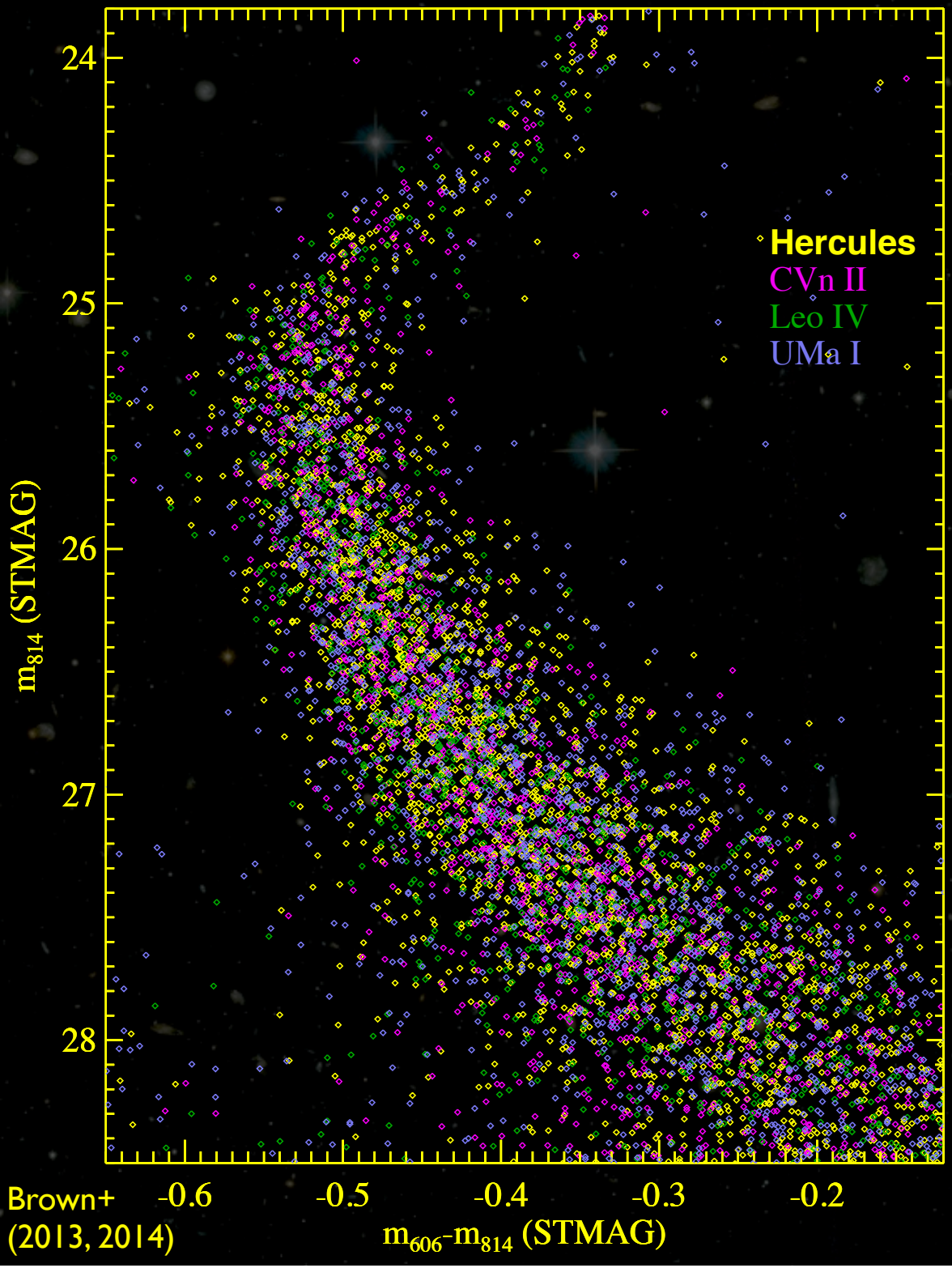
CMDs of the UFDs, all look very similar

Composite UFD CMD looks like a single-age population (to first order)



