Milky Way Satellites: Cosmologically Useful or Just For Astrophysics?

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Asteroseismologists: Why You Should Pay Attention

Belokurov et al. (2006)

Asteroseismologists: Why You Should Pay Attention

Image credit: NASA, ESA, A. Sarajedini, & G. Piotto

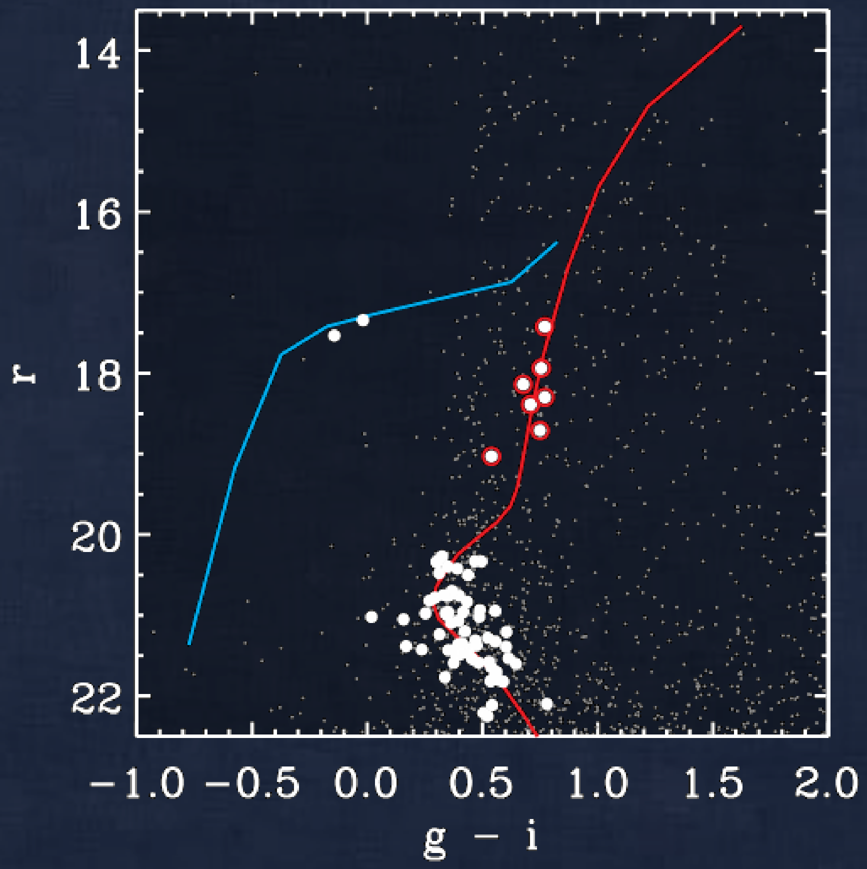
Asteroseismologists: Why You Should Pay Attention

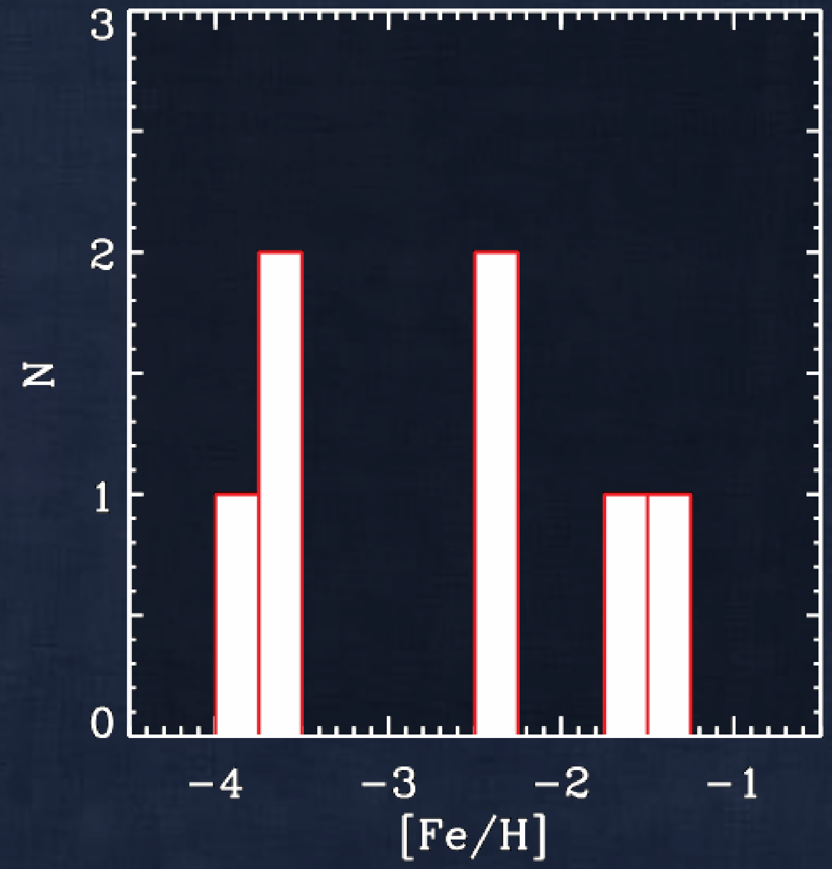
- Galaxies are the defining constituents of the universe
- Dwarf galaxies are the best probes of the dark matter distribution
- (Old) stellar populations and chemical evolution can be observed most cleanly in dwarfs

Asteroseismologists: Why You Should Pay Attention

Dwarf galaxies are the smallest, oldest, most metal-poor, most DM-dominated stellar systems in the universe

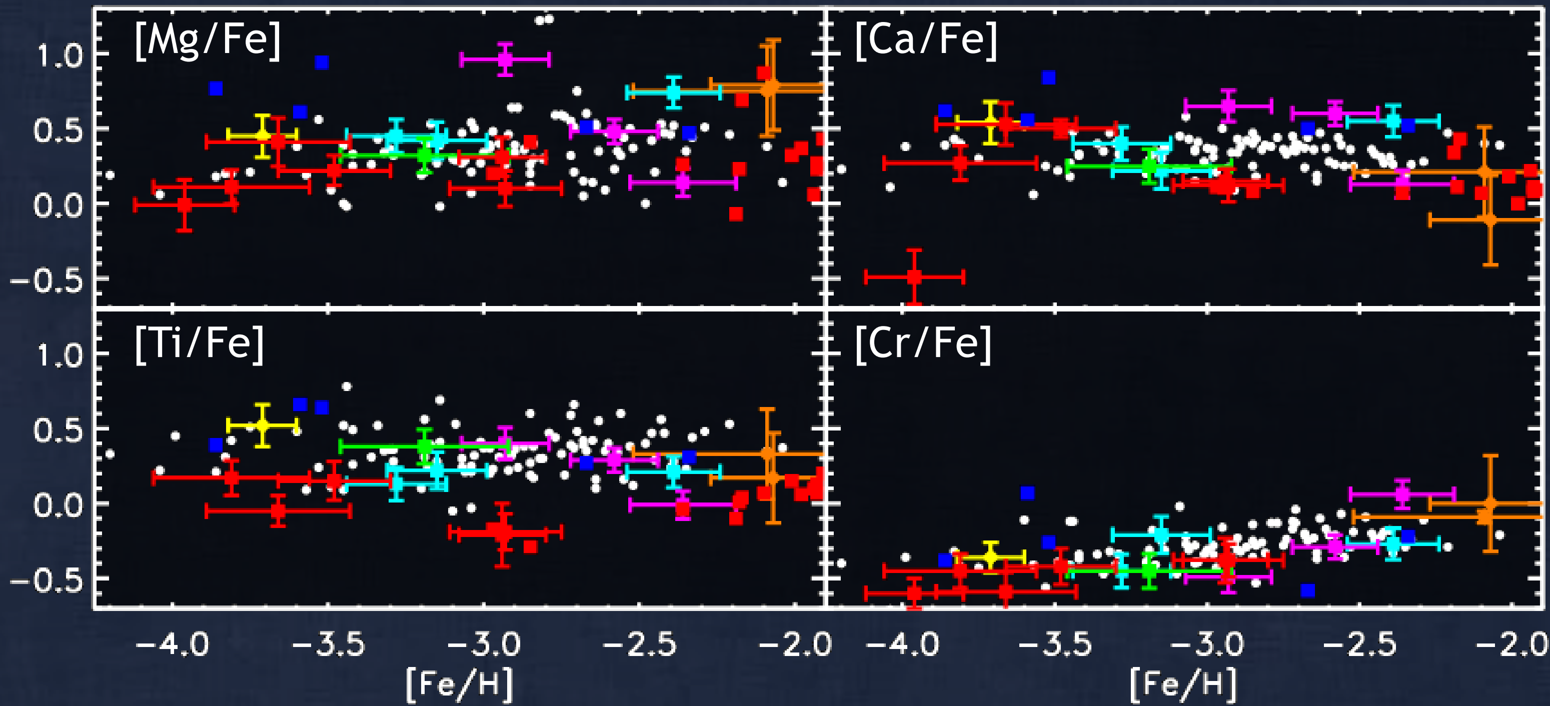
Segue 1: An Unevolved Fossil





Frebel, Simon, & Kirby (2014)

Universal Early Chemical Evolution?



