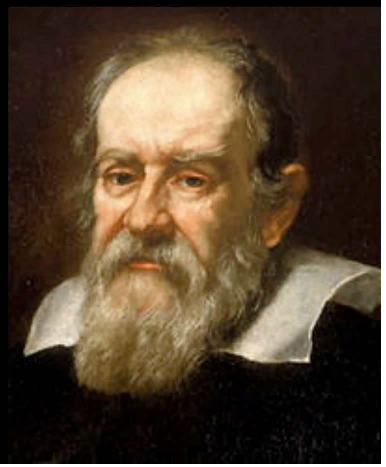
Galactic Archaeology

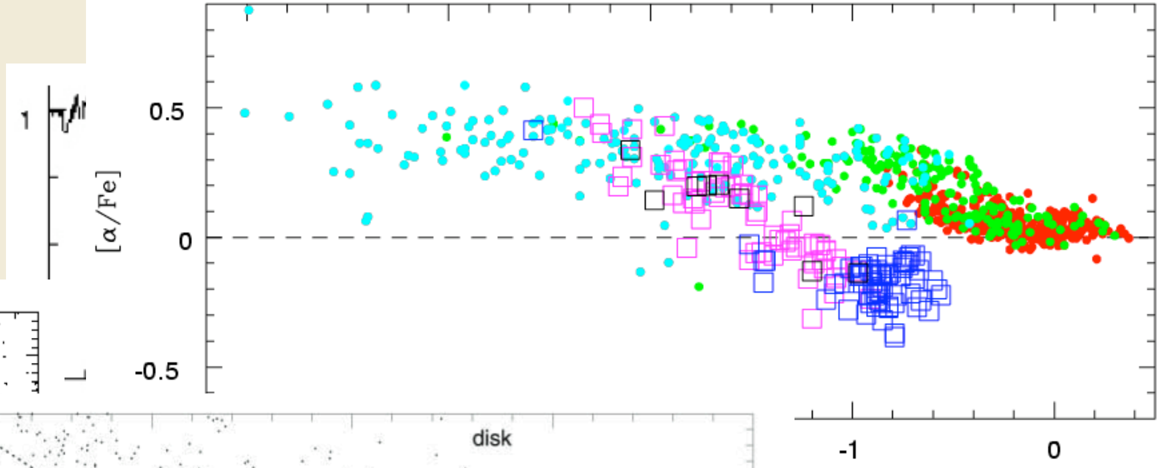
Stars are direct tracers of the Early Universe

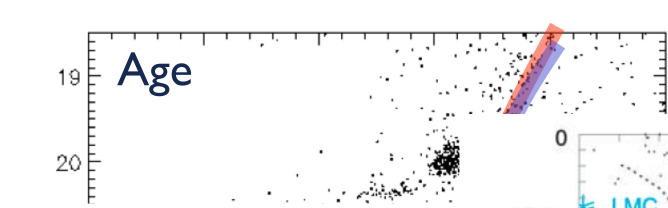
The Closest Galaxy

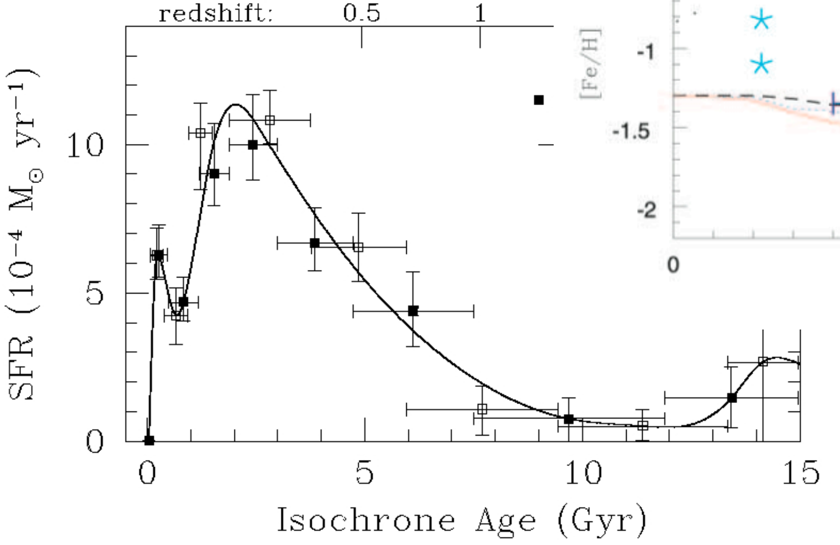
...congeries
stellularum...