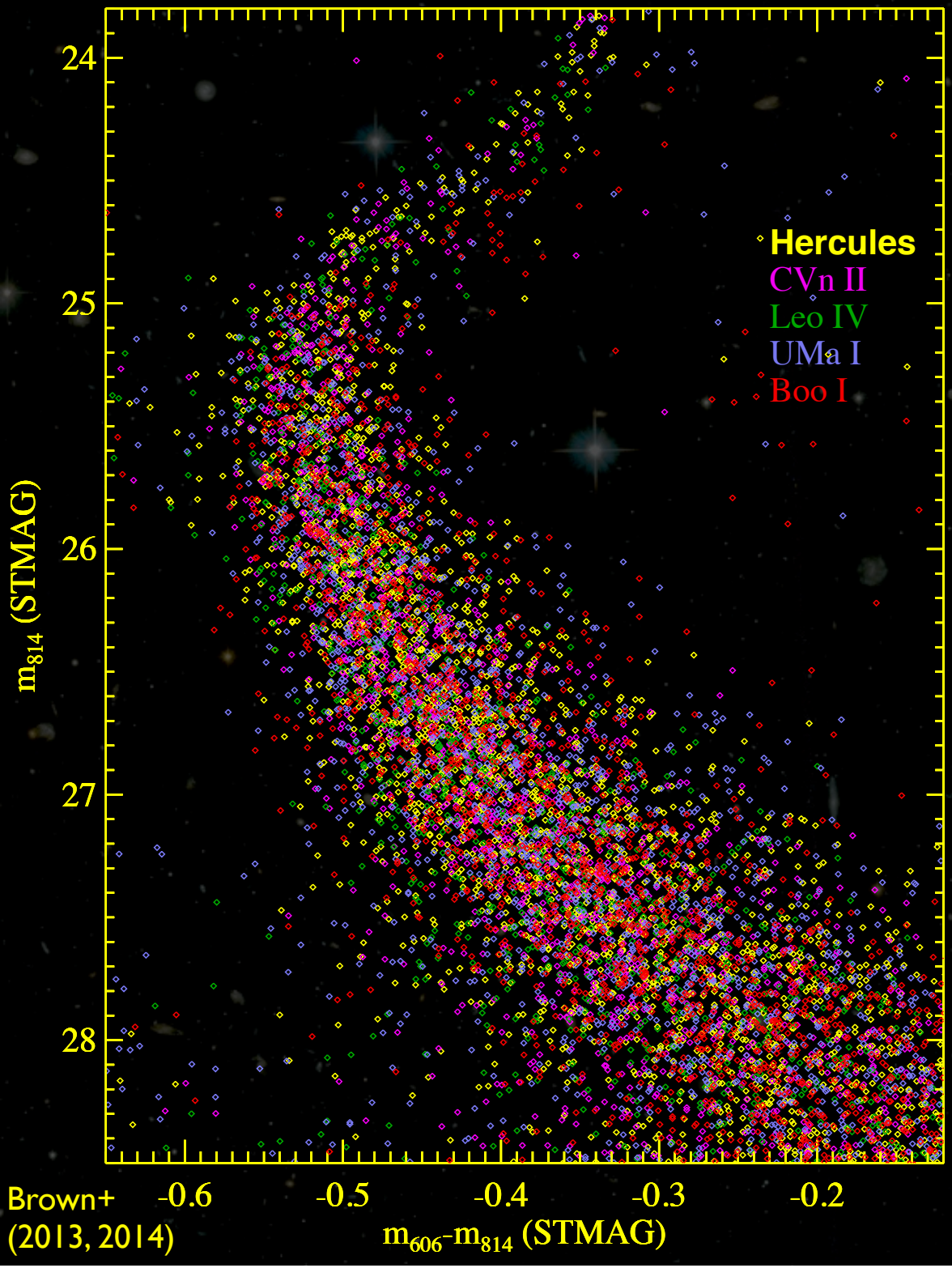
CMDs of the UFDs, all look very similar

Composite UFD CMD looks like a single-age population (to first order)