M_V = -20.5

M_V = -5.7

-8 < M_V < -14

M_V = -3.9

M_V = -6.6

M_V = -3.8

M_V = -6.3

M_V = -1.5

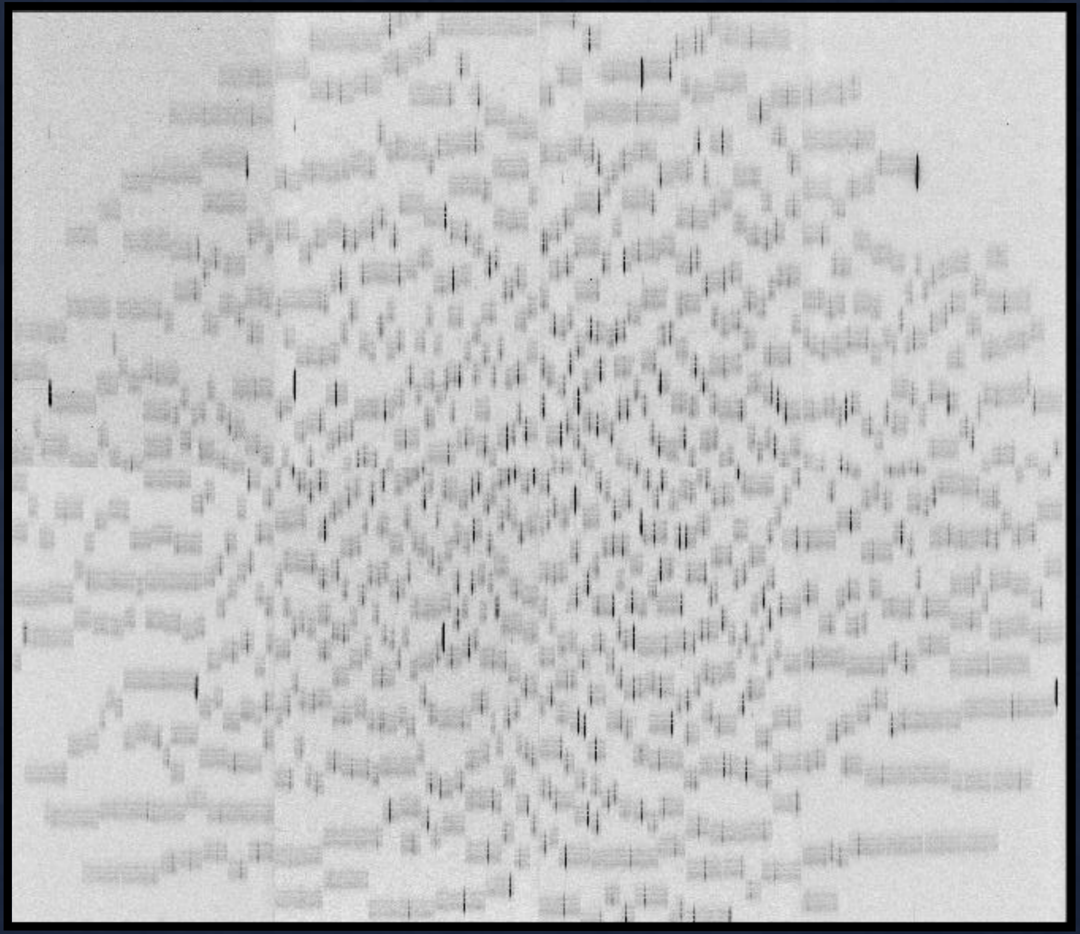
Data from Cayrel, Frebel, Norris, Shetrone, Simon, etc.

Finding the Most Metal-Poor Stars in dSphs

- Complete, magnitude limited survey (to V~20) of southern dSphs
- Uses IMACS spectrograph at Magellan

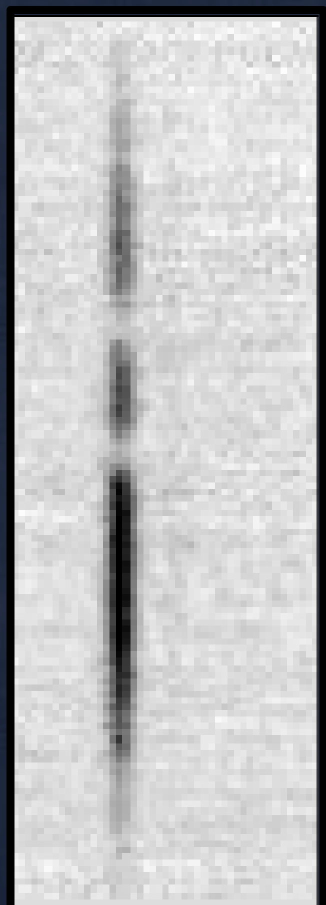
CCKSUMOMPSDG

(Complete Ca K SUrvey for the MOst Metal-Poor Stars in Dwarf Galaxies)