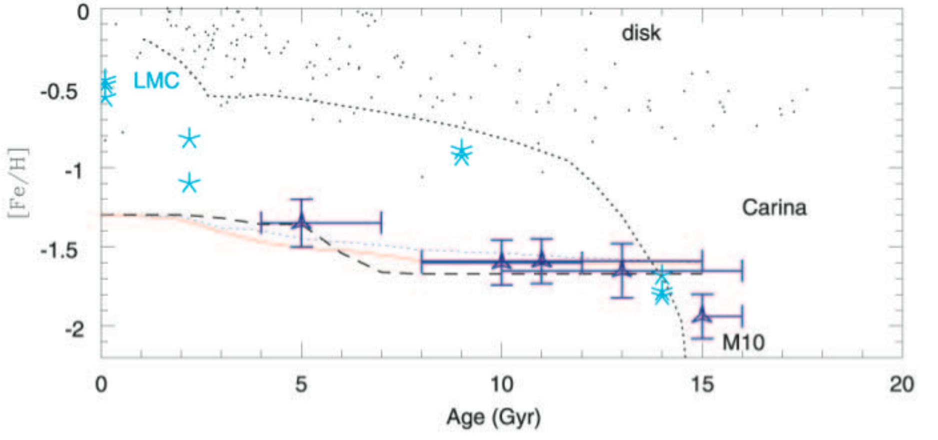


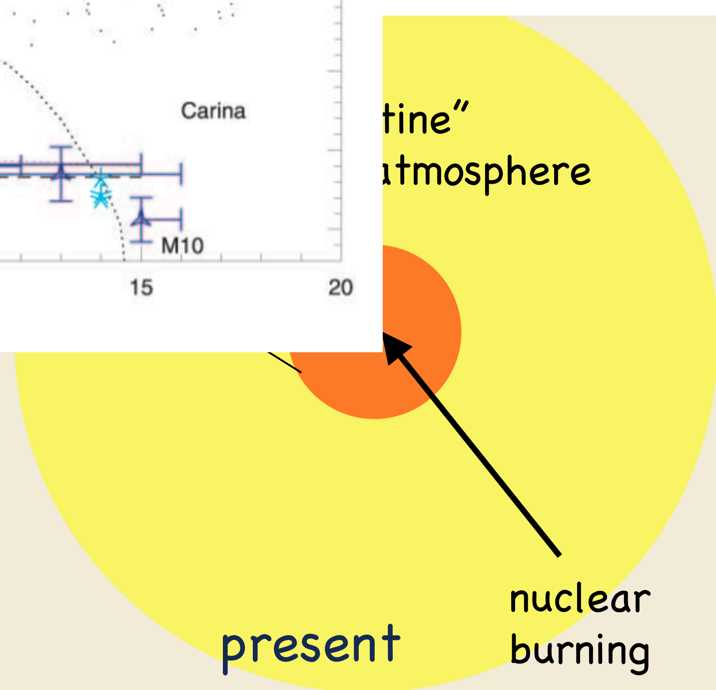
Old Stars











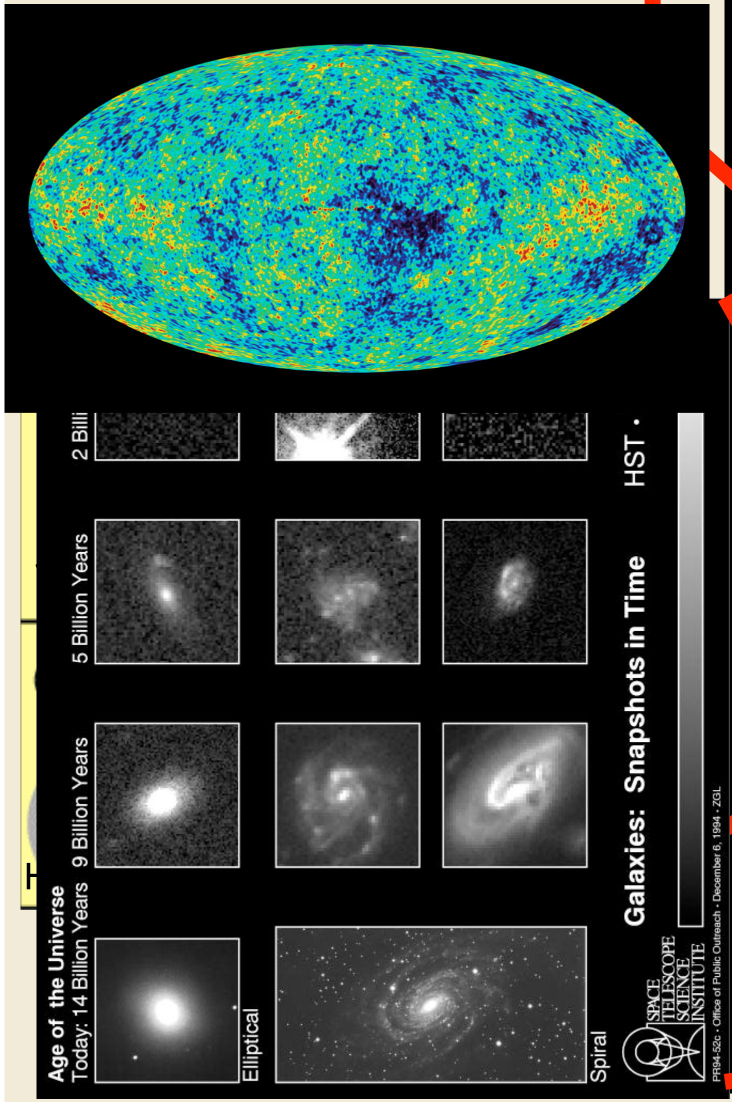
< $1M_\odot$

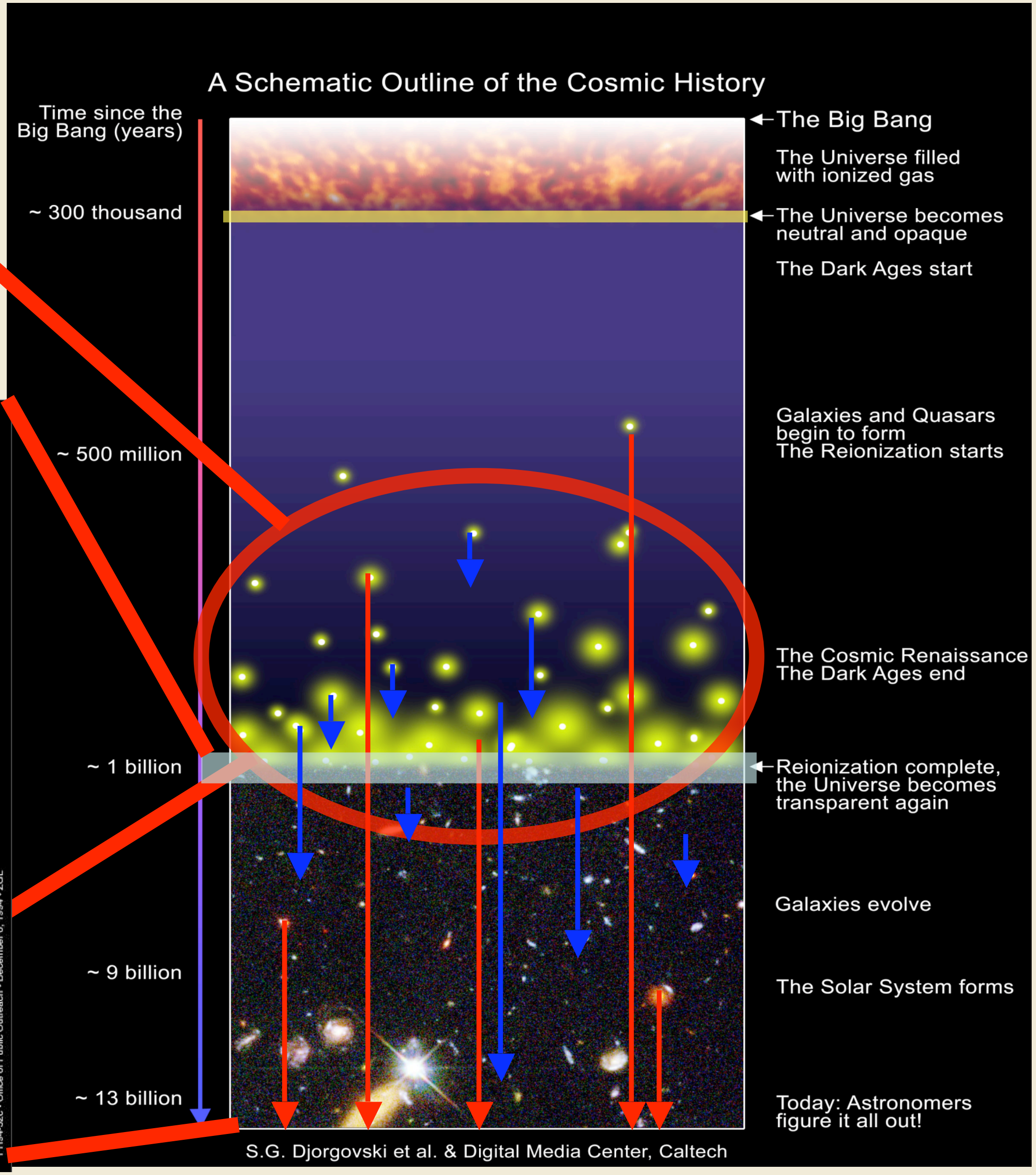
13.5 12.7 11.5 10.3 7.7 Gyr present

Z= 20 6 3 2 1 0

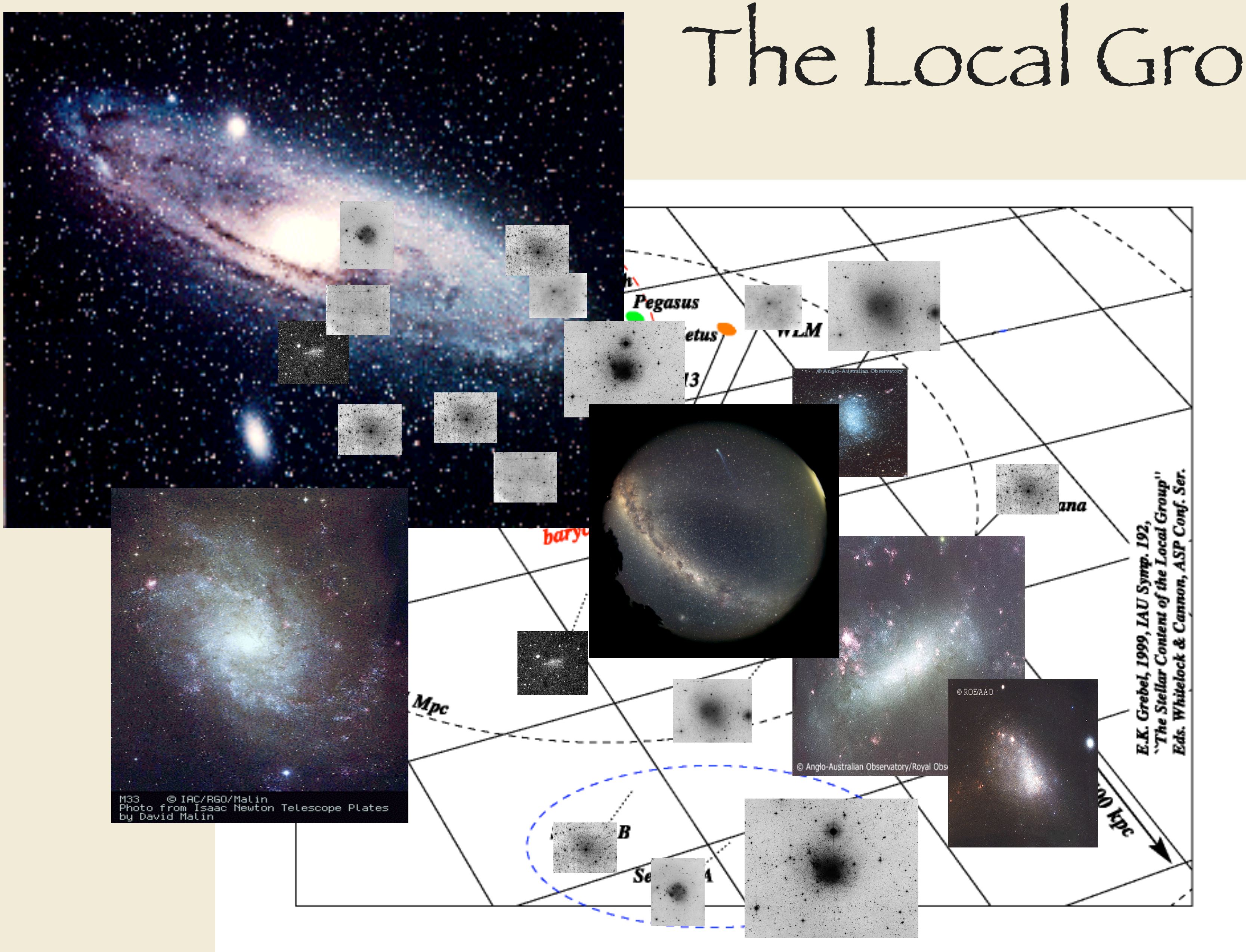
Cosmic History

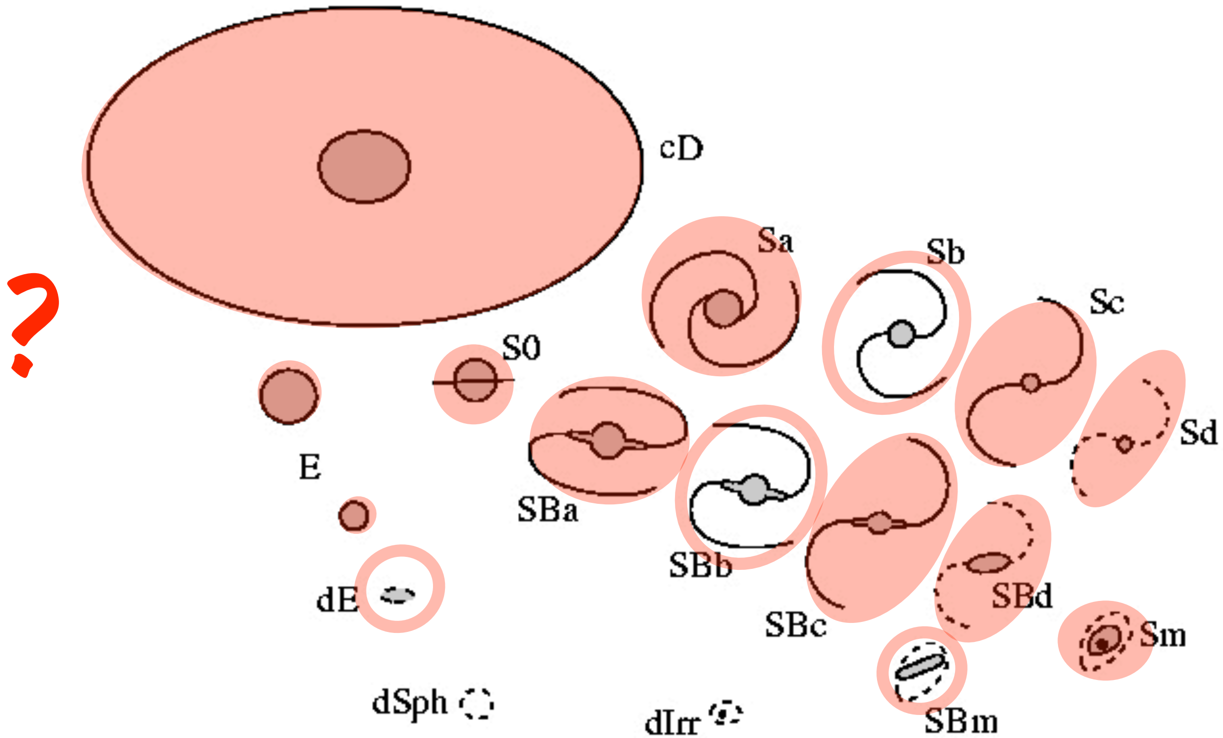
Big Bang





The Local Group





?
cD
Sa
Sb
Sc
S0
Sd
E
SBa
SBb
SBc
SBd
dE
Sm
dSph
dIrr
SBm

Stellar Pops DRM

- Imaging
- Low resolution spectroscopy (R ≈ 5000)