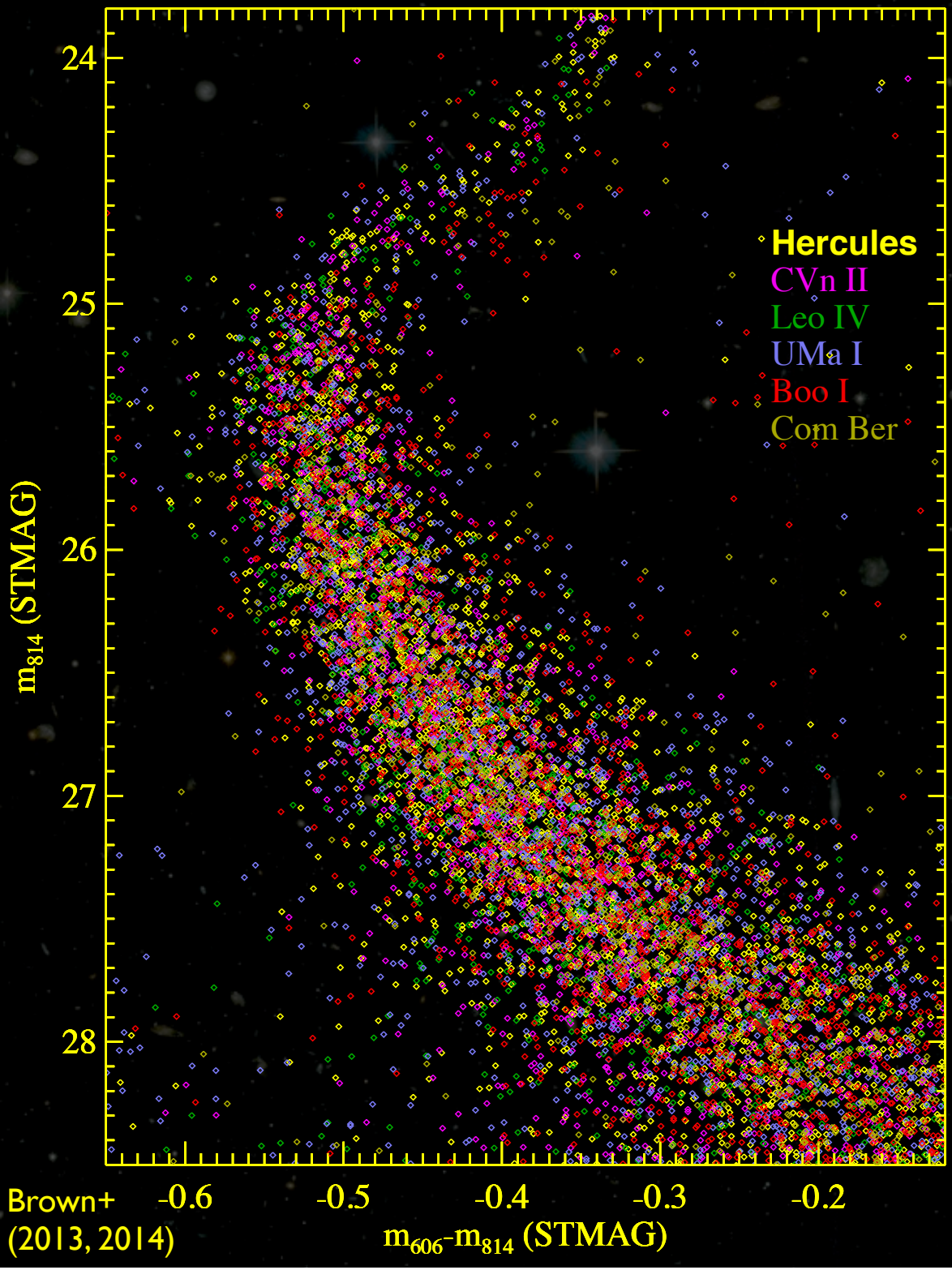
CMDs of the UFDs, all look very similar

Composite UFD CMD looks like a single-age population (to first order)