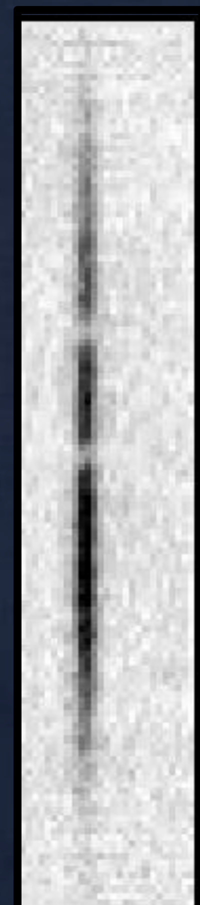


IMACS Survey Data

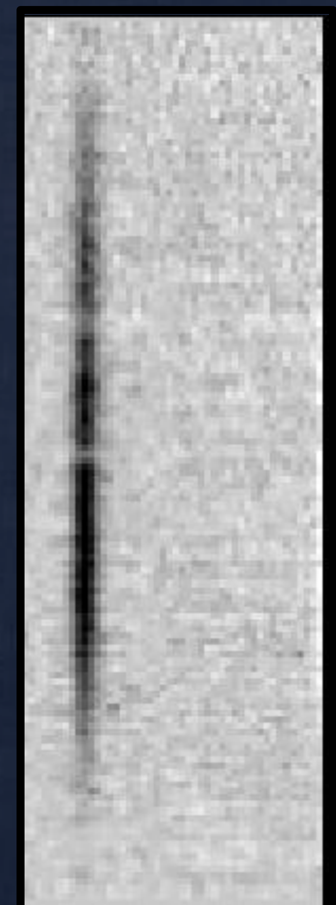
[Fe/H] = -1.5



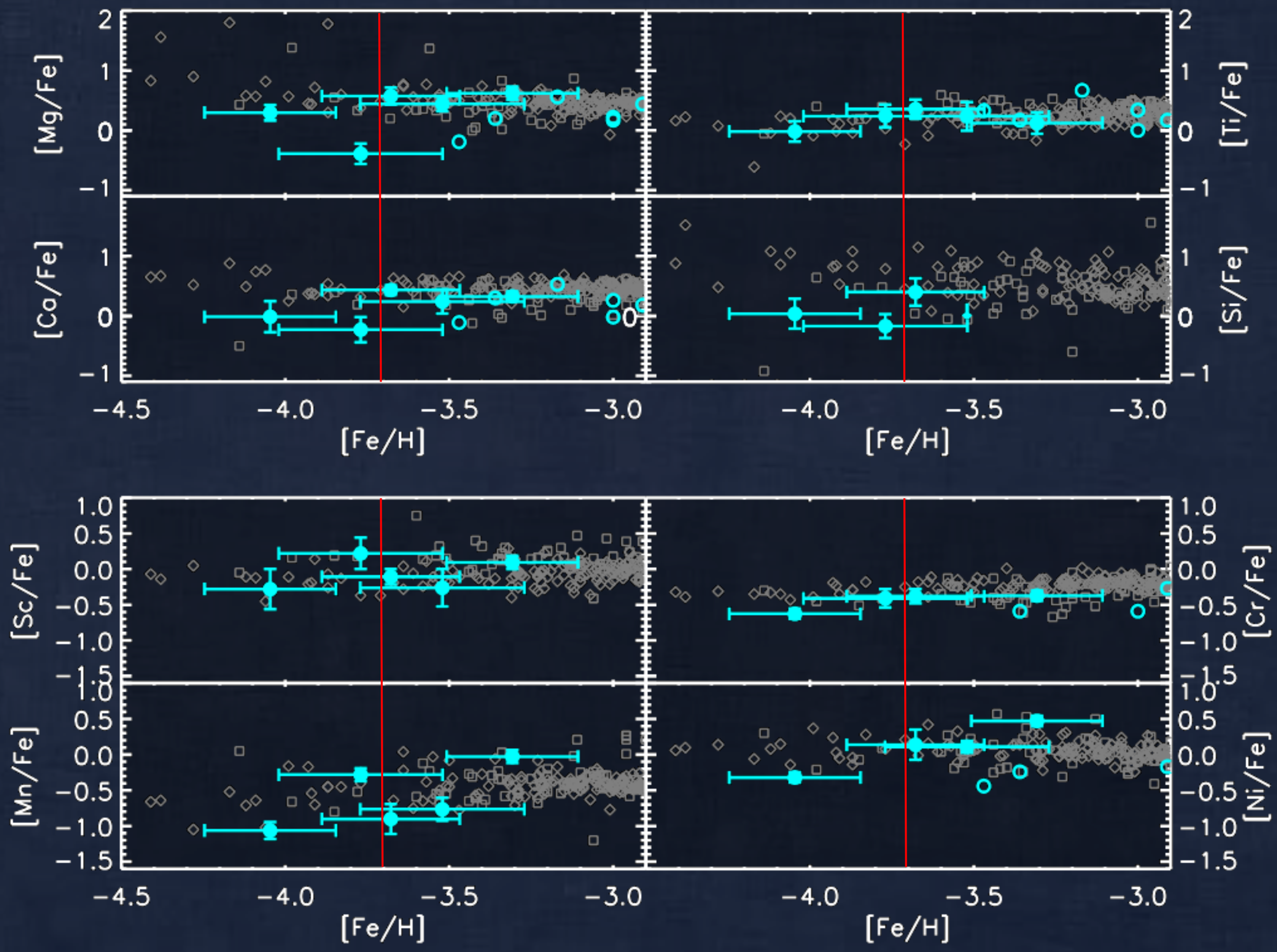
[Fe/H] = -2.5



[Fe/H] = -3.8



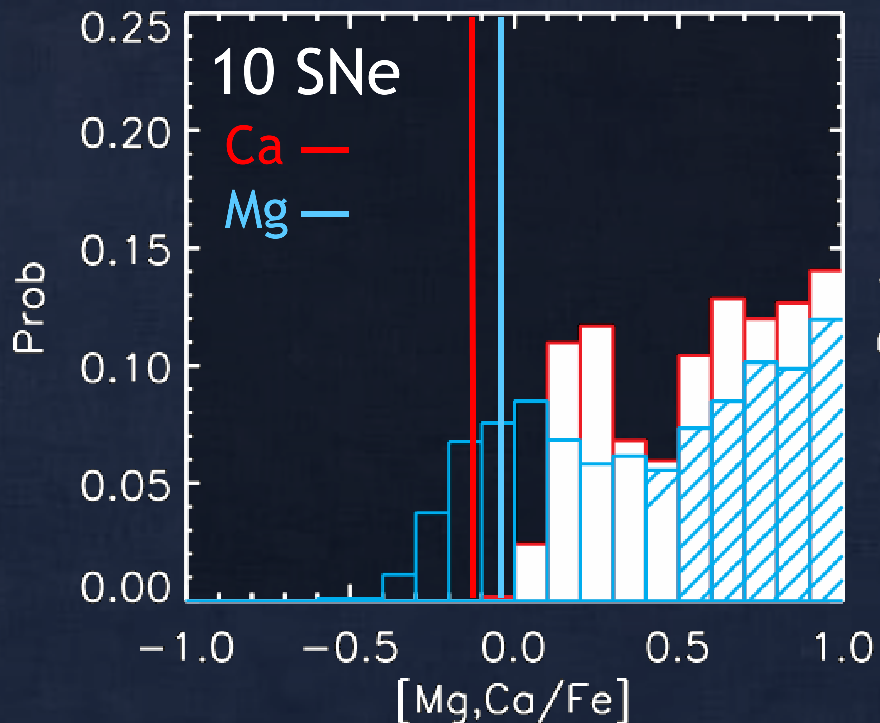
Chemical Fingerprints of the First Supernovae

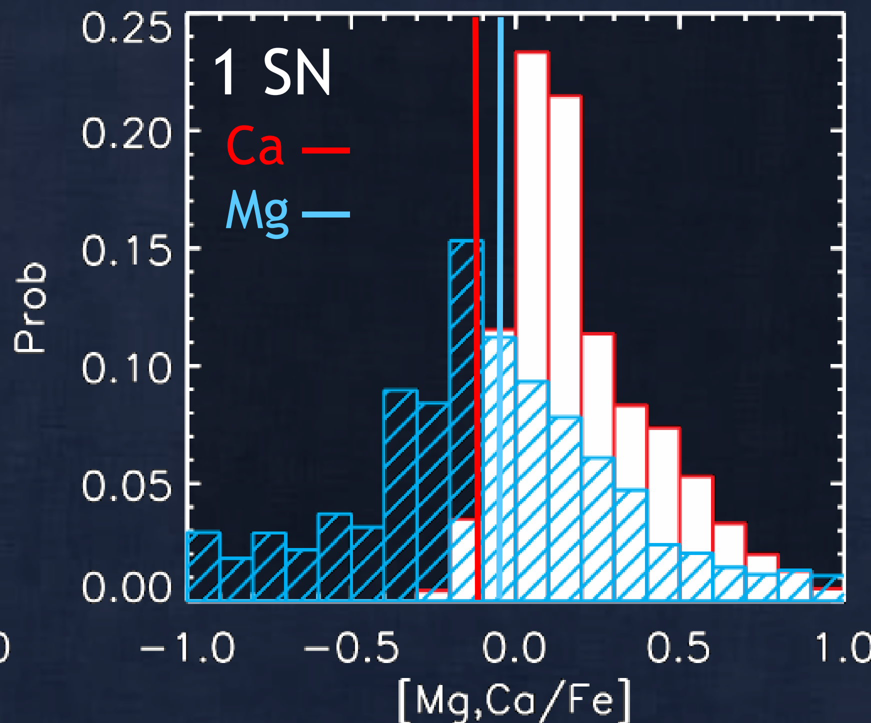


Simon et al. (2014)

Chemical Fingerprints of the First Supernovae

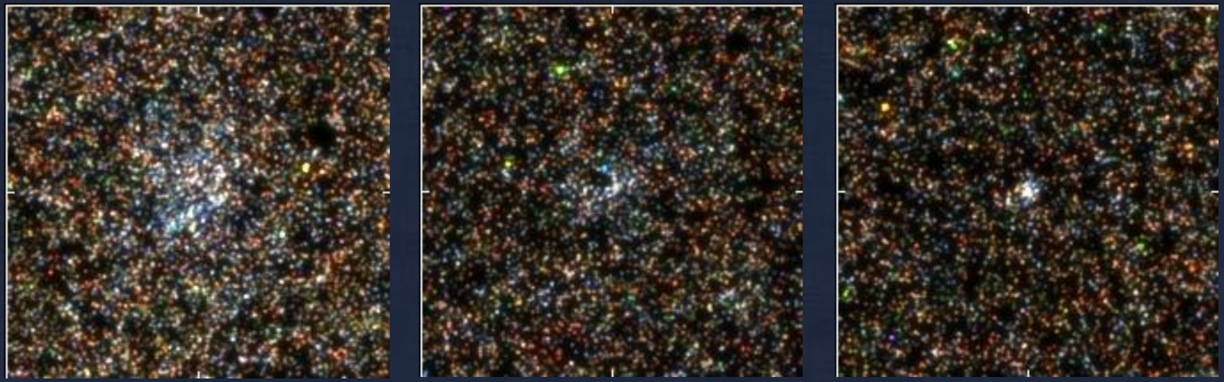
- Low alpha abundances can only be produced with ≤ 4 SNe





Simon et al. (2014)

HST Survey of Ultra-Faint Dwarfs



Boo I　　Can Ven II　　Coma Ber

+ Hercules, Leo IV, and UMa I

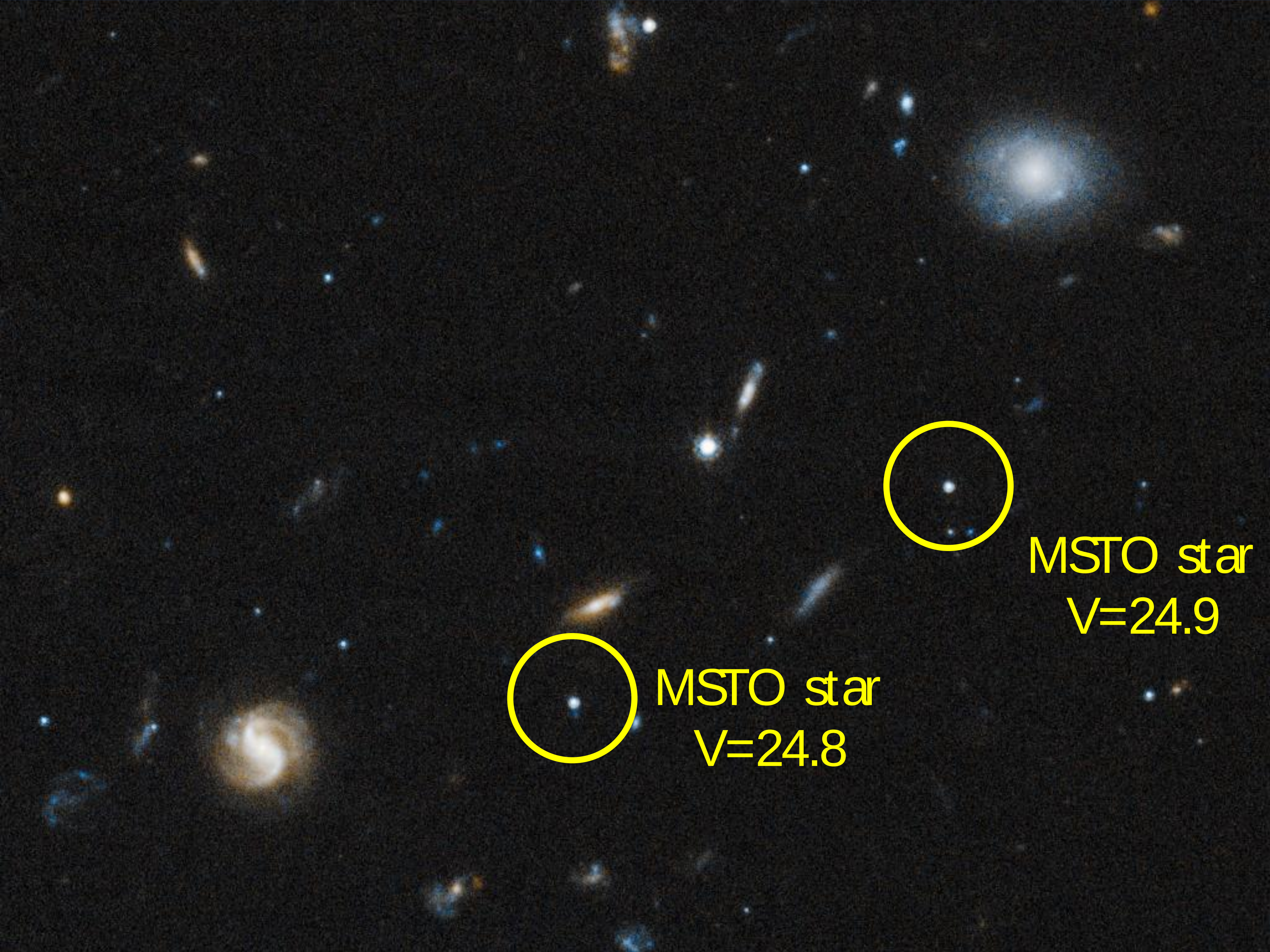
- Absolute magnitudes -3.8 to -6.2
- Distances 38-160 kpc
- S/N = 100 at the main sequence turnoff
  - Goal: ages to better than 1 Gyr