- High Resolution spectroscopy (R ≥ 20000)

Why Optical?

✶For low metallicity stars most of the observable lines which are easy to interpret are at optical wavelengths (and mostly quite blue, < 680nm).

✶Higher diffraction-limited spatial resolution in the optical (a factor of 3 to 4 higher than in the infrared, corresponding to magnitudes of depth in crowded fields) - most stellar population applications are confusion-limited rather than sky-background or photon limited and typically attainable depths are 7 magnitudes fainter in V than in K.

✶The derivation of stellar parameters such as age and metallicity is more robust in the optical than in the near-IR.

HIGH RESOLUTION SPECTROSCOPY:

Stars are direct tracers of the early universe

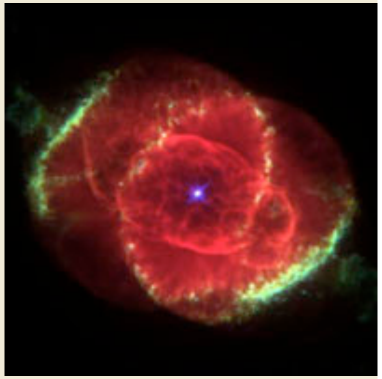
Chemical Tagging

- Light Elements – e.g., O Na Mg Al
tracers of deep mixing abundances patterns (globular clusters versus field stars)

- α- Elements – e.g., O Mg Si Ca Ti
dominated by products of Supernovae II

- Iron-peak Elements e.g., V Cr Mn Co Ni Cu Zn
explosive nucleosynthesis (supernovae I)