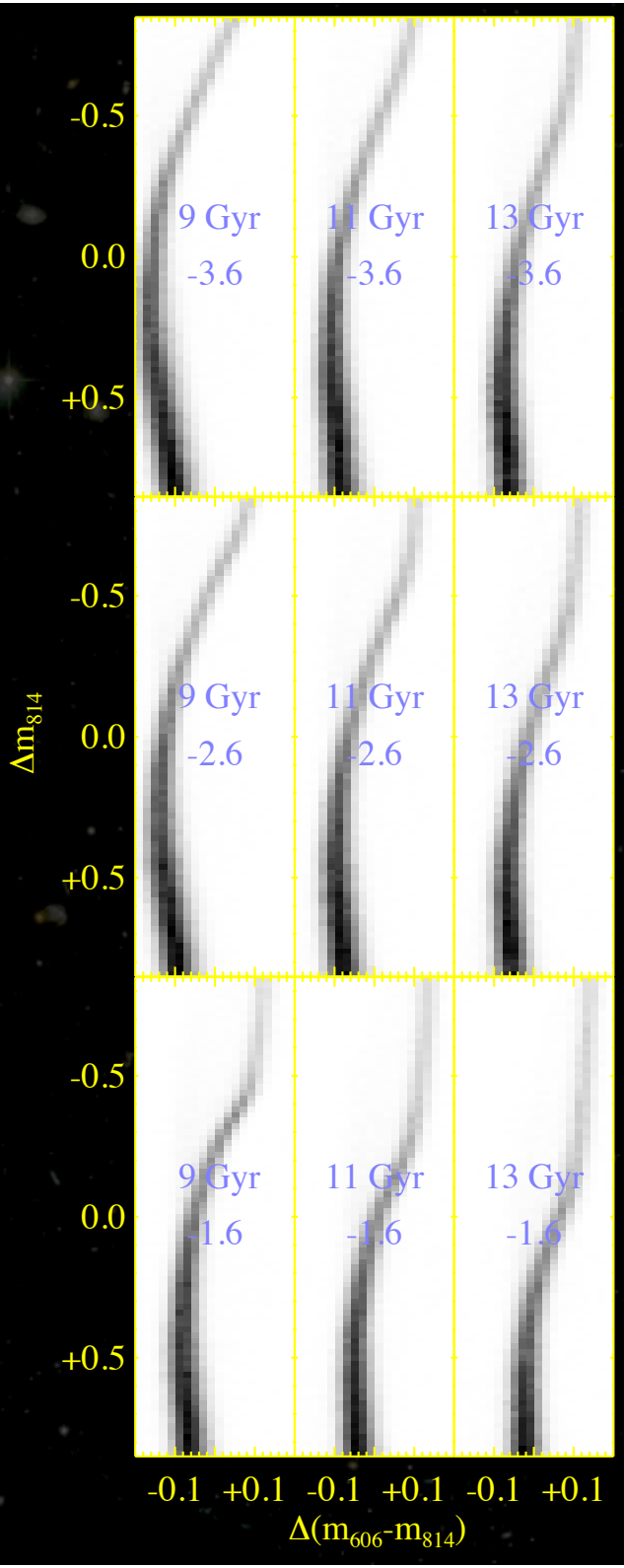
CMDs of the UFDs, all look very similar

Composite UFD CMD looks like a single-age population (to first order)



CMDs of the UFDs, all look very similar

Composite UFD CMD looks like a single-age population (to first order)



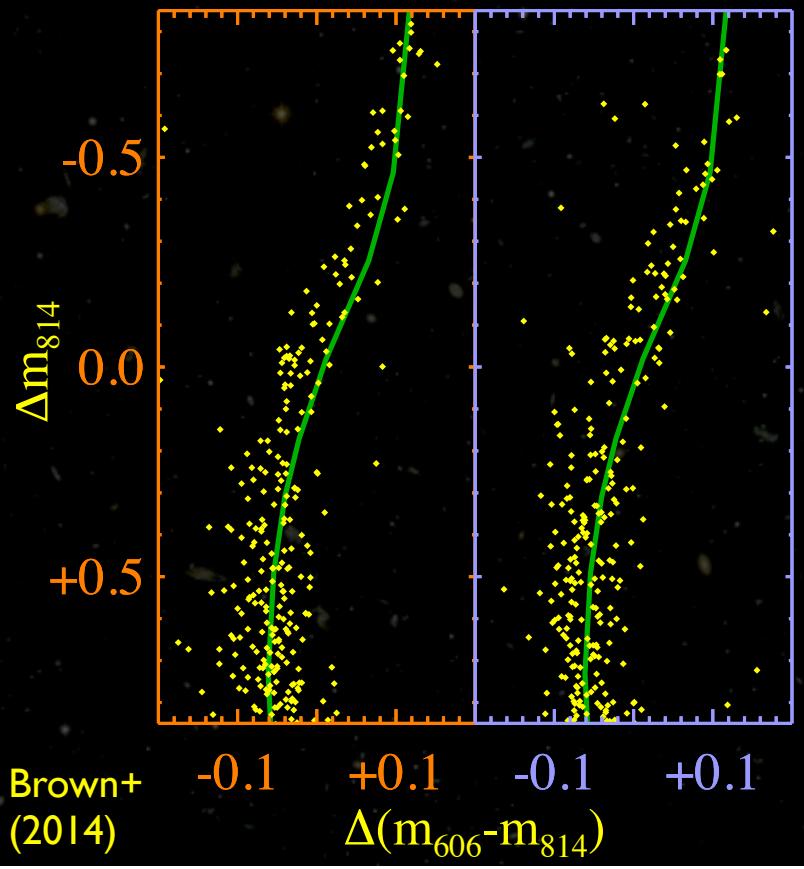
Synthetic CMD fitting

- Isochrones with updated physics
  - He diffusion, new nuclear reaction rates
- Abundance profile appropriate to UFDs
  - Extended metallicities down to [Fe/H] = -4
  - [alpha/Fe] = +0.4
  - [O/Fe] enhanced at low [Fe/H]
- Fine isochrone grid
  - -4 < [Fe/H] < -1 0.2 dex steps
  - 8 < Age < 14.5 Gyr 0.1 Gyr steps
- Isochrones → synthetic CMDs
  - Over 5 million artificial star tests per galaxy
  - Completeness, scatter, CTE, calibration residuals
- Two-burst model
- Ages float but MDF matches spectra
- SFHs relative to M92 age of 13.2 Gyr