Brown et al. (2012)

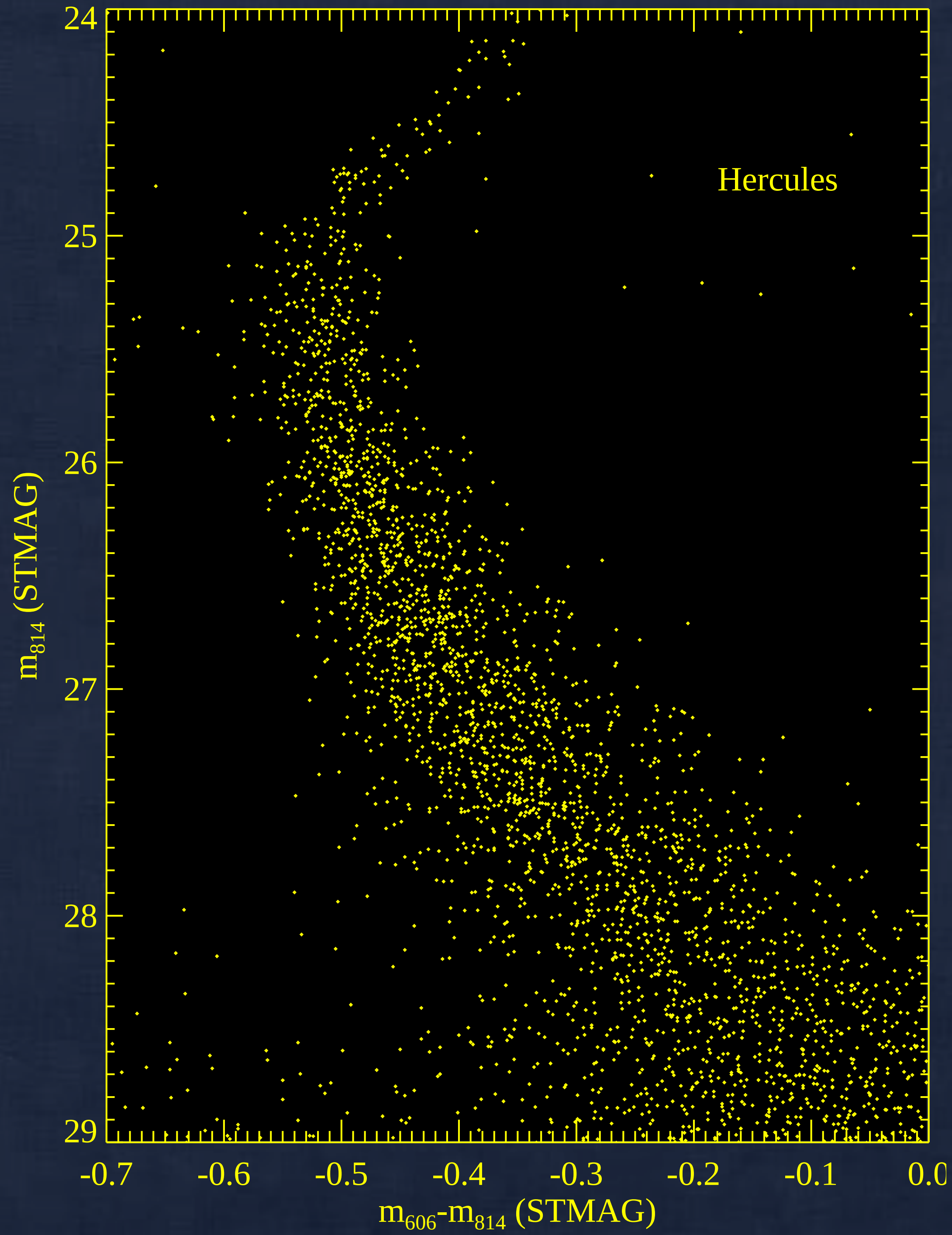
Leo IV

16 orbits

faint limit
V~28.5


MSTO star
V=24.9
MSTO star
V=24.8

Hercules ACS CMD

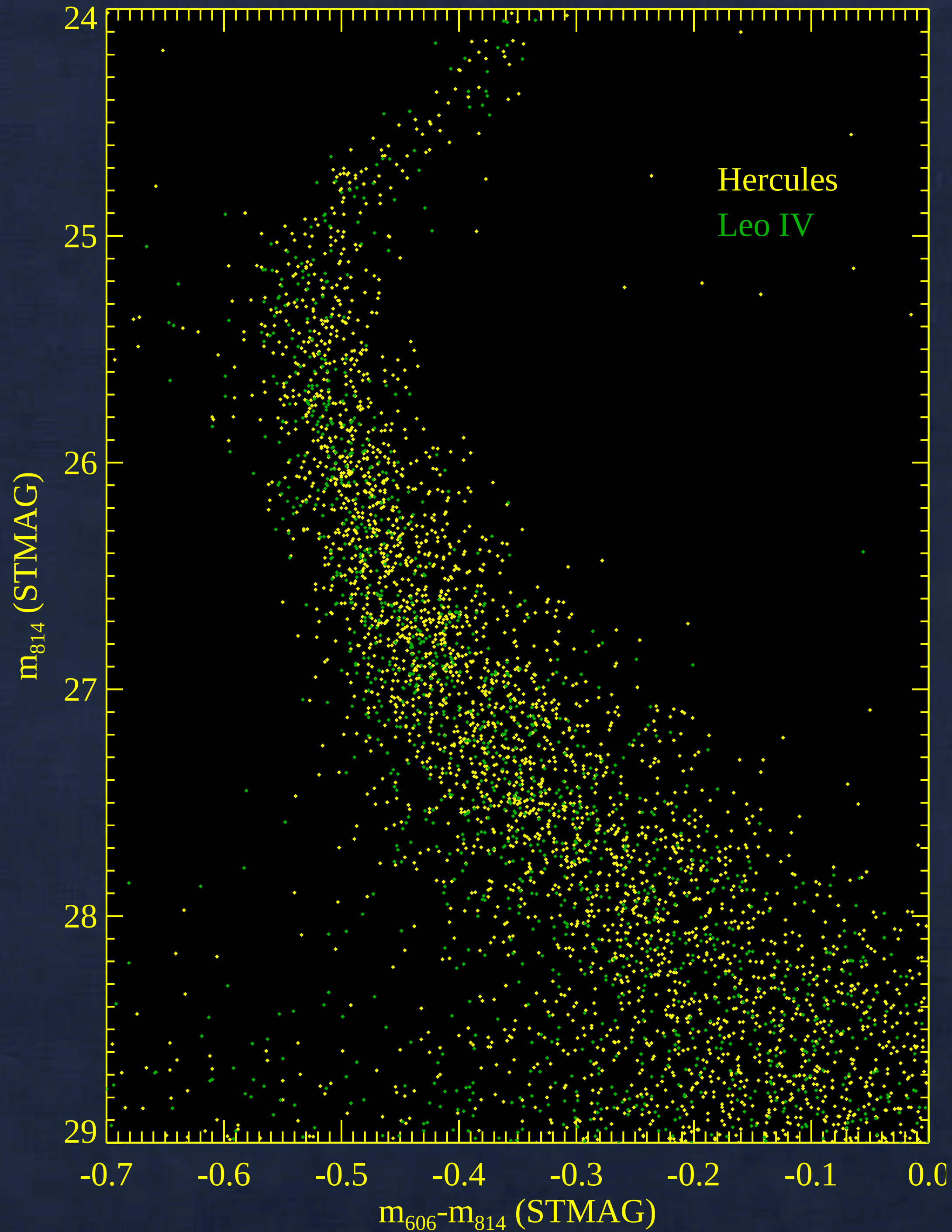


Reaches down to I=29
(M2 dwarf at 133 kpc)