- Heavy Elements ($Z > 30$)
mix of r- and s- process elements
e.g., s-process e.g., Ba, La (stellar winds)
r-process e.g., Eu



e.g., McWilliam 1997

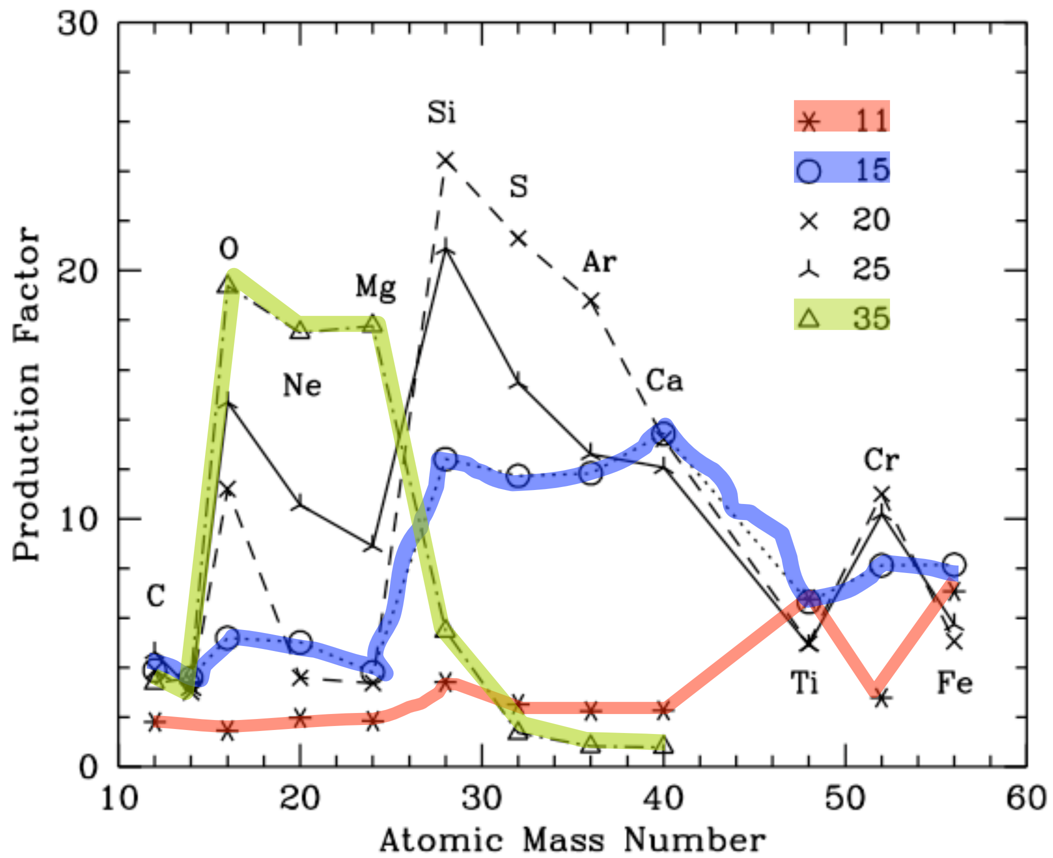
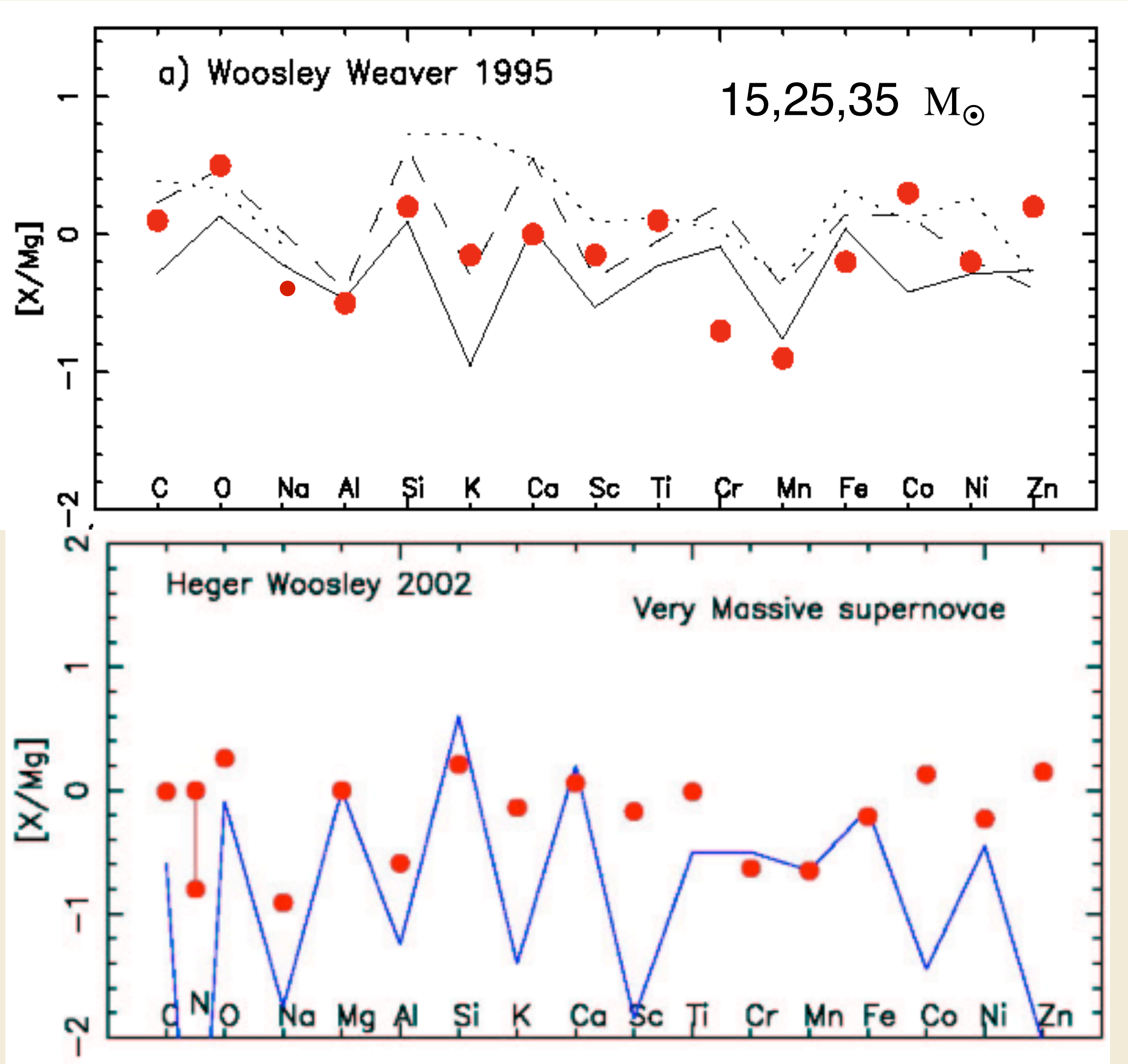
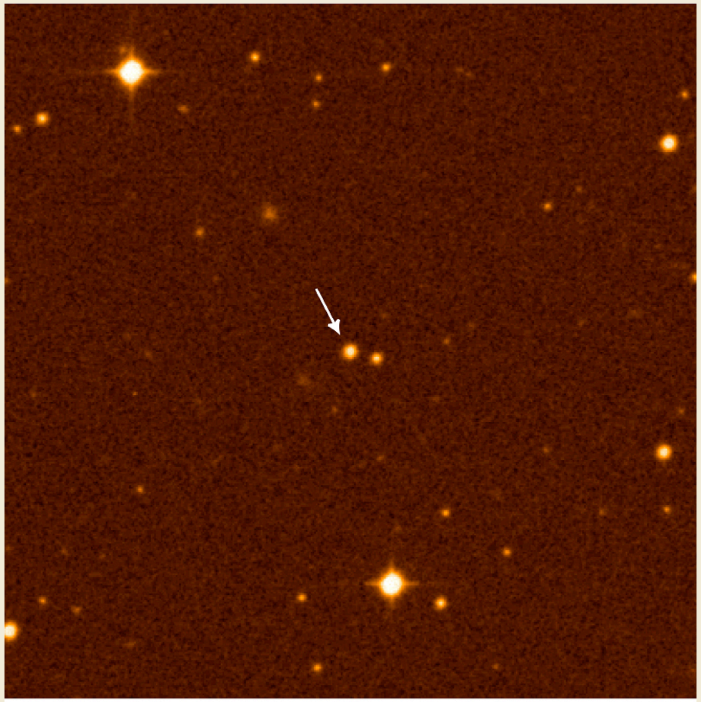