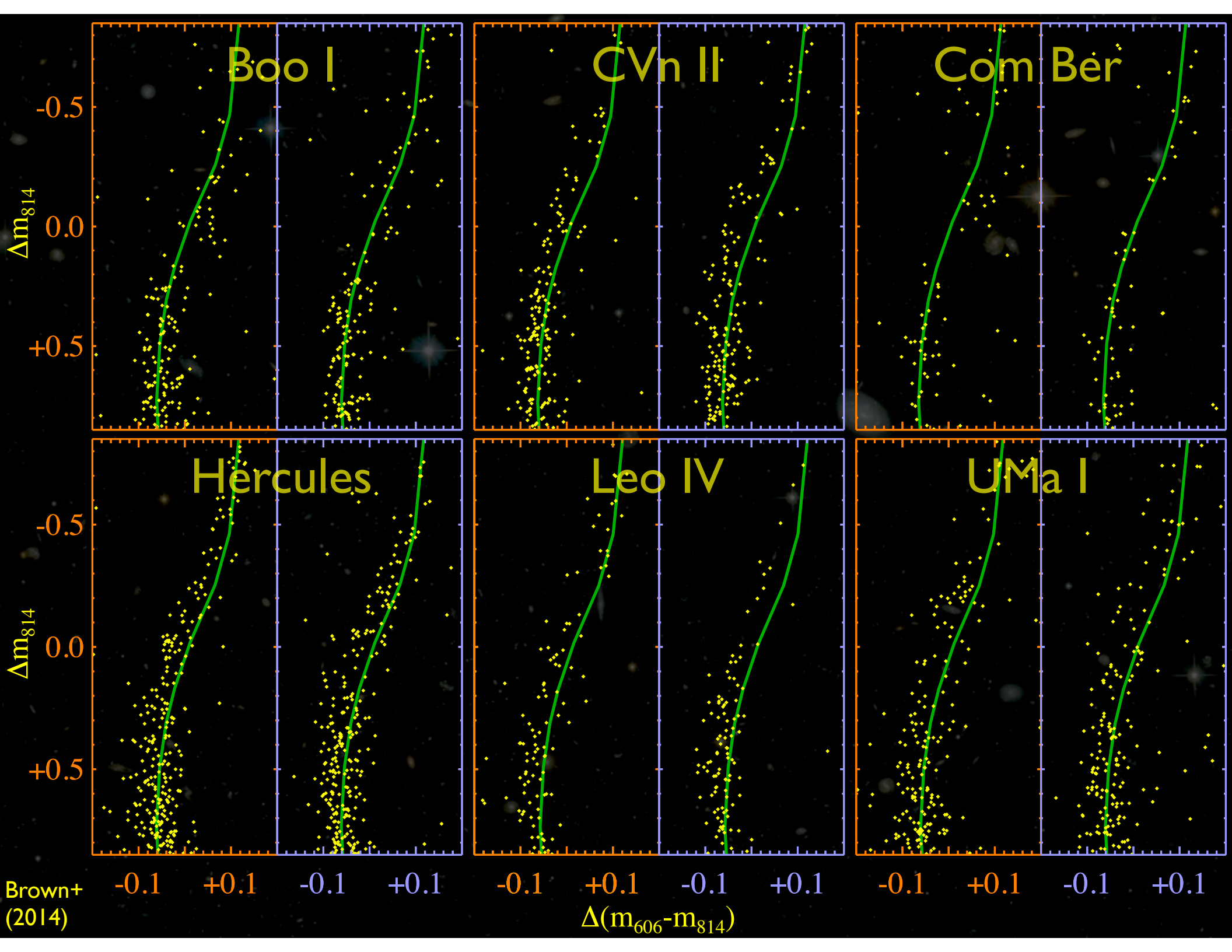
Comparison of observed CMD and random realization of best-fit model