Brown et al. (2014)

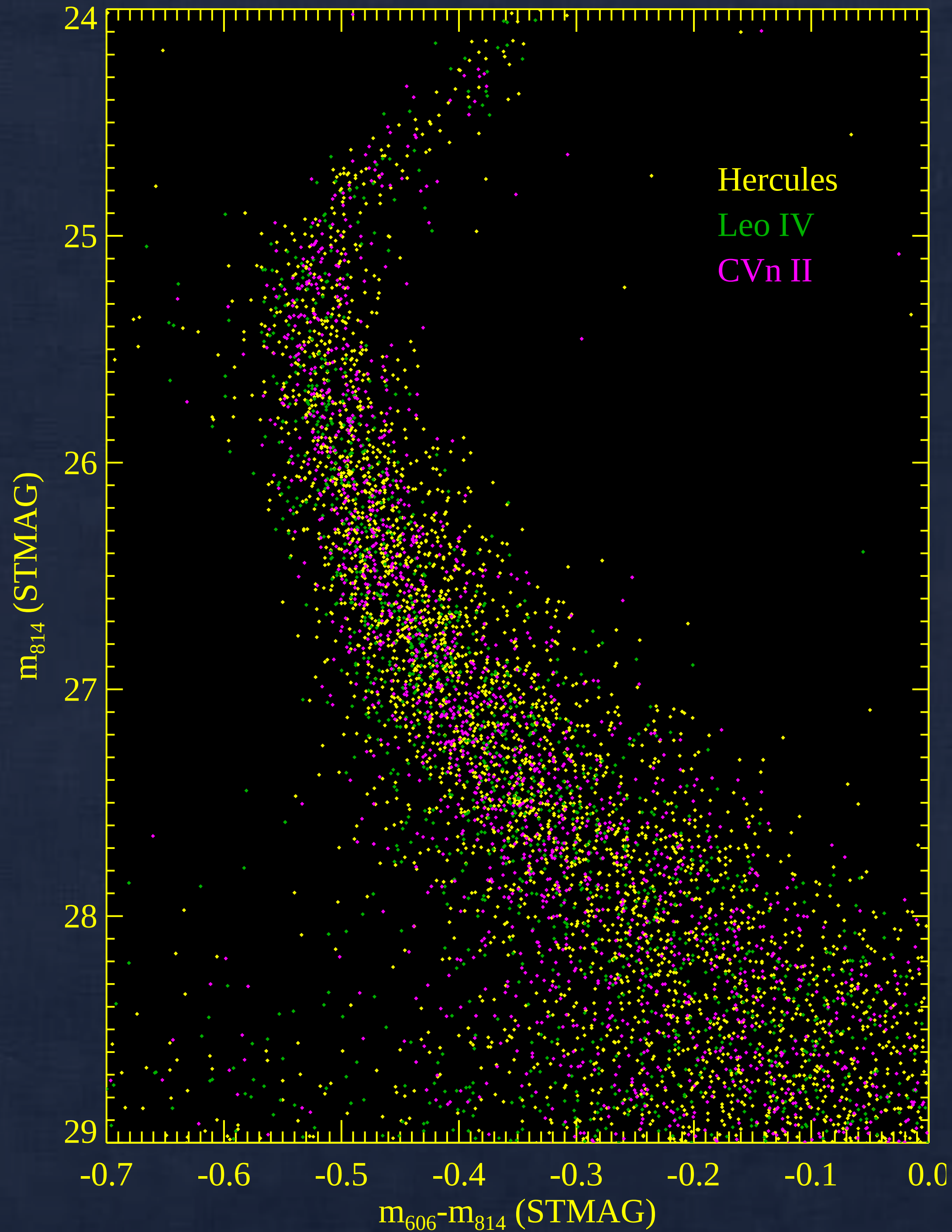
Leo IV ACS CMD

(Shifted to distance/reddening of Hercules)



Brown et al. (2014)

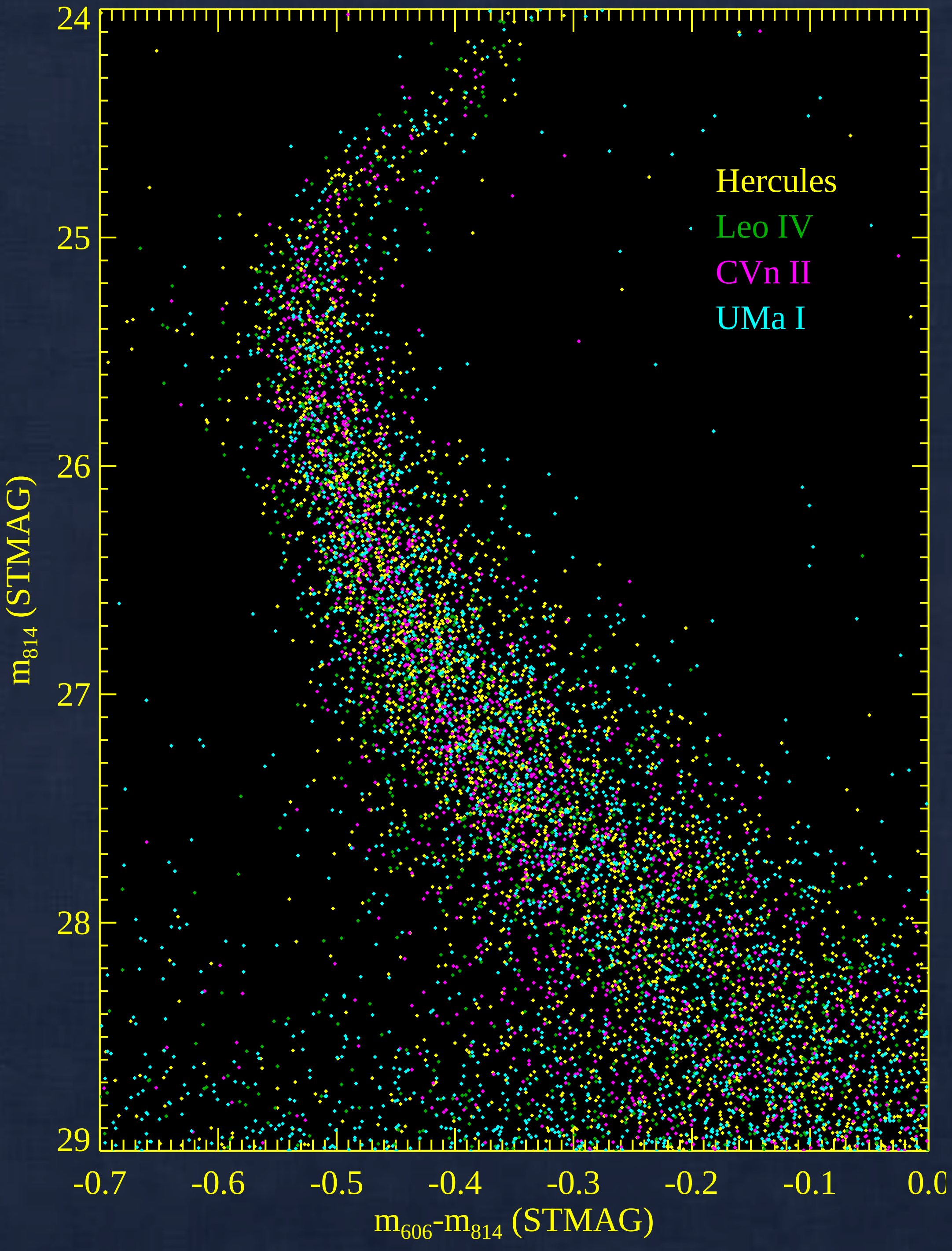
CVn II ACS CMD



(Shifted to distance/reddening of Hercules)

Brown et al. (2014)