Figure 6 Production factors from models of SN II by Woosley & Weaver (1995). Ejected element abundances for various progenitor masses are indicated by *connected symbols*; O and Mg are produced in large quantitiesat high mass (~35 $M_\odot$) but not in the lower mass (15–25 $M_\odot$) SN, which are responsible for most of the Si and Ca production. None of the models give significant enhancements of Ti relative to Fe, contrary to observations of stars in the Galactic bulge and halo. Note that production factor is defined as the ratio of the mass fraction of an isotope in the SN ejecta, divided by its corresponding mass fraction in the Sun. The mass of the progenitor making the indicated elements is given in the key in the upper right.

Constraining early chemical enrichment

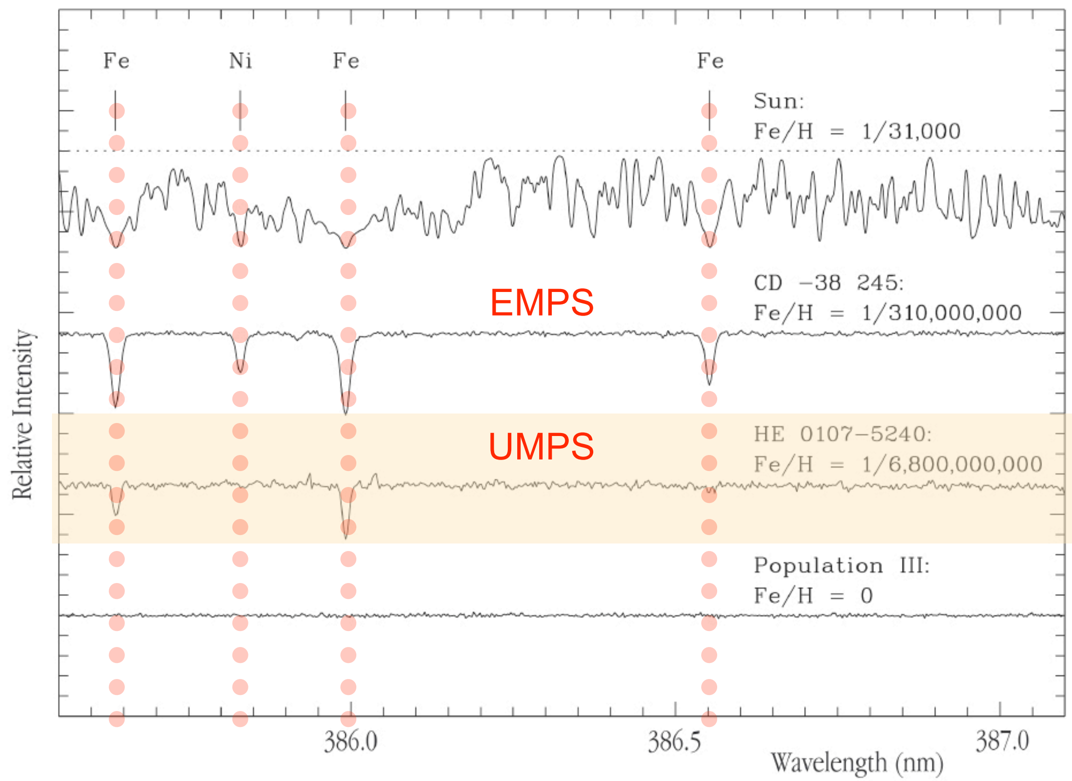


HE0107-5240:
The Most ancient object we know of ?