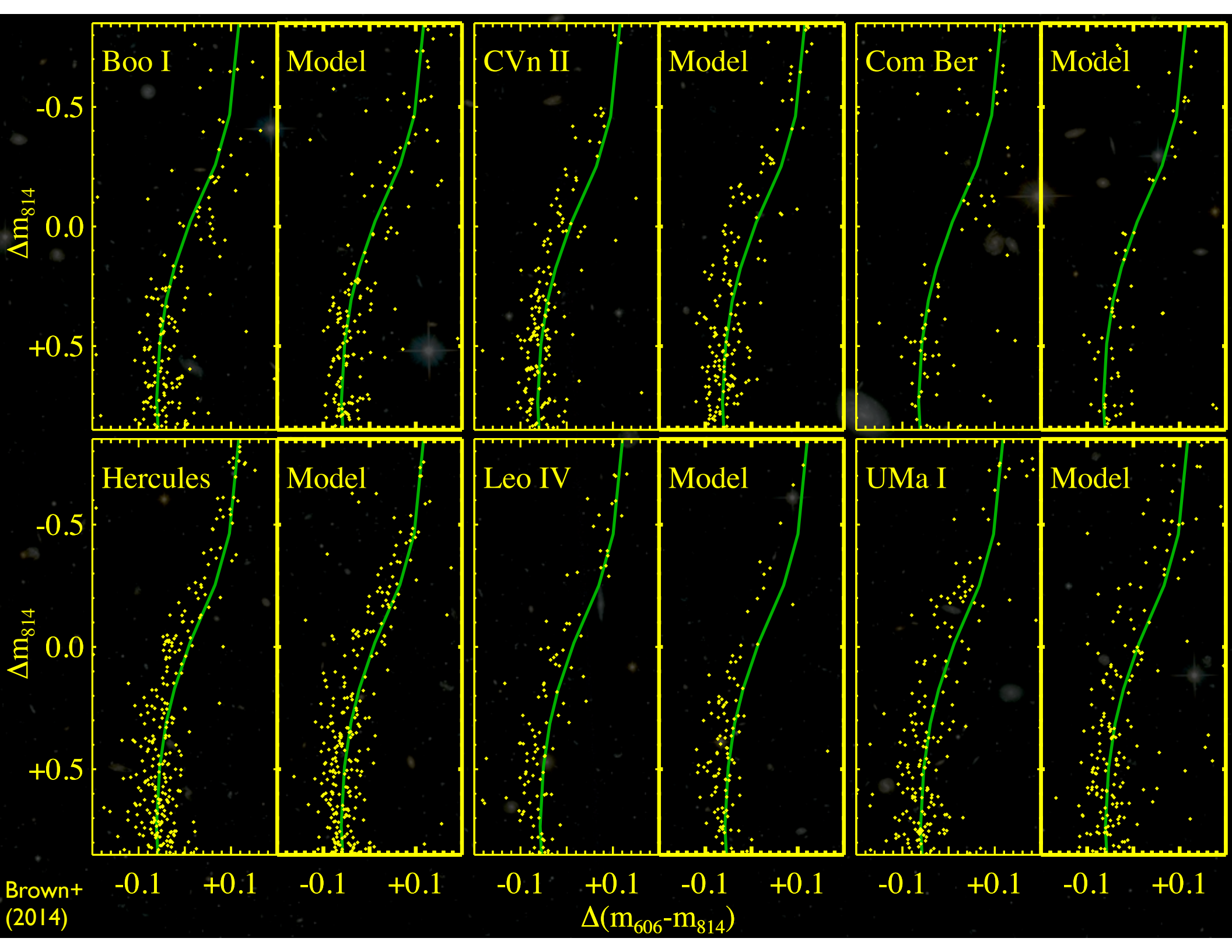
Which CMD shows the observed CMD?
Orange or Blue?