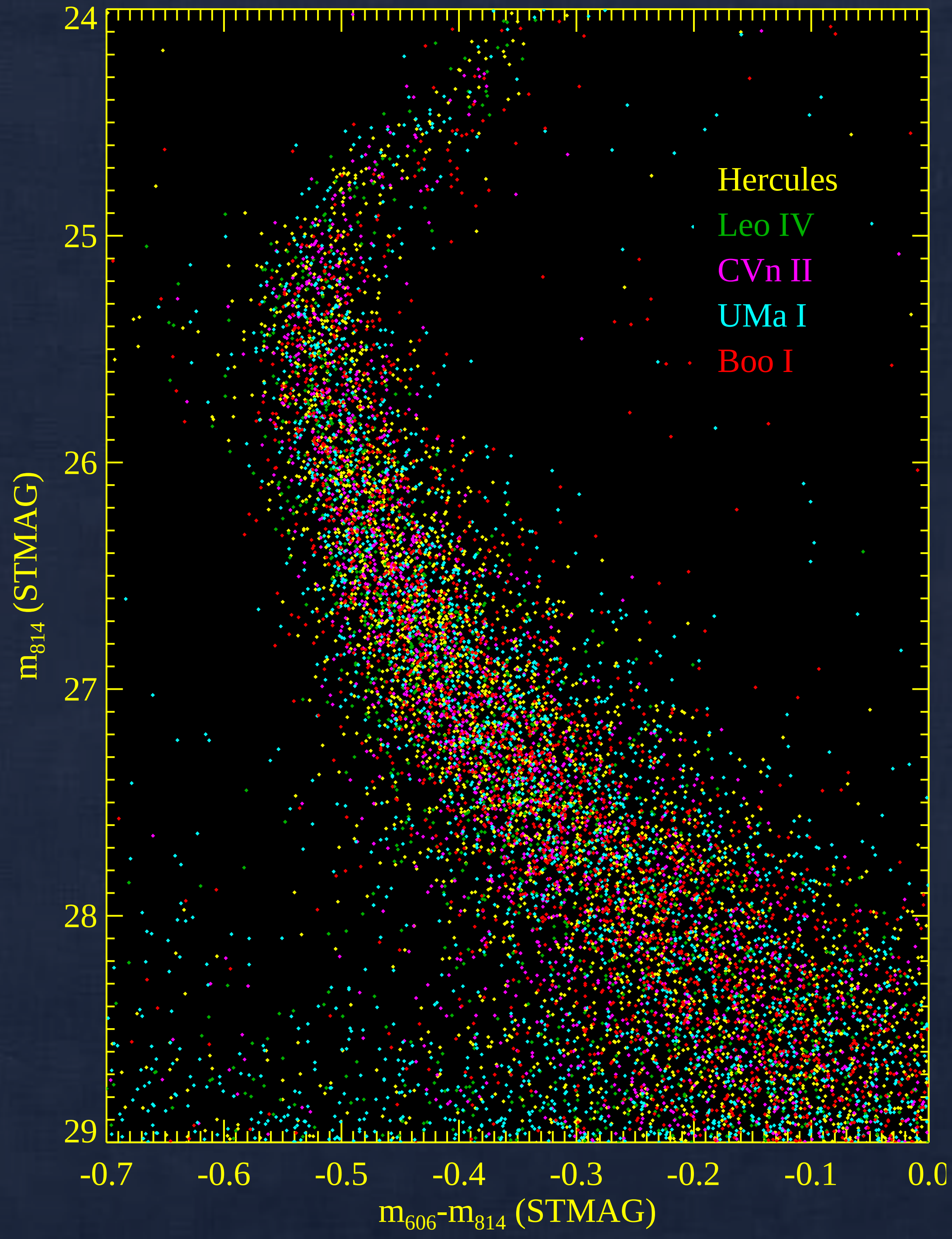
UMa I ACS CMD



(Shifted to distance/reddening of Hercules)

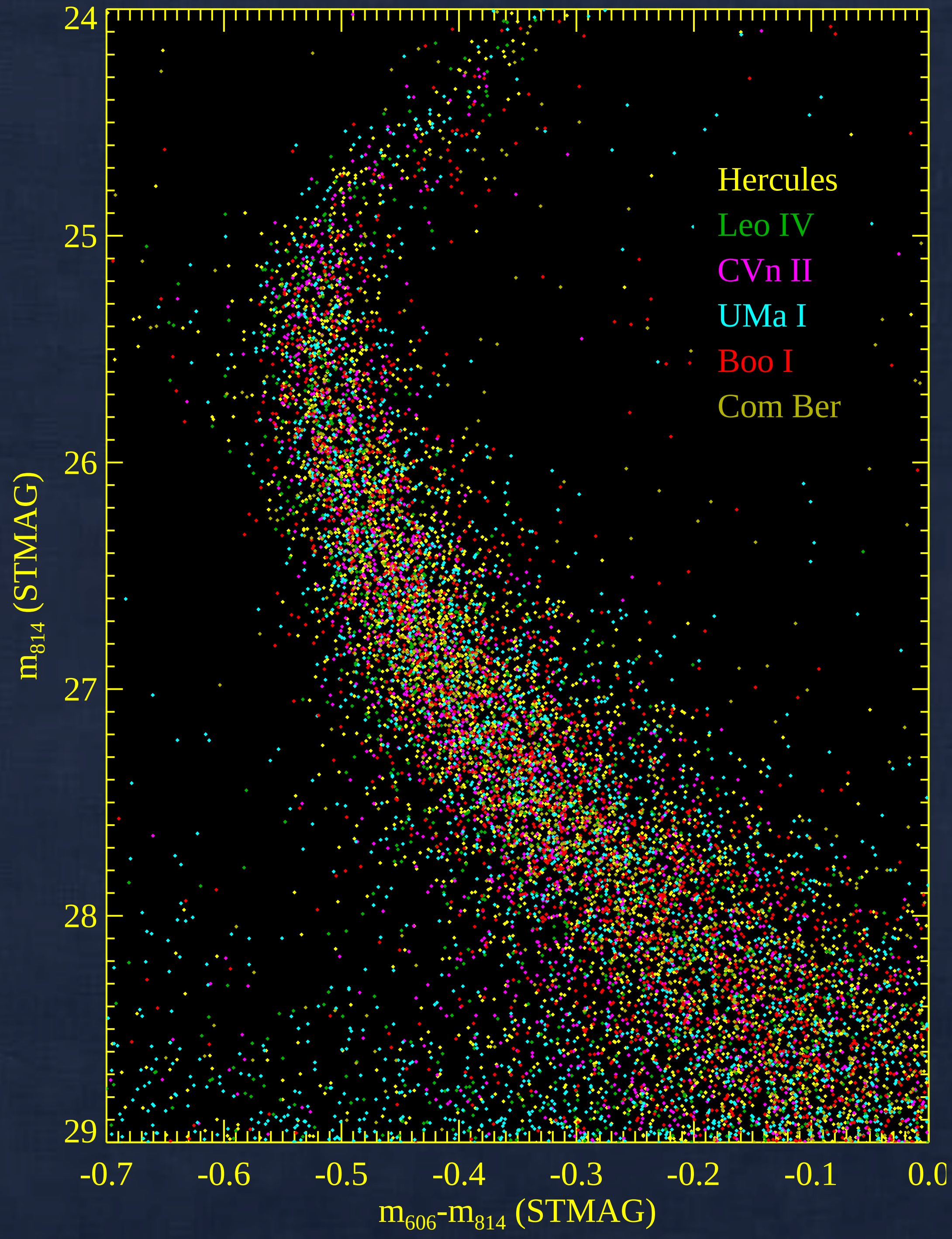
Brown et al. (2014)

Boötes I ACS CMD



(Shifted to distance/reddening of Hercules)

Brown et al. (2014)



ComBer ACS CMD

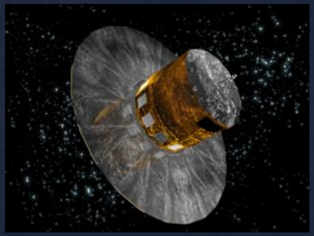
All 6 ultra-faint dwarfs have nearly identical CMDs, with ages as old as M92

SFHs are consistent with >80% of stars formed by z=6 (12.8 Gyr ago)

Brown et al. (2014)

Limiting Factors on Age Accuracy

- Stellar isochrones (Δ_{age} ~ 1 Gyr)
- Distance (Δ_{age} ~ 500 Myr)



- [O/Fe] ratio (Δ_{age} ~ 500 Myr)

Planes of Satellites

- MW plane first identified by Lynden-Bell (1976) and Kunkel & Demers (1976)

Mon. Not. R. astr. Soc. (1976) **174**, 695–710.

DWARF GALAXIES AND GLOBULAR CLUSTERS IN HIGH VELOCITY HYDROGEN STREAMS

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(Received 1975 July 11)

SUMMARY

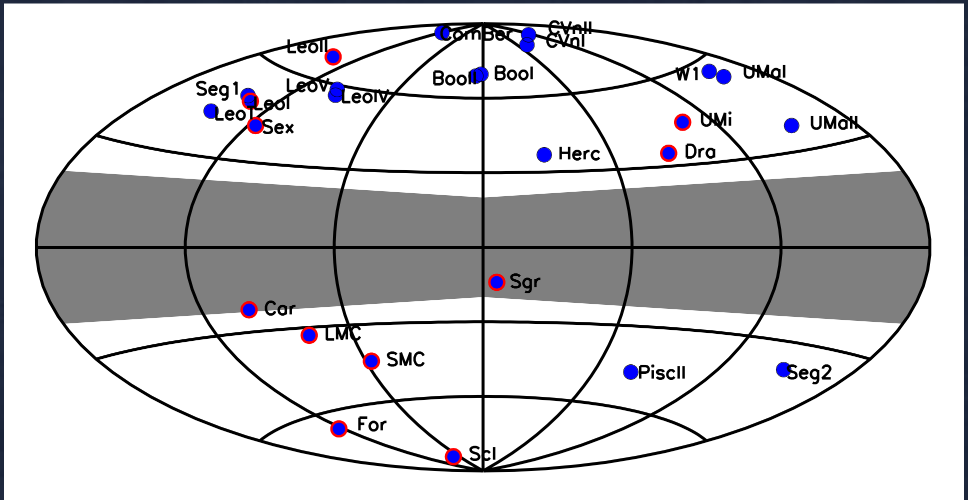
The dwarf spheroidal galaxies Draco and Ursa Minor lie in a stream of high velocity clouds, while Sculptor lies within 3° of the Magellanic stream. Of the distant diffuse globular clusters, Palomar 13 lies in the tail of the Magellanic stream, while Palomar 1 lies in another prominent northern stream. Four farther distant globulars of concentration class XII appear to be unrelated.