The Very Metal-Deficient Star HE 0107-5240

ESO PR Photo 25a/02 (30 October 2002) ©European Southern Observatory



Spectra of Stars with Different Metal Content

ESO PR Photo 25b/02 (30 October 2002) ©European Southern Observatory

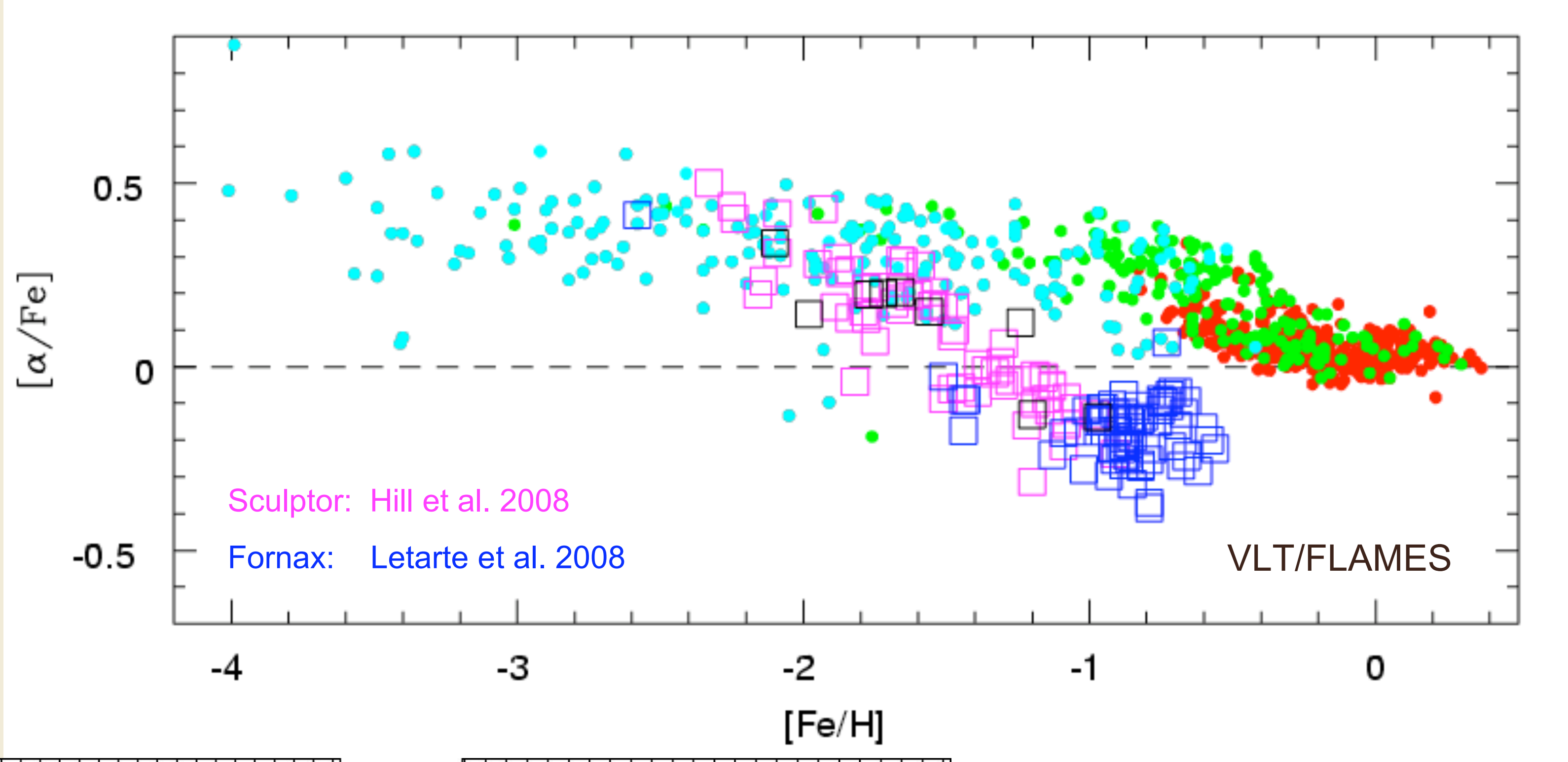
HE 0107-5240

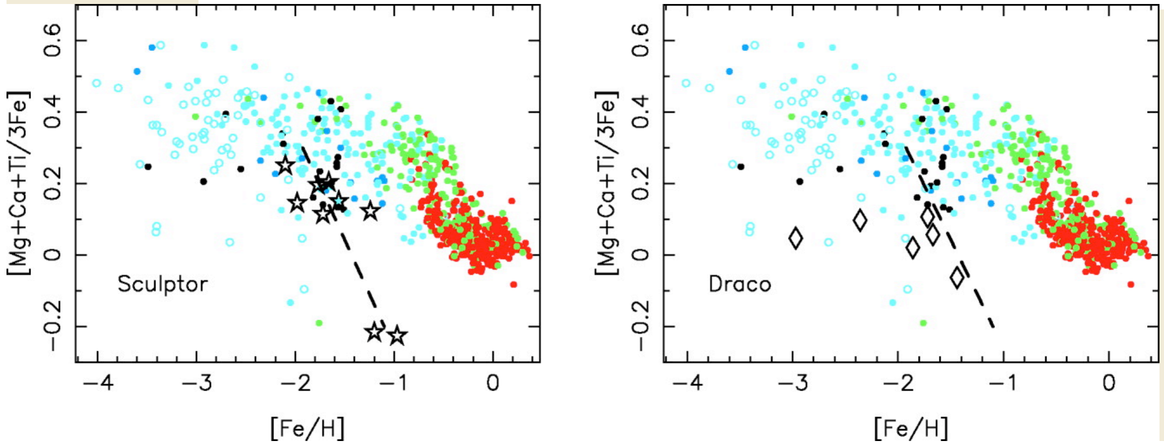
[Fe/H] = -5.4

Christlieb & HES

Alpha Abundances in dSph

Hard to make any component of MW from dwarf satellites...





Shetrone et al. 2001,2003;
Tolstoy et al. 2003

HR spectroscopy cases:

R~20000 resolution spectroscopy in the visible an near-infrared, to measure detailed abundances of metals in a variety of stars, to probe the source and timescales of metal enrichment in galaxies. Examples of prominent science cases include:

-Detailed abundances in old red giants at the edge of the Local-Group (dwarf Irregular galaxies, isolated dwarf spheroidal galaxies, M31, M32, M33) to unravel the chemical enrichment timescale and nature within range of galaxy types.

-Detailed abundances of B-A super-giants in spiral galaxies outside the Local Group, out to the Sculptor or M82 groups (2Mpc away). The 0.2" resolution provided by the GLAO corresponds to 0.6 pc at the distance of M31 and 1.8 pc at the distance of the Sculptor group, it will be perfectly suited for this study.

-Detailed abundances of metal poor dwarf & giants stars in the halo of MW & M31 there are a number of lines which are too weak to be detected with present day instrumentation (e.g., Li, U, Be, r-process elements).

The spectrograph extension towards visible wavelengths will have a large impact in this science case, since most of the strong metal-lines are located in the visible. On the other hand, detailed abundances in metal-rich populations (such as bulges and young stellar disks) can be measured in the infrared.

Stell param

[Fe/H]<-5.

R-process

Quantity	Indicator	Minium $R=\lambda/\Delta\lambda$ G/−5.2	SG/−5.4	r-II giant	Minium S/N per pixel G/−5.2	SG/−5.4	r-II giant	Notes