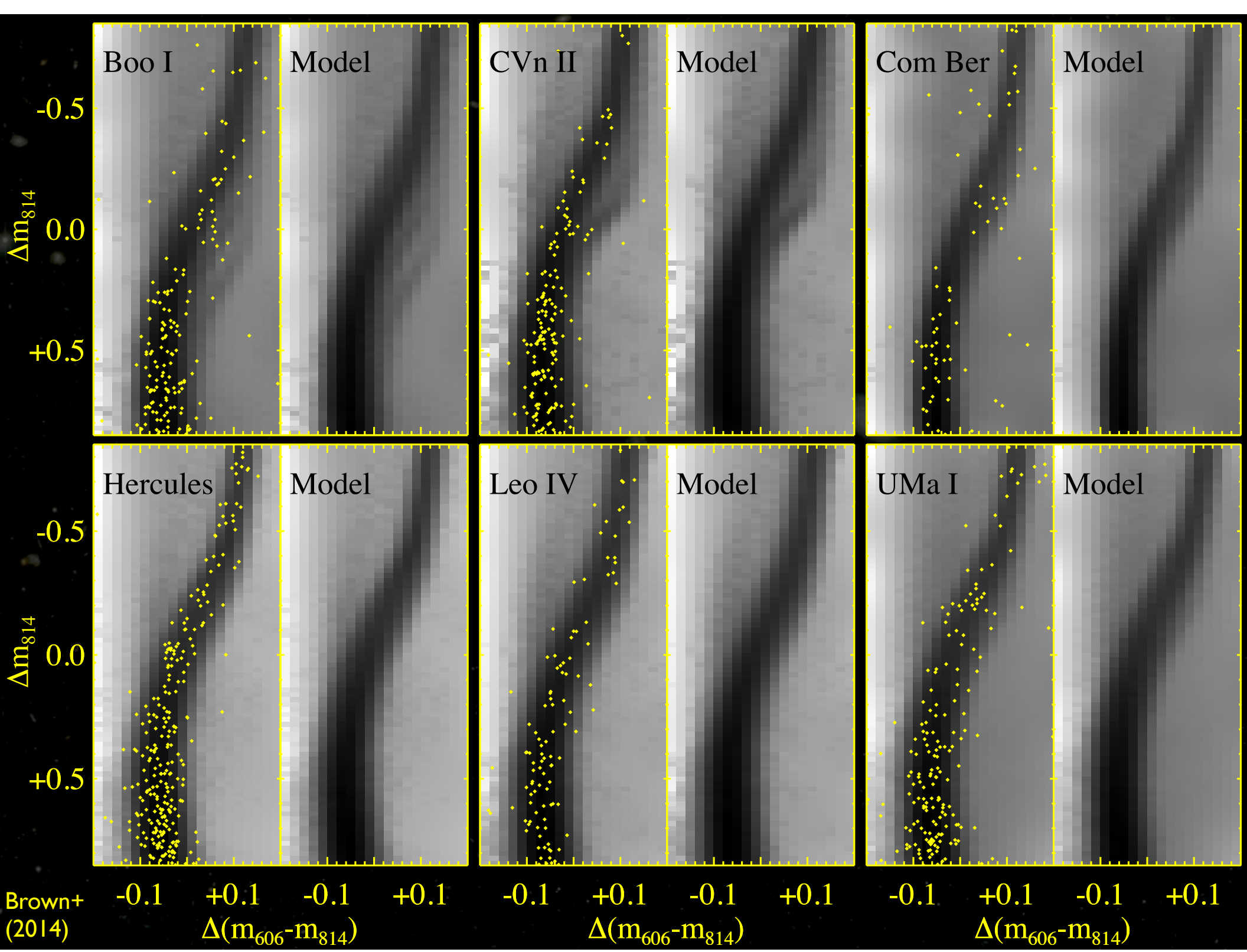
Hercules

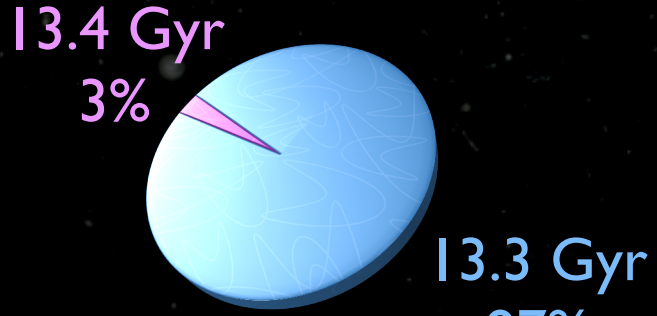


Brown+ (2014)


Boo I
CVn II
Com Ber
Hercules
Leo IV
UMa I
-0.5
0.0
+0.5
Δm_{814}
-0.1
+0.1
$\Delta(m_{606}-m_{814})$
Brown+
(2014)


Boo I
Model
CVn II
Model
Com Ber
Model
Hercules
Model
Leo IV
Model
UMa I
Model
-0.5
0.0
+0.5
Δm814
-0.1
+0.1
Δ(m606-m814)
Brown+
(2014)


Boo I
Model
CVn II
Model
Com Ber
Model
Hercules
Model
Leo IV
Model
UMa I
Model
-0.5
0.0
+0.5
Δm814
-0.1
+0.1
-0.1
+0.1
Δ(m606-m814)
Brown+
(2014)