Using the known distances to the optical objects, the parallaxes due to the offset of the Sun from galactic centre are calculated. Not only the Magellanic stream, but also Sculptor and the Draco–Ursa Minor stream are then seen to lie in a plane which is presumably the plane of the orbit of the Magellanic

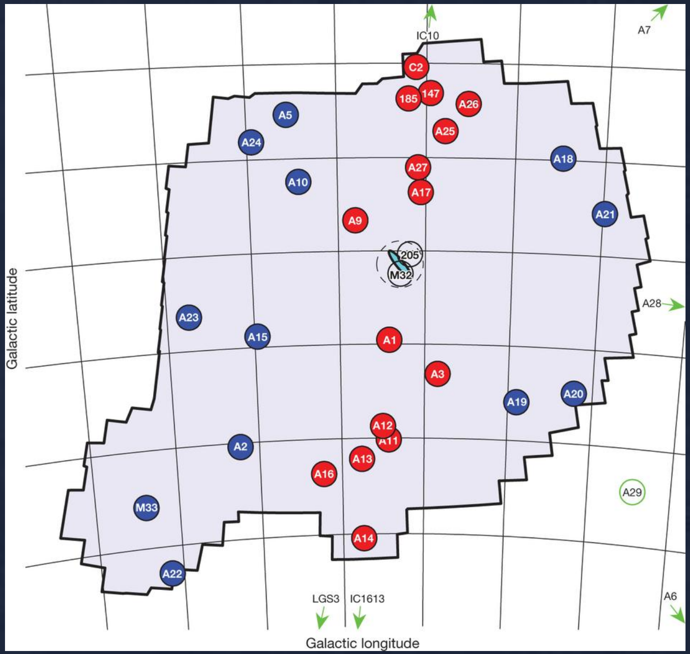
Planes of Satellites

- Planes now found around both Milky Way and M31

Milky Way



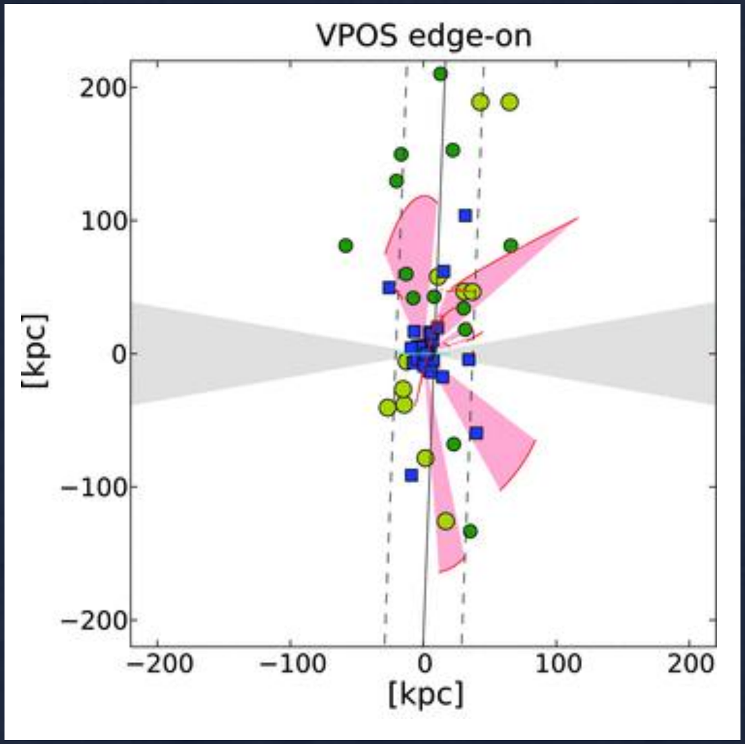
M31



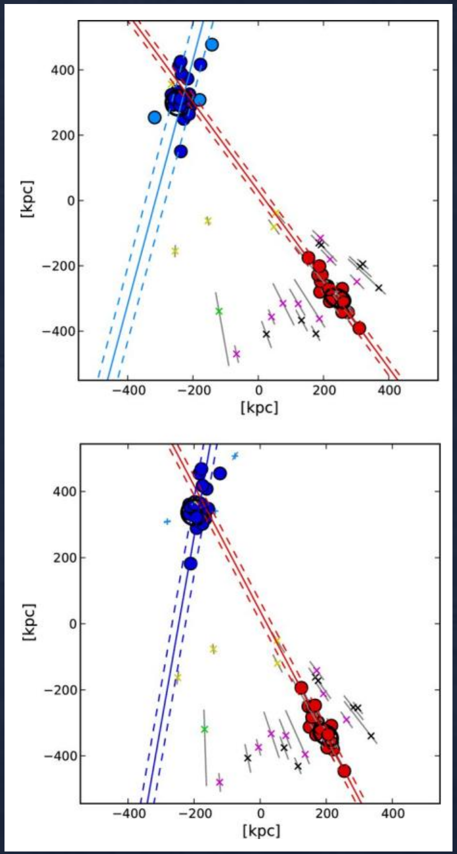
Ibata et al. (2014)

Planes of Satellites

- Planes now found around both Milky Way and M31



Pawlowski et al. (2012)



Pawlowski et al. (2013)

Planes of Satellites

Planes are common in ΛCDM

D'Onghia & Lake (2008)
Libeskind et al. (2009)
Deason et al. (2011)
Lovell et al. (2011)
Wang et al. (2013)
Goerdt et al. (2013)
Bahl & Baumgardt (2014)
Sawala et al. (2014)

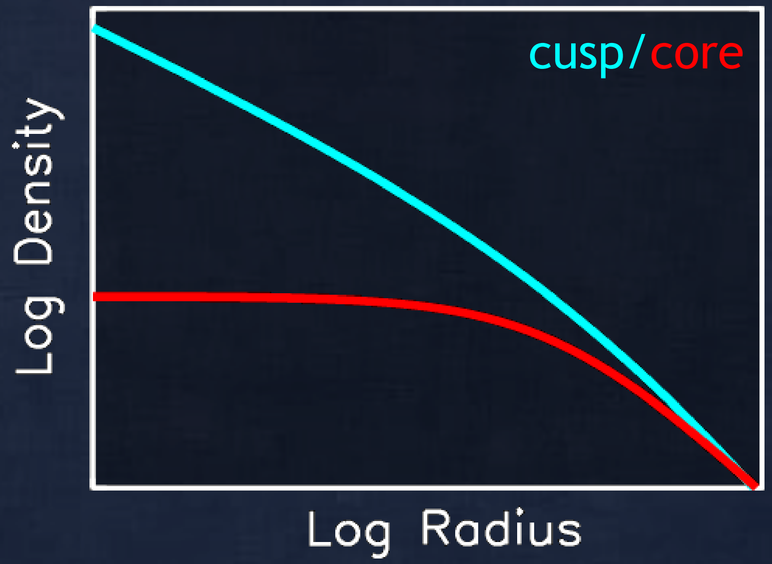
Planes are extremely rare in ΛCDM

Metz et al. (2009)
Pawlowski et al. (2012)
Pawlowski et al. (2014)
Ibata et al. (2014a)
Ibata et al. (2014b)

The Cusp/Core Problem

- Navarro, Frenk, & White (1996)

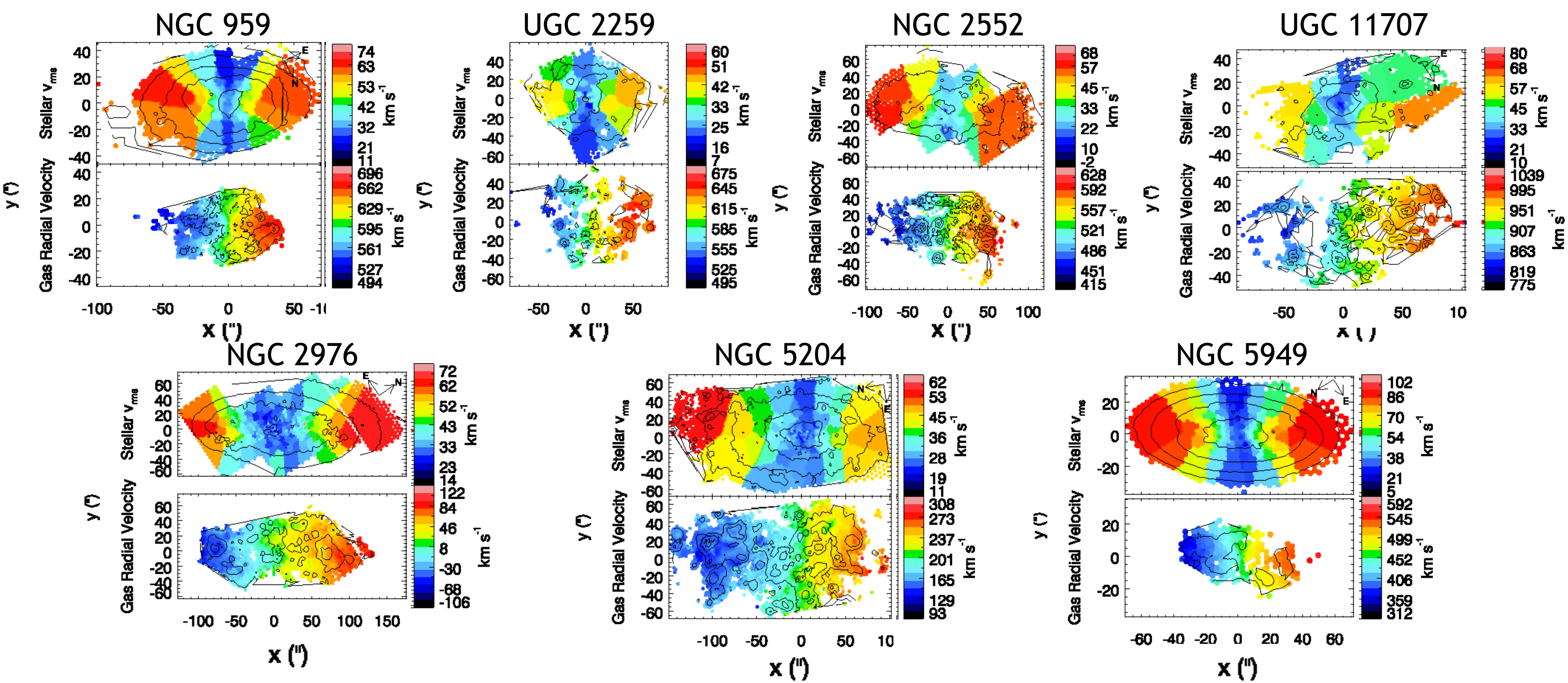
$$\rho(r) \sim \frac{1}{(r/r_s)(1 + r/r_s)^2}$$