$T_{\rm eff}$	Hα	40,000	40,000	40,000	150	150	150	
$\log g$	Fe I/Fe II	20,000	20,000	20,000				1
$\log g$	Ca I/Ca II	20,000	20,000	20,000				
$\xi_{\rm micr}$	Fe I	40,000	60,000	20,000	50	200	30	2
$\log\epsilon\,(^7{\rm Li})$	^{7}Li 6707.76 Å	–	40,000	–	–	120	–	3
$\log\epsilon$ (C)	CH	20,000	20,000	20,000				
$\log\epsilon$ (N)	CN	20,000	20,000	20,000				
$\log\epsilon$ (N)	NH 3360 Å	40,000	20,000		70	50		
$\log\epsilon$ (O)	OH 3100 Å	40,000	40,000	40,000	30	40		
^{12}C/^{13}C	^{12}CH, ^{13}CH	40,000	–	40,000	100			
$\log\epsilon$ (Mg)	Mg I 3838.29 Å	40,000	40,000	20,000	40	40	50	
$\log\epsilon$ (Mg)	Mg I 5183.60 Å	40,000	40,000	20,000	100	60	50	
$\log\epsilon$ (Ca)	Ca I 4226.73 Å	40,000	60,000	20,000	60	370	50	
$\log\epsilon$ (Ca)	Ca II			20,000			50	
$\log\epsilon$ (Ti)				20,000			50	
$\log\epsilon$ (Mn)				20,000			50	
$\log\epsilon$ (Fe)	Fe I 3859.91 Å	40,000	40,000	20,000	20	200	50	
$\log\epsilon$ (Fe)	Fe II 3227.74 Å	40,000	–	20,000			50	
$\log\epsilon$ (Co)	Co I			20,000			50	
$\log\epsilon$ (Ni)				20,000			50	
$\log\epsilon$ (Zn)				20,000			50	
$\log\epsilon$ (Sr)	Sr II4077.72 Å	–	40,000	20,000	–	200	30	
$\log\epsilon$ (Y)		–	–	20,000			50	
$\log\epsilon$ (Zr)		–	–	20,000			50	
$\log\epsilon$ (Ba)	Ba II 4554.03 Å	–	–	20,000			30	
$\log\epsilon$ (La)		–	–	20,000			50	
$\log\epsilon$ (Eu)	Eu II 4129.73 Å	–	–	20,000			30	
$\log\epsilon$ (Os)		–	–					
$\log\epsilon$ (Ir)		–	–					
$\log\epsilon$ (Pb)		–	–					
$\log\epsilon$ (Th)		–	–	40,000	–	–	50	
$\log\epsilon$ (U)		–	–	75,000	–	–	150	

Notes:

1 – Detection of at least one Fe II line required.

2 – Detection of at least a couple of Fe I lines required.

3 – Assuming an abundance of $\log\epsilon\,(^7{\rm Li}) = 2.2$.

Table 3: Data quality requirements for spectroscopic analyses of metal-poor stars.

compiled by Christlieb & Hill

HR spectroscopy: requirements

MOS: > 100 stars per galaxy; 0.48-2.2μm; R~20000

SOS: 10-100 stars per local galaxy; 300-700nm; R~40000 (min)

$M_I > -4$

The Effect of Resolution