Boo I

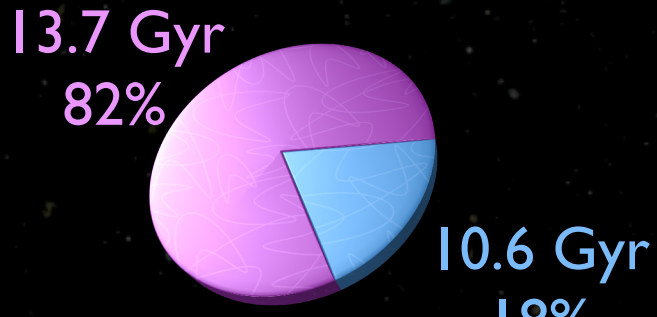
<age> = 13.3 +/- 0.3 Gyr

CVn II

<age> = 13.6 +/- 0.3 Gyr

Com Ber

<age> = 13.9 +/- 0.3 Gyr

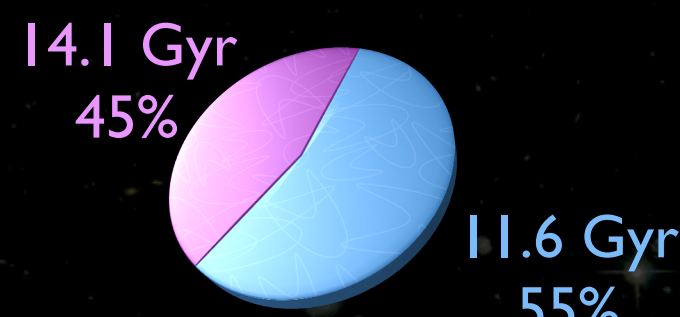


Hercules

<age> = 13.1 +/- 0.3 Gyr

Leo IV

<age> = 13.1 +/- 0.4 Gyr

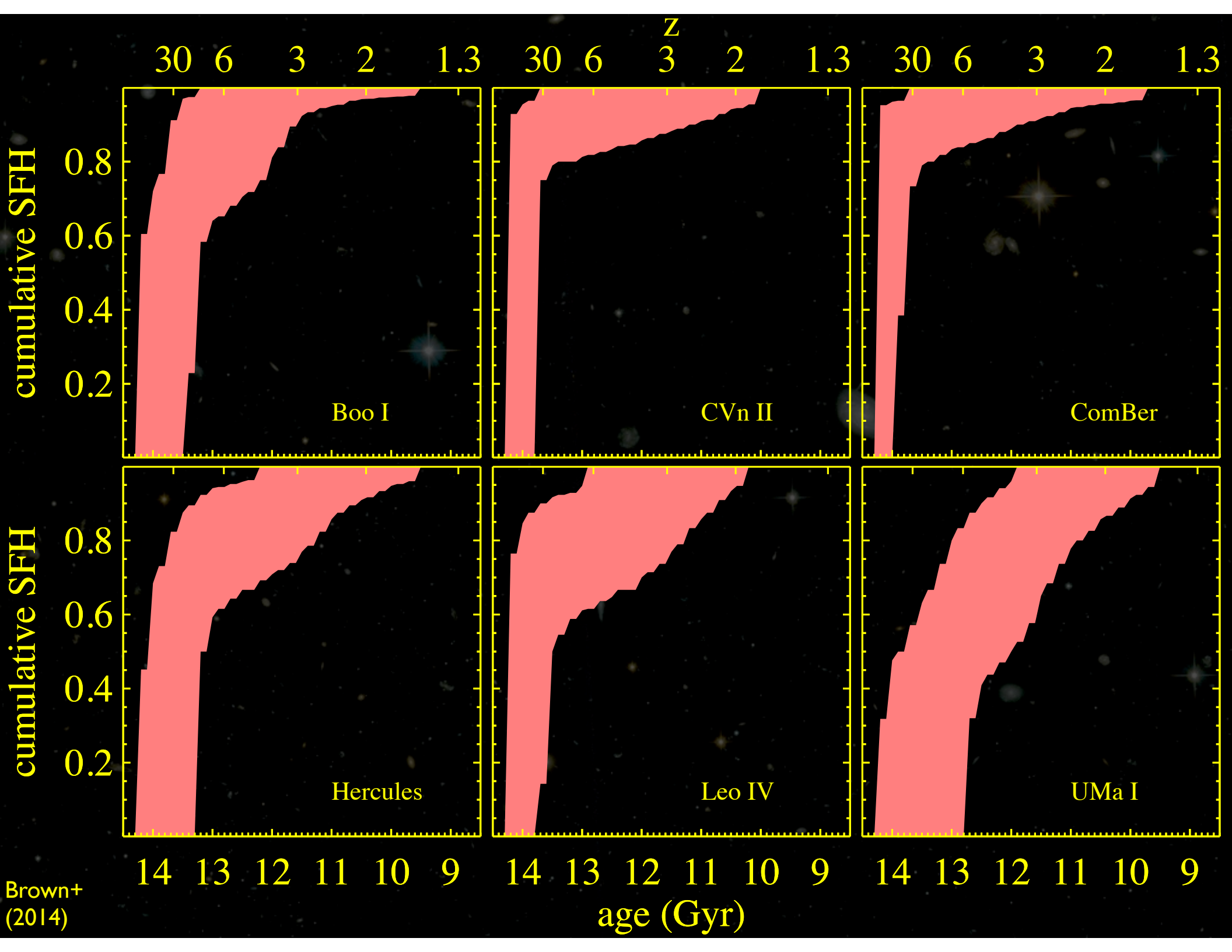


UMa I

<age> = 12.7 +/- 0.3 Gyr

Age uncertainties are statistical (systematic age uncertainty is ~1 Gyr)

Brown+ (2014)


z
30 6 3 2 1.3
30 6 3 2 1.3
30 6 3 2 1.3
cumulative SFH
0.8
0.6
0.4
0.2
Boo I
CVn II
ComBer
cumulative SFH
0.8
0.6
0.4
0.2
Hercules
Leo IV
UMa I
14 13 12 11 10 9
14 13 12 11 10 9
14 13 12 11 10 9
age (Gyr)
Brown+
(2014)

Summary

- The UFD populations look ancient, metal-poor, and similar to one another
- For five of the UFDs, the best-fit model forms 75% of the stars by z~10
- For all six of the UFDs, the SFH is consistent with:
  - 80% of the stars forming by z~6
  - 100% of the stars forming by z~3
- Data are consistent with truncation by reionization
- However, significant uncertainties in absolute age (~1 Gyr; distance, abundance profile)