dSph Density Profile Results

- Fornax
  - $\gamma = 0.39^{+0.37}_{-0.43}$ (Walker & Penarrubia 2011)
  - core (Jardel & Gebhardt 2012)
  - core or cusp (Breddels & Helmi 2013)
- Sculptor
  - core or cusp (Battaglia et al. 2008)
  - $\gamma = 0.05^{+0.39}_{-0.51}$ (Walker & Penarrubia 2011)
  - core (Amorisco & Evans 2012)
  - $\gamma = 0 \pm 1.2$ (Breddels et al. 2013)
  - core or cusp (Breddels & Helmi 2013)
  - $\gamma = 0$ or 1.2 (Richardson & Fairbairn 2014)

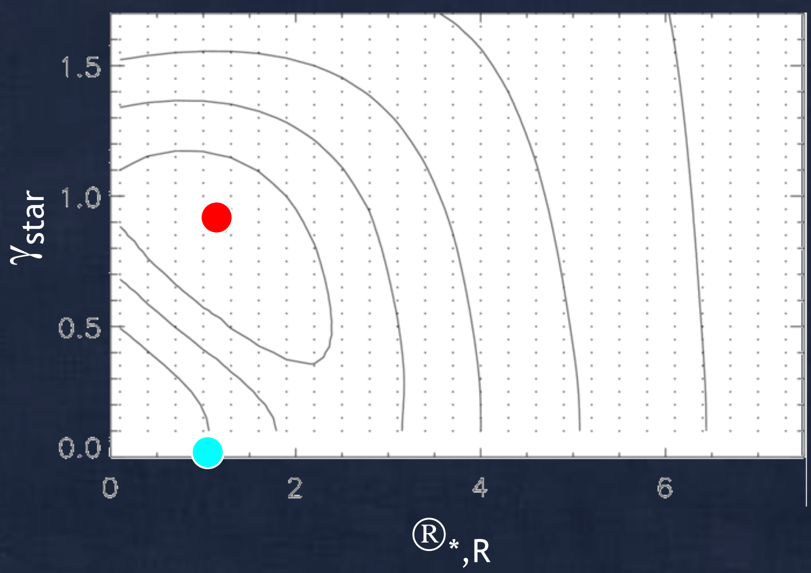
Stellar + Gas Velocity Fields of 7 Dwarfs



Adams et al. (2014)

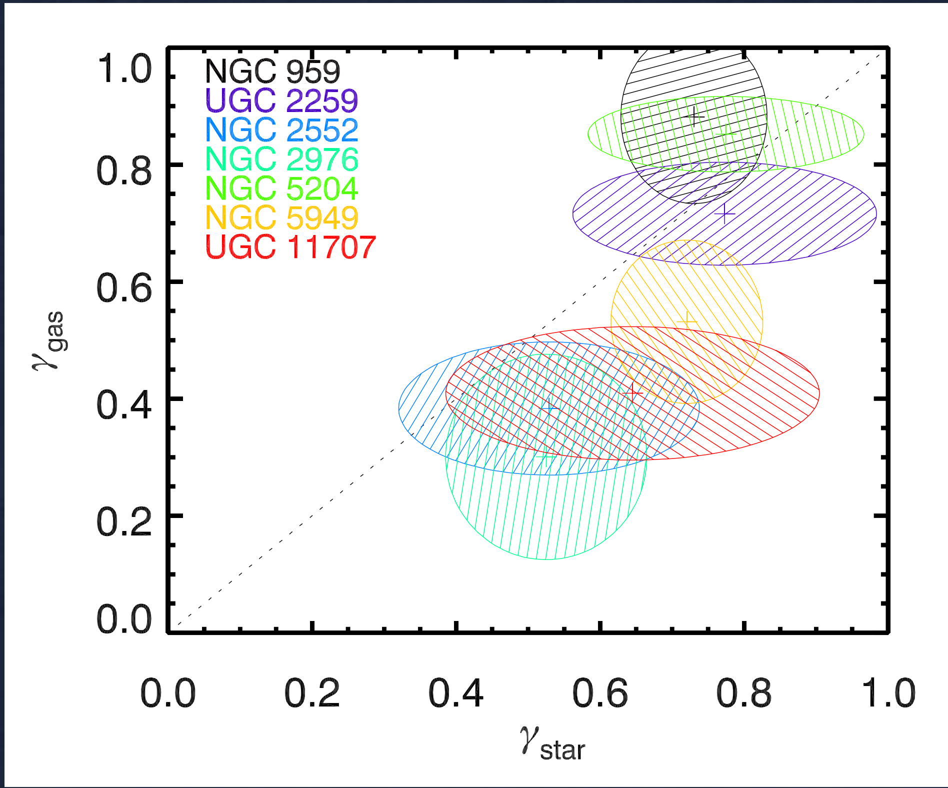
Stars vs. Gas

- Initial suggestions of disagreement between stars and gas, now resolved



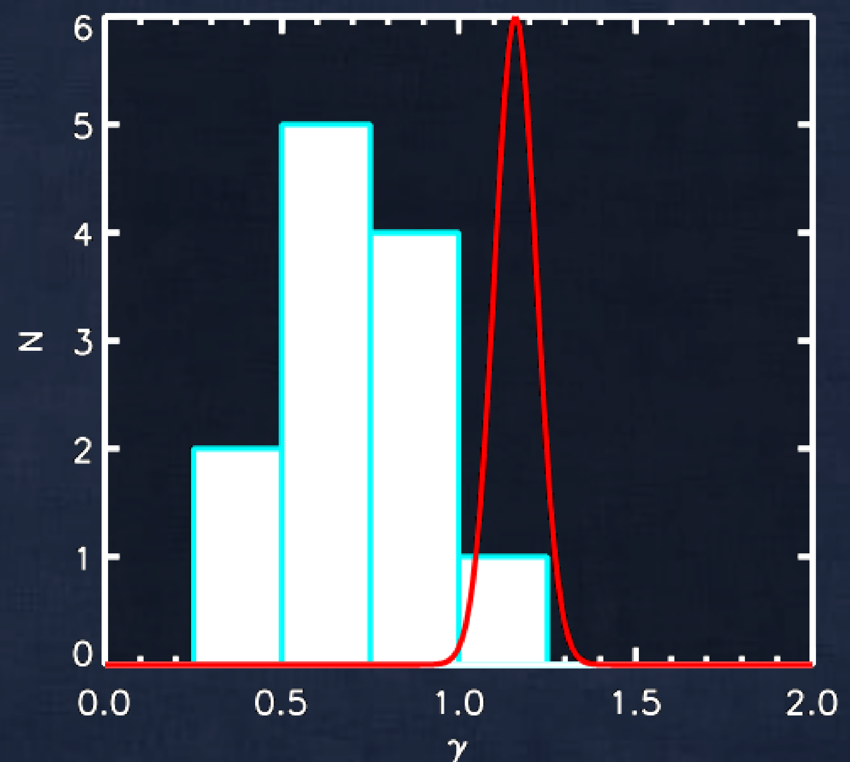
Adams et al. (2012) - stars

Simon et al. (2003) - gas



Adams et al. (2014)

Observed Distribution of Central Slopes



Galaxy sample: Adams et al. (2014) + Simon et al. (2005) + Oh et al. (2011)

Simulations: Diemand et al. (2004)

Average DM profile has © = 0.63 ± 0.28

Adams et al. (2014)

Summary

- Early chem evolution similar in all galaxies
  - Second generation stars discovered in Sculptor
- Faintest dwarfs have ages >12 Gyr
  - Consistent with SF shut off by reionization
- Both Milky Way and M31 satellites appear to be concentrated in planar structures
- Density profiles less problematic than thought
  - Careful sample selection and high quality data are key