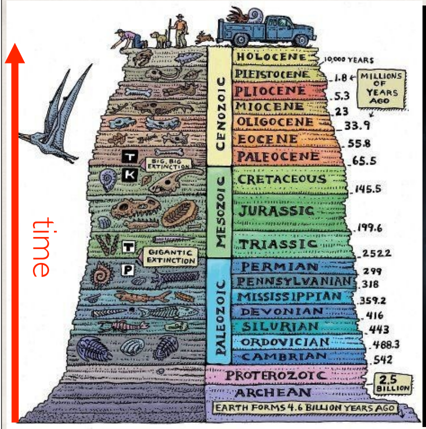
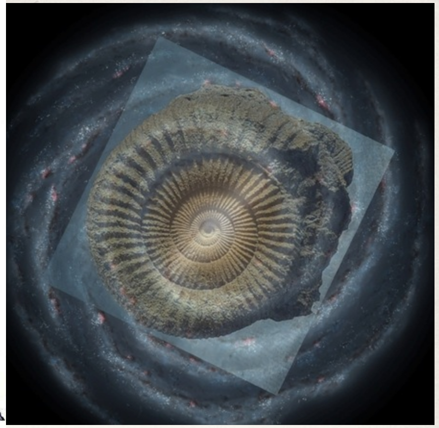
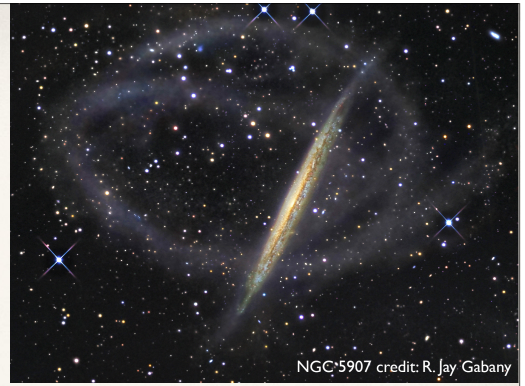


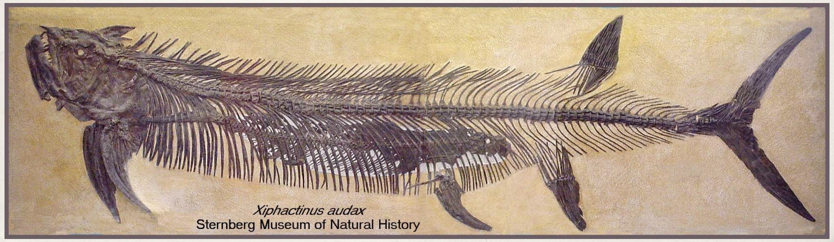


Galactic Palaeontology

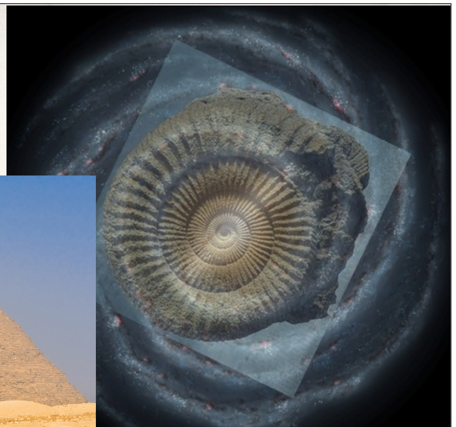
Eline Tolstoy, Kapteyn Astronomical Institute, University of Groningen



NGC 5907 credit: R. Jay Gabany



Xiphactinus audax
Sternberg Museum of Natural History



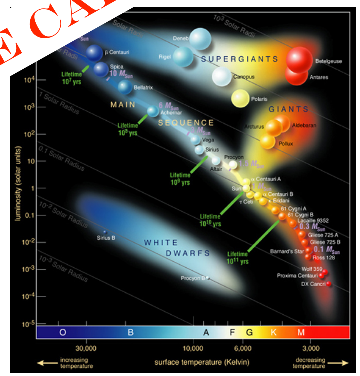
Galactic Archaeology

Eline Tolstoy, Kapteyn Astronomical Institute, University of Groningen

Stars have well defined and well understood & useful properties

STARS ARE TIME CAPSULES

Colo… …ude Di… …s going back …early Universe



…ged" gas in atmosphere: a sample of IS… in which star formed; can measure the changing chemistry of the Universe with time.

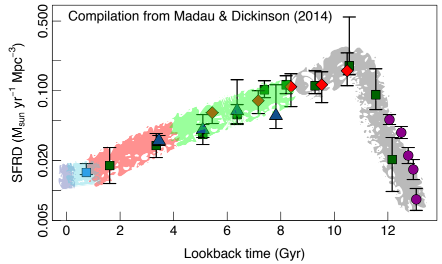
Resolved Stellar Systems

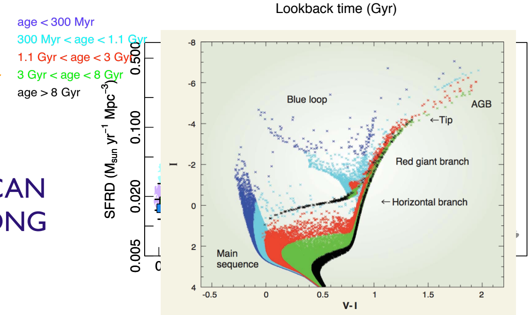
Simulation of Omega Centauri
credit: NASA, ESA & J.Anderson (STScI)

Stars as living fossils

mass		lifetime
120M⊙	O3 star	~ 2.5Myr
12M⊙	B0 star	~ 16 Myr
2.5M⊙	B9 star	~ 600 Myr
1.25M⊙	F5 star	~ 5 Gyr
1M⊙	G8 star	~10 Gyr
0.8M⊙	K2 star	~25 Gyr
0.5M⊙	M0 star	~100 Gyr

increasing numbers: IMF





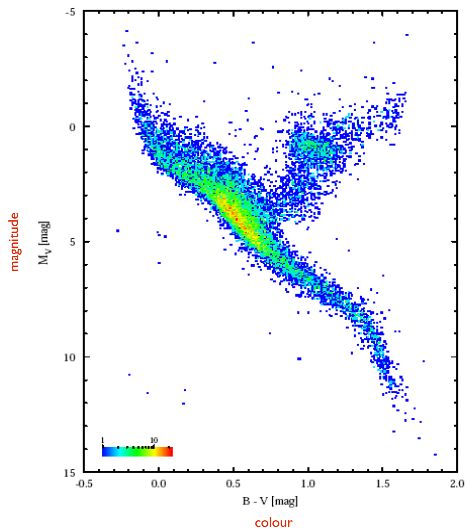
LOW MASS STARS CAN LIVE A VERY VERY LONG TIME

The Milky Way: star by star

Milky Way from Paranal credit: ESO/Yuri Beletsky

Selecting stars in the Milky Way

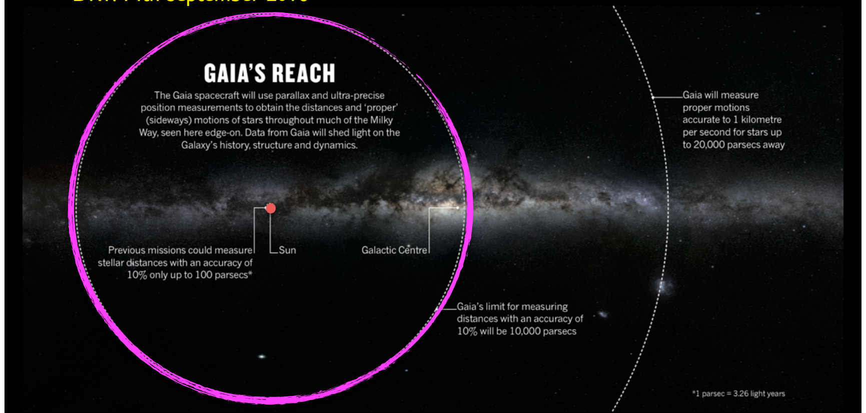
~ 100 000 stars



Hipparcos: Perryman et al. 1995, A&A, 304, 69

The GAIA revolution

Launch: 20th December 2013
DR1: 14th September 2016



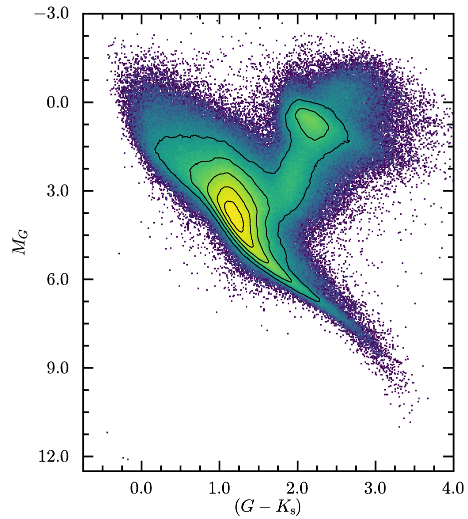
Picture: S. Brunier/ESO; GRAPHIC SOURCE: ESA

> 1 billion sources

Nature, 3rd Oct 2013

First Improvements from GAIA DR1

~1 000 000 stars



GAIA (G) and 2MASS (K) photometry

larger volume
- more bright giants
- effects of reddening
- 3 white dwarfs
- binary sequence

Brown et al. 2016, A&A, 595, A2

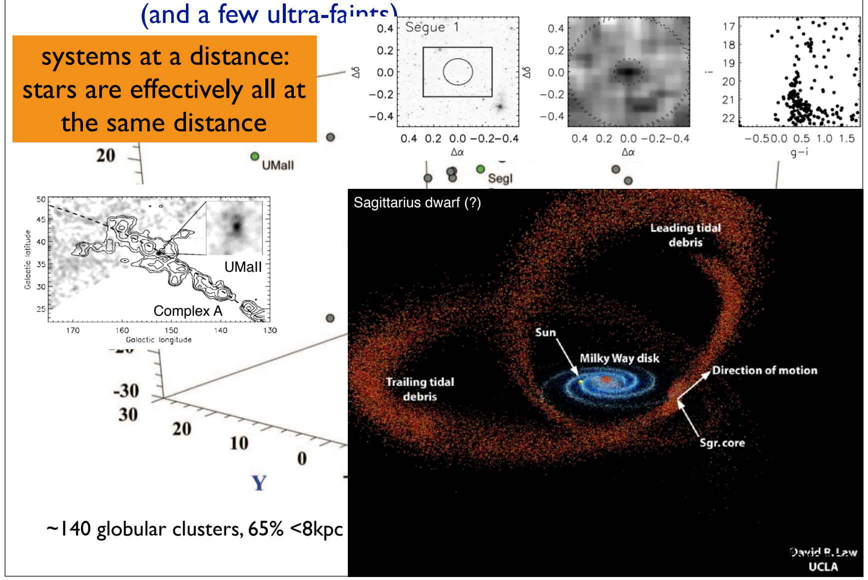
GAIA allows a range of new results, even from DR1 (combined with other facilities):

relation between Galaxy and satellites and globular clusters

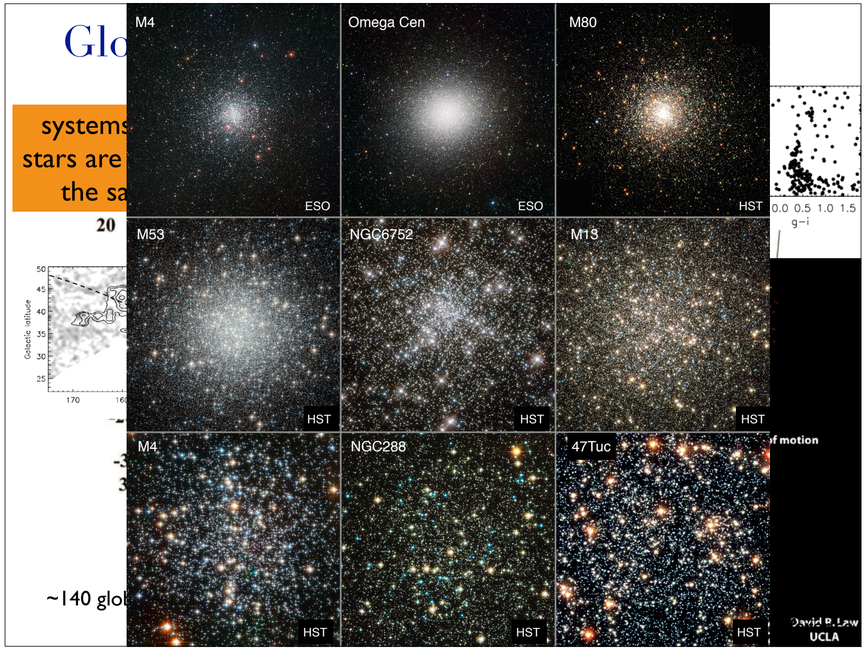
Globular Clusters

(and a few ultra-faints)

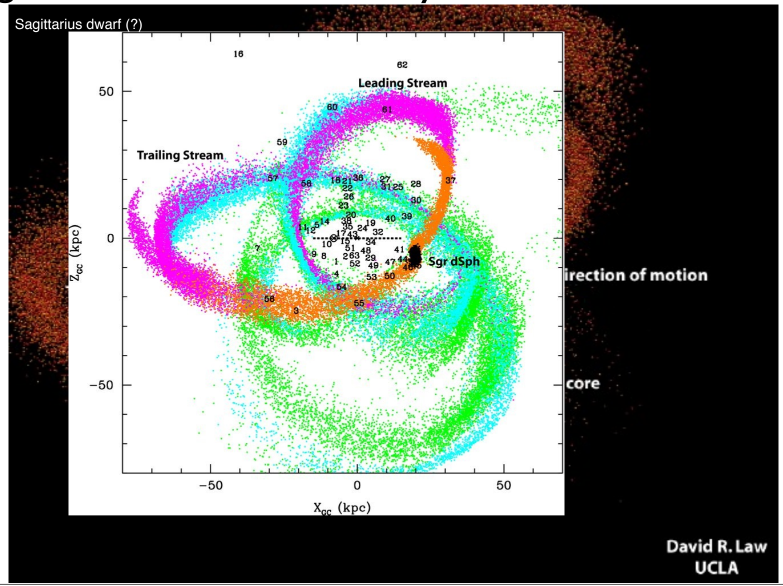
systems at a distance: stars are effectively all at the same distance



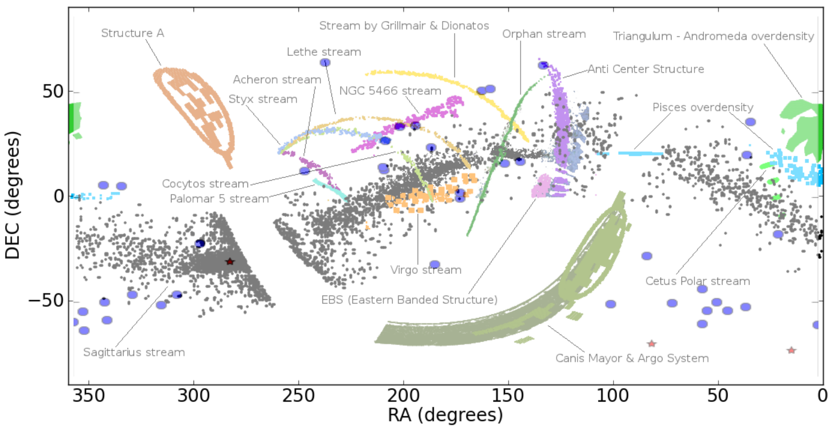
~140 globular clusters, 65% <8kpc



Sagittarius Stream - N-body model



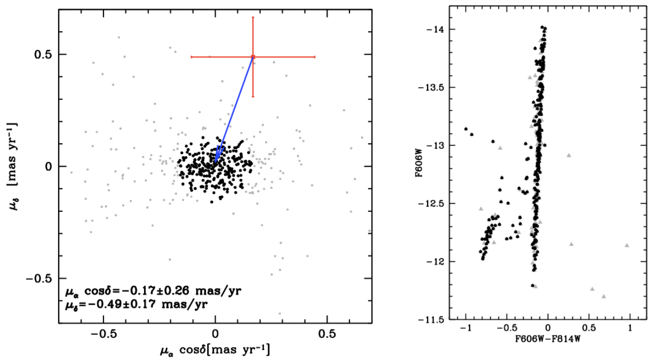
sub-structure in Milky Way halo: not only Sagittarius



compilation by Berenice Pila Diez

Proper Motion for NGC 2419: HST+GAIA

v_{rad} = −20.3 km s^{-1}
distance = 87.5 kpc



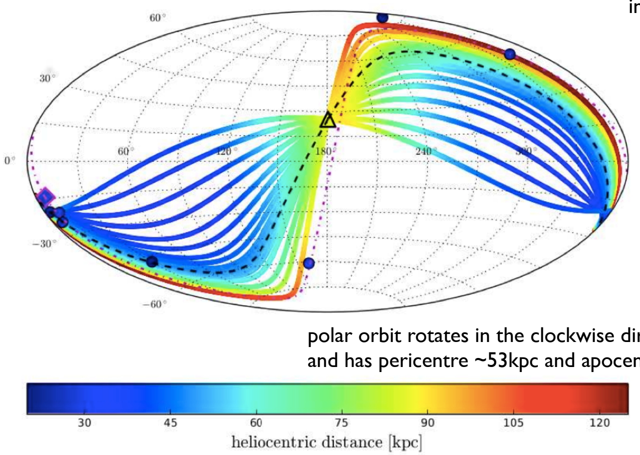
Epoch 1 (HST): 2002 Sep
Epoch 2 (GAIA-DR1): 2015 Jan

Massari et al. 2017, A&ALett, 598, 9

Proper Motion for NGC 2419: HST+GAIA

v_{rad} = −20.3 km s^{-1}
distance = 87.5 kpc

integrated ±4Gyr

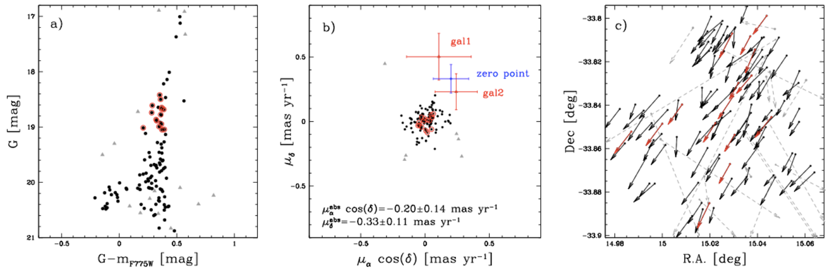


polar orbit rotates in the clockwise direction (same as Sag)
and has pericentre ~53kpc and apocentre ~98kpc

Massari et al. 2017, A&ALett, 598, 9

Proper Motion for Scl dSph: HST+GAIA

For the first time measure the internal motions of stars in a dSph



stars in sample move preferentially
on radial orbits, β ~ 0.9 around the core radius (large uncertainties due to small numbers)

Massari et al. 2017, Nat. Astro., in press

GAIA DR2 - first Gaia PM, colours, spectra, Teff

April 2018

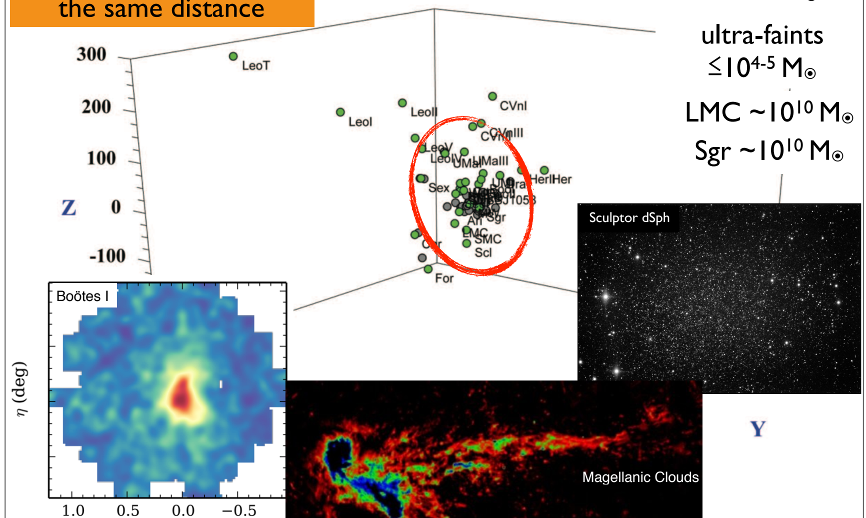
systems at a distance: stars are effectively all at the same distance

Milky Way - halo

dwarfs
~10^{6-9} $M_\odot$

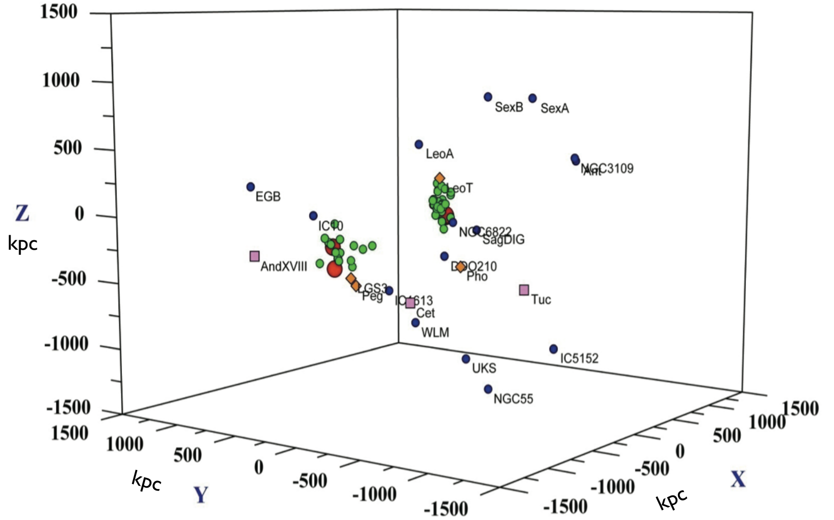
ultra-faints
≤10^{4-5} $M_\odot$

LMC ~10^{10} $M_\odot$
Sgr ~10^{10} $M_\odot$



Joint Conference

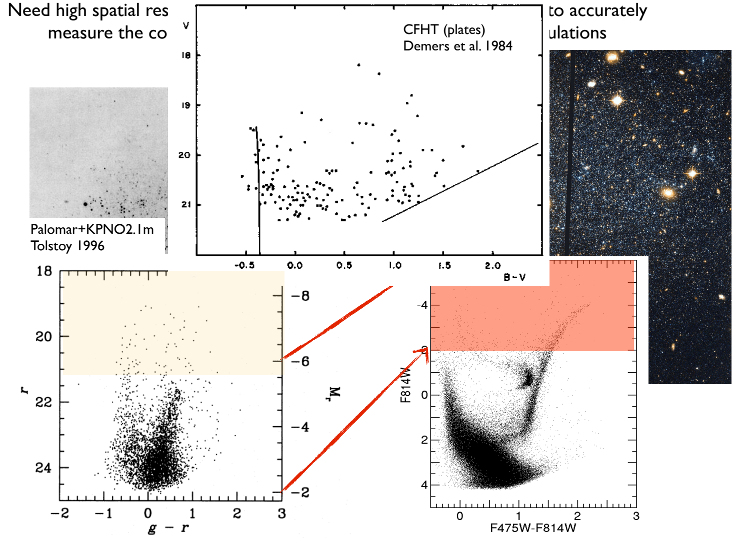
The Local Group



Mateo 2008, MPA/ESO/MPE/USM Joint Conference

Resolution AND Stability: HST legacy

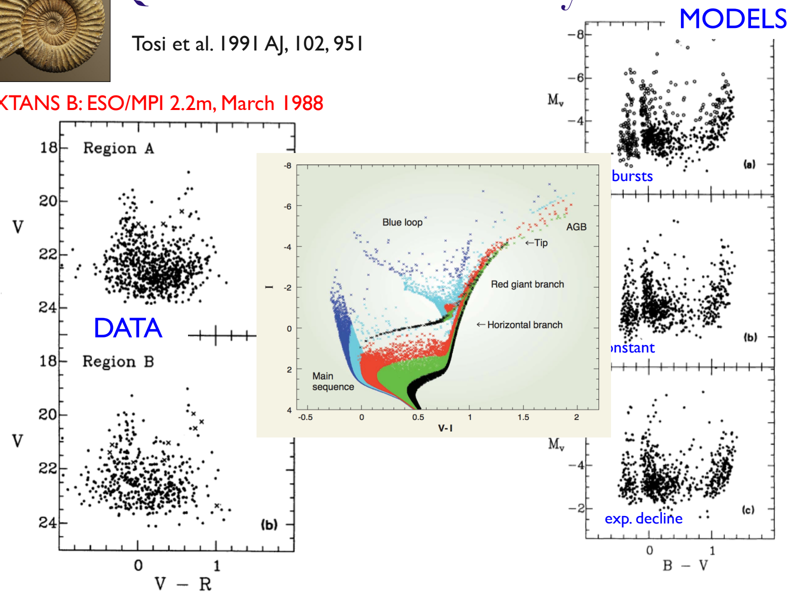
Need high spatial res ... to accurately
measure the co... ulations



Quantitative CMD analysis

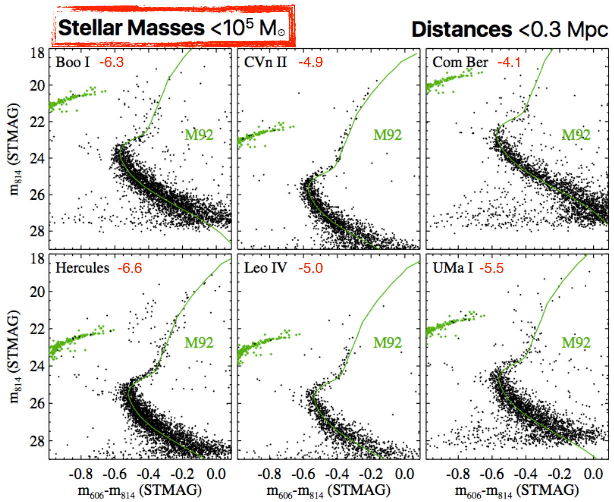
Tosi et al. 1991 AJ, 102, 951

SEXTANS B: ESO/MPI 2.2m, March 1988



HST CMDs for Local Group ultra-faint dwarf galaxies

Brown et al. 2014 ApJ, 796, 91



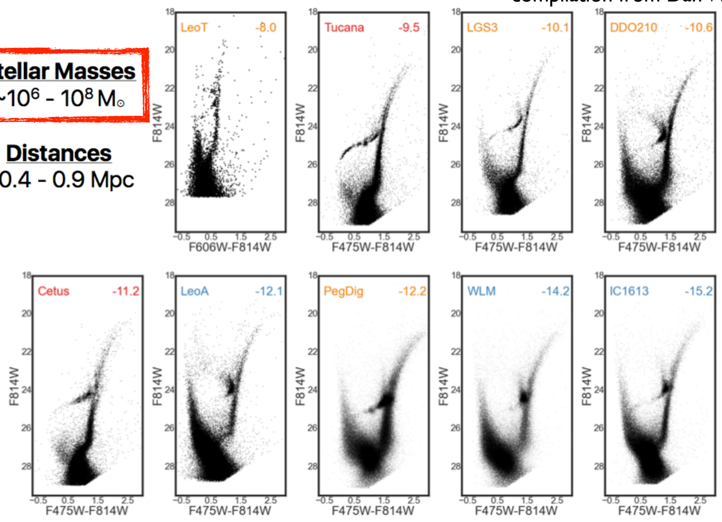
from HST programmes led by Tom Brown

HST CMDs for Local Group dwarf galaxies

compilation from Dan Weisz

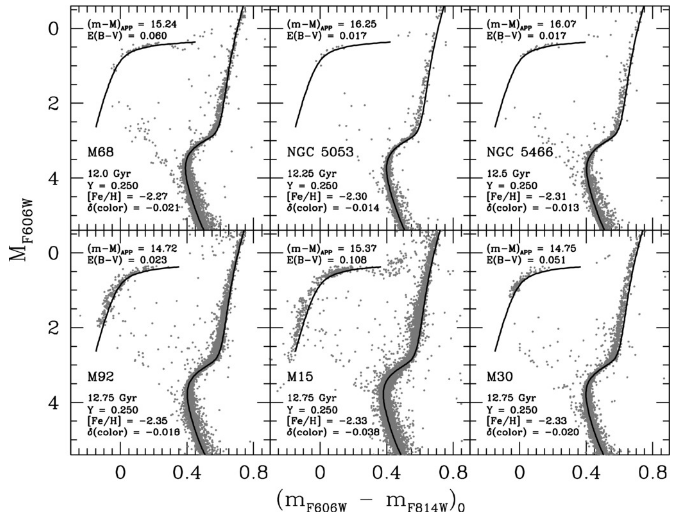
Stellar Masses
~10^6 - 10^8 M☉

Distances
~0.4 - 0.9 Mpc



from HST programmes led by Gallart, Cole, Weisz

HST CMDs for Galactic Globular Clusters

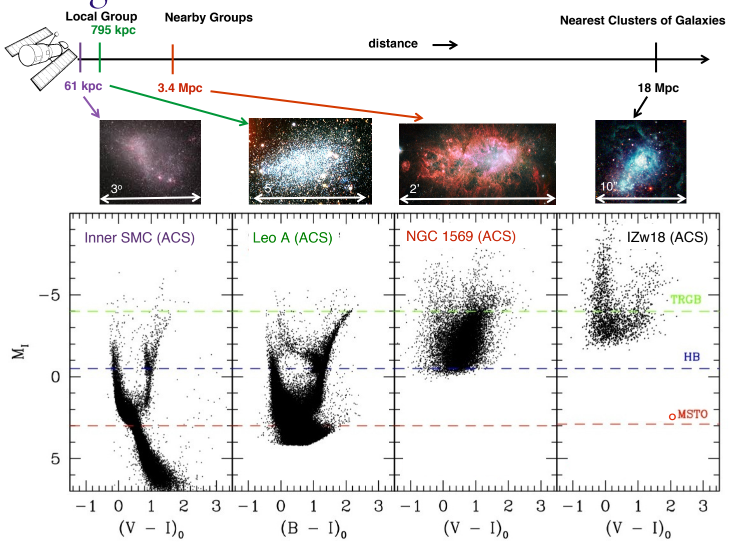


Stellar Masses
10^5 -10^6 M☉

distance
6-15kpc

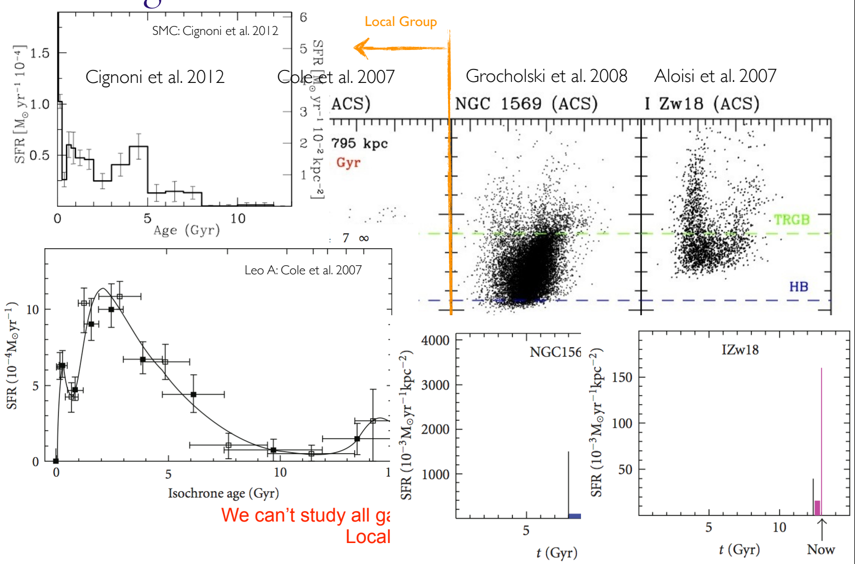
from VandenBerg et al. 2013 ApJ, 775,

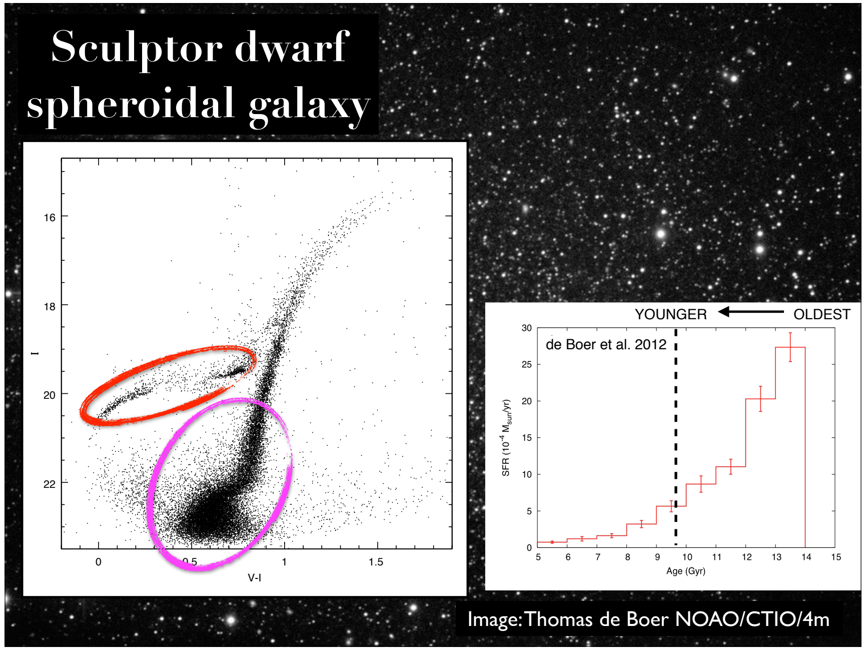
Probing Different Environments



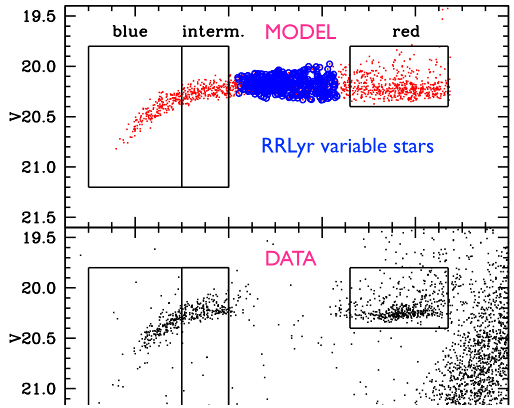
Cignoni et al. 2012 Cole et al. 2007 Grocholski et al. 2008 Aloisi et al. 2007

Probing Different Environments





Modelling the Horizontal Branch: Scl dSph



Need to use "known" SFH to constrain the MASS LOSS

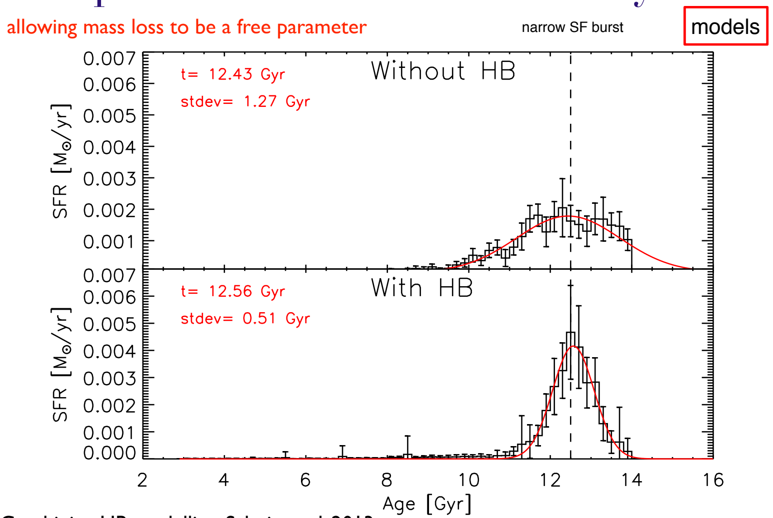
There are no indications of enhanced-He subpopulations

1. $\langle \Delta M_{RGB} \rangle = 0.10\, M_\odot$ for [M/H] < −1.8;
2. $\langle \Delta M_{RGB} \rangle = 0.14\, M_\odot$ for −1.8 ≤ [M/H] ≤ −1.6;
3. $\langle \Delta M_{RGB} \rangle = 0.14–0.15\, M_\odot$ for −1.6 < [M/H] ≤ −1.4;
4. $\langle \Delta M_{RGB} \rangle = 0.14–0.16\, M_\odot$ for −1.4 < [M/H] ≤ −1.3;
5. $\langle \Delta M_{RGB} \rangle = 0.16\, M_\odot$ for [M/H] > −1.3;

Salaris et al. 2013 A&A, 559, A57

Carina: Savino et al. 2015 A&A, 583, A126

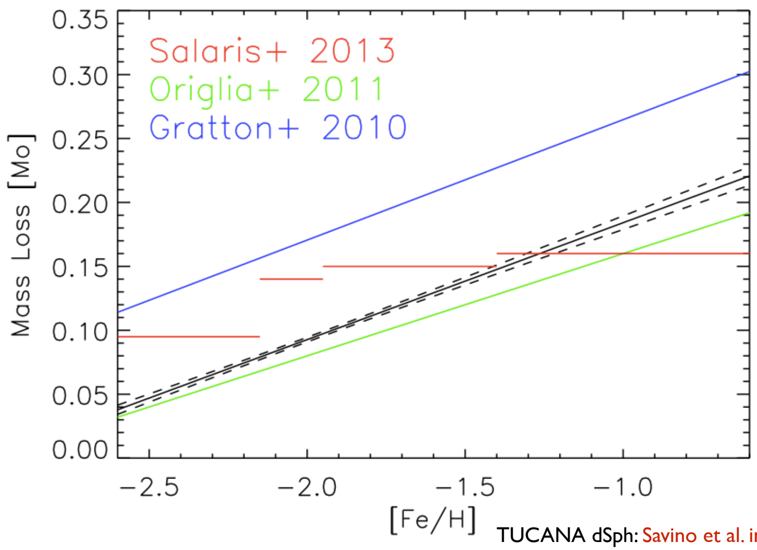
An improved star formation history:



Combining HB modelling: Salaris et al. 2013
CMD modelling: de Boer et al. 2012

Alessandro Savino, in prep.

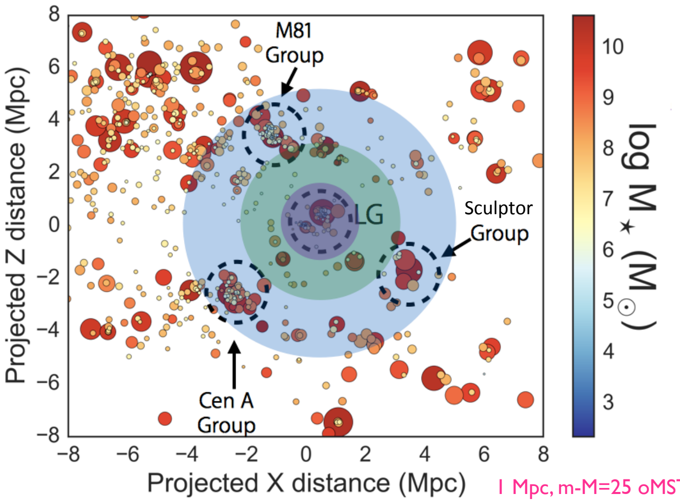
Modelling the Horizontal Branch: Mass Loss



TUCANA dSph: Savino et al. in prep.

Local Volume

image taken from talk by Dan Weisz, at JWST@ROE, July 2016



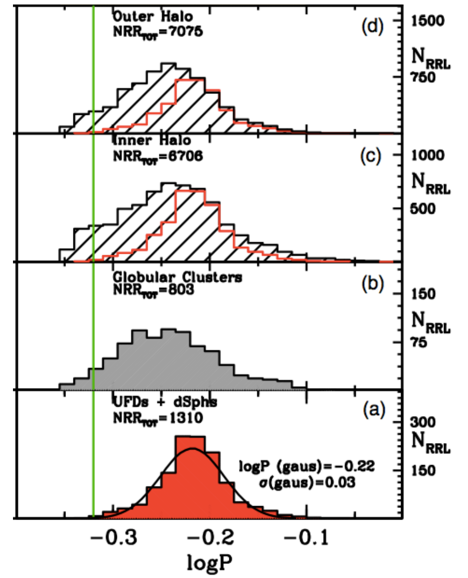
1 Mpc, m-M=25 oMSTO~29; HB~24.7

1.7 Mpc, m-M=26.1 oMSTO~30.1; HB~25.8

4 Mpc, m-M=28 oMSTO~32; HB~27.7

RRLyrae in Galactic Halo

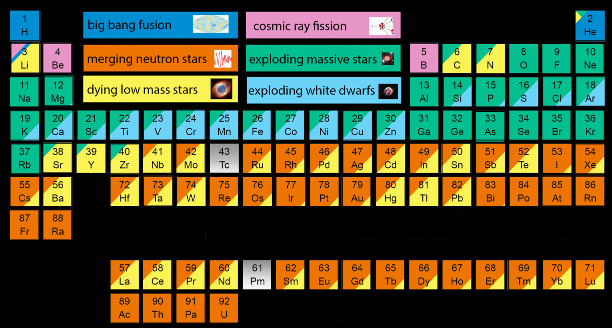
Galaxies similar to present day dSph & UFDs have only contributed ~10-20% of the halo stellar mass



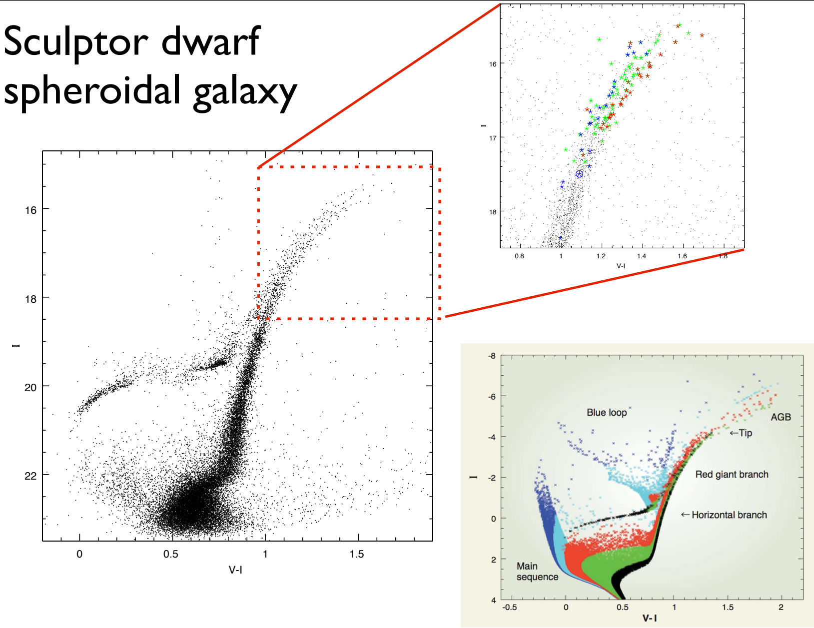
Fiorentino et al. 2015 ApJL, 798, L12

Chemical Elements

The Origin of the Solar System Elements

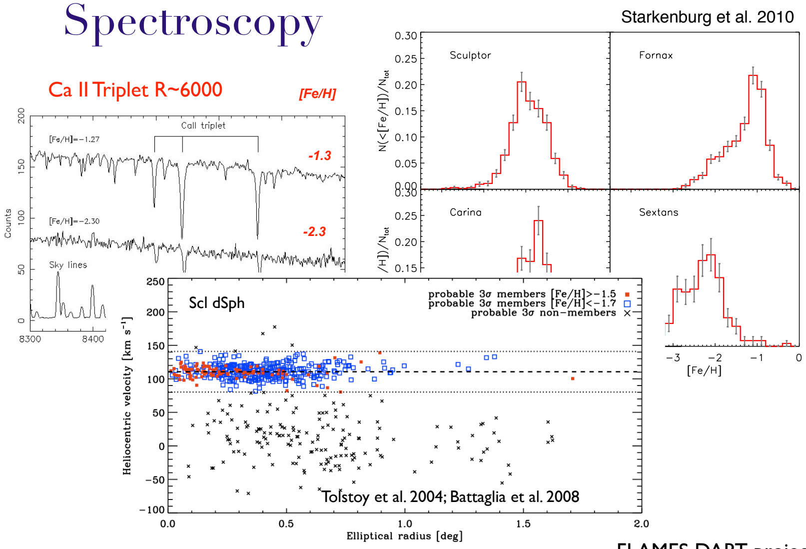


Sculptor dwarf spheroidal galaxy



Low Resolution Spectroscopy

[Fe/H] ∝ EW of CaII triplet lines

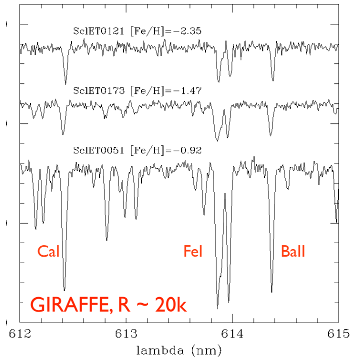


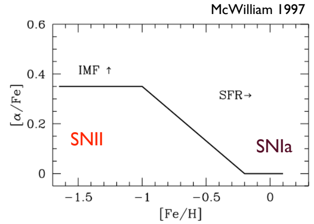
FLAMES DART project

Intermediate Resolution Spectroscopy

Fe Mg, Si, Ti, Ca Ni, Cr, Y, Ba, La, Nd, Eu

alpha-elements





SNII - fast enrichment, by massive stars

SNI - long term slow enrichment by low mass stars

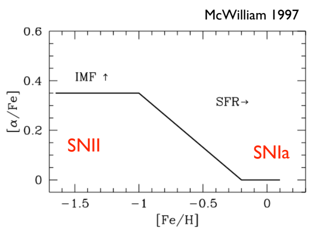
Gilmore & Wyse 1991
Matteucci & François 1989

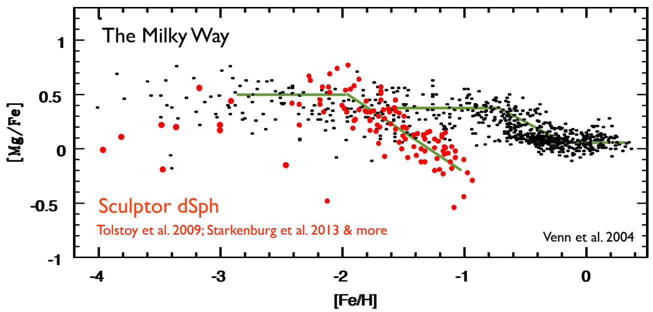
FLAMES DART project

Alpha-Elements

"The Knee"

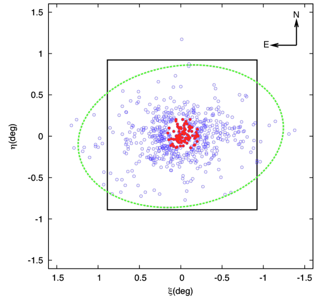
can only make halo out of existing dwarf galaxies at very early times

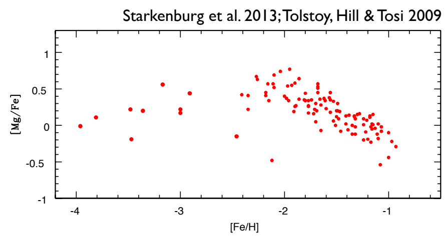


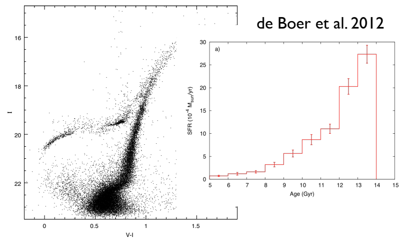


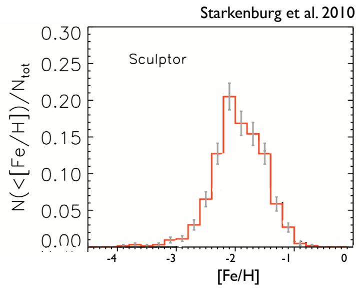
FLAMES DART project

Putting it altogether in Sculptor



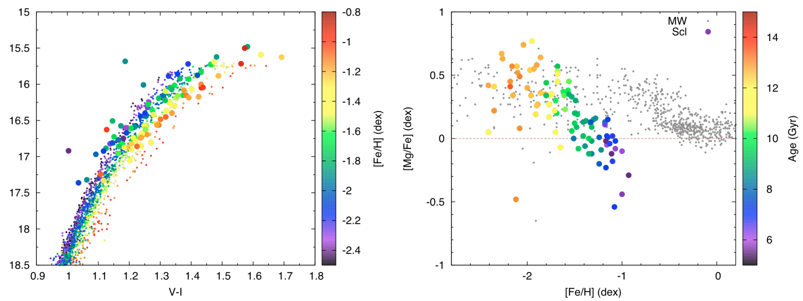






FLAMES DART project

Measuring the Timescale for Chemical Evolution in Sculptor

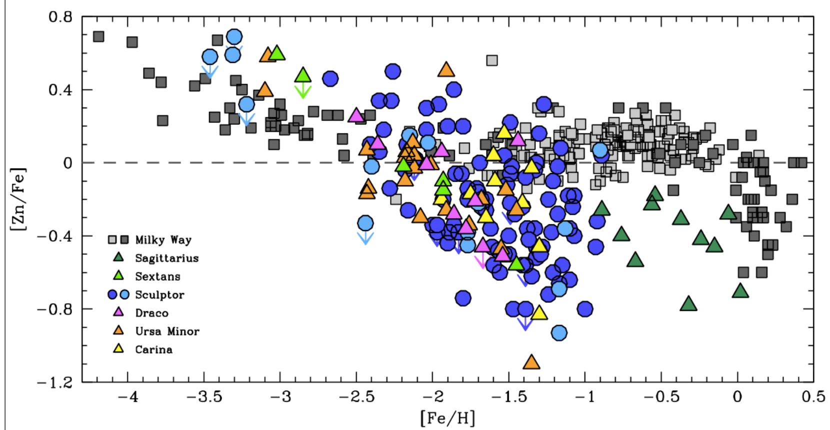


SNIa start to contribute to the chemical enrichment of the Sculptor dSph galaxy 2±1 Gyr after star formation began

de Boer et al. 2012, A&A, 539, A103

Zinc in Sculptor

VLT/FLAMES/UVES

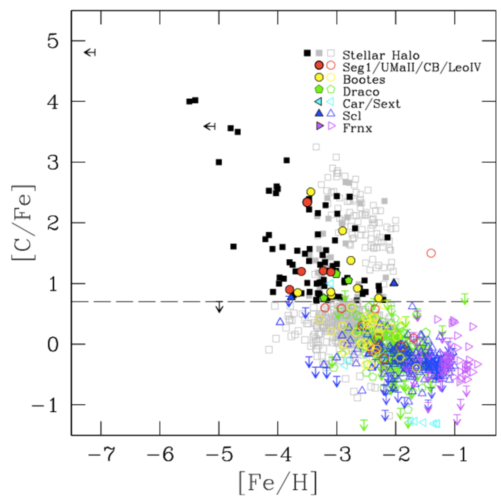


Zinc is an important element for tying down supernovae masses and energies

Skúladóttir et al. 2017, A&A, 606, A71

stars in the Milky Way & in dSph galaxies
appear to have fundamentally different properties

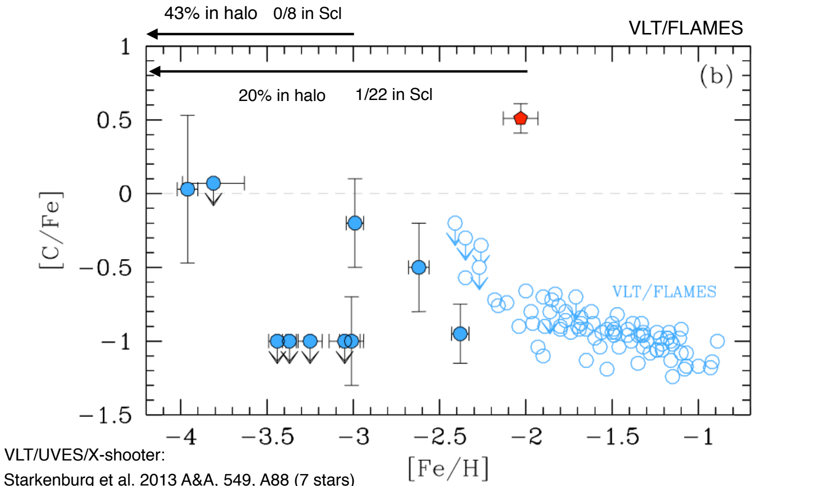
Differences between UFDs & dSph



CEMP-no
Carbon rich stars

Salvadori et al. 2015 MNRAS, 454, 1320

The First CEMP-no star in Sculptor.



VLT/UVES/X-shooter:
Starkenburg et al. 2013 A&A, 549, A88 (7 stars)
Tafelmeyer et al. 2010 A&A, 524, A58 (2 stars)
Magellan/MIKE: Frebel et al. 2010 Nature (1 star)

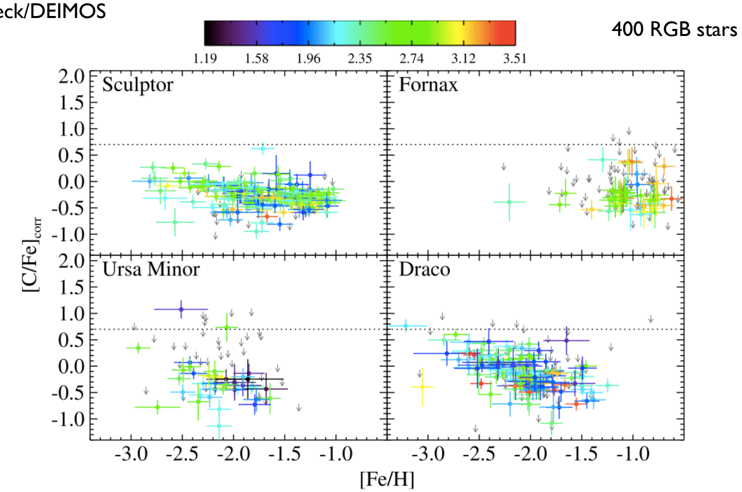
Skúladóttir et al. 2015, A&A, 574, A129

FLAMES DART project

Are there Carbon Rich Stars in dSph?

Keck/DEIMOS

400 RGB stars



selection biases preclude a detailed comparison to the MW stellar halo

Kirby et al. 2015 ApJ, 801, 125

high Carbon (without s/r process enhancement) is more prevalent for low Z halo stars and also stars in UFDs. Not in dSph.

Massive star formation? in such small stellar systems?

The low Ba, high [Mg/Ca] and [Co/Cr] in Hercules stars (Koch et al. 2013)

High carbon ultra-faints (Frebel & Norris 2015)

The high Eu in Rec II stars (Ji et al. 2016a,b) - r-process rich system

These results suggest high mass SNII in UFDS, higher than for dSph

Did these stars form in a larger system that was destroyed?

e.g., Sagittarius or LMC/SMC systems?

ALSO true for Globular Clusters: O-Na and Mg-Al anti-correlations
(Gratton et al. 2001; Caretta et al. 2009)

Future instrumentation will address the current questions about the uncertainty in the global context of star formation properties within the Local Group:

GAIA + WEAVE, 4MOST, PFS, MOONS
distances, proper motions, large samples of HR spectra

JWST, ELT-MAORY-MICADO, ELT-HARMONI, optical AO?
allowing us to go beyond the Local Group and probe other large galaxies (eg Sculptor, Centaurus Groups; Virgo, Fornax clusters) to look in detail at Elliptical galaxies and also see if we can generalise our understanding of the Milky and its environment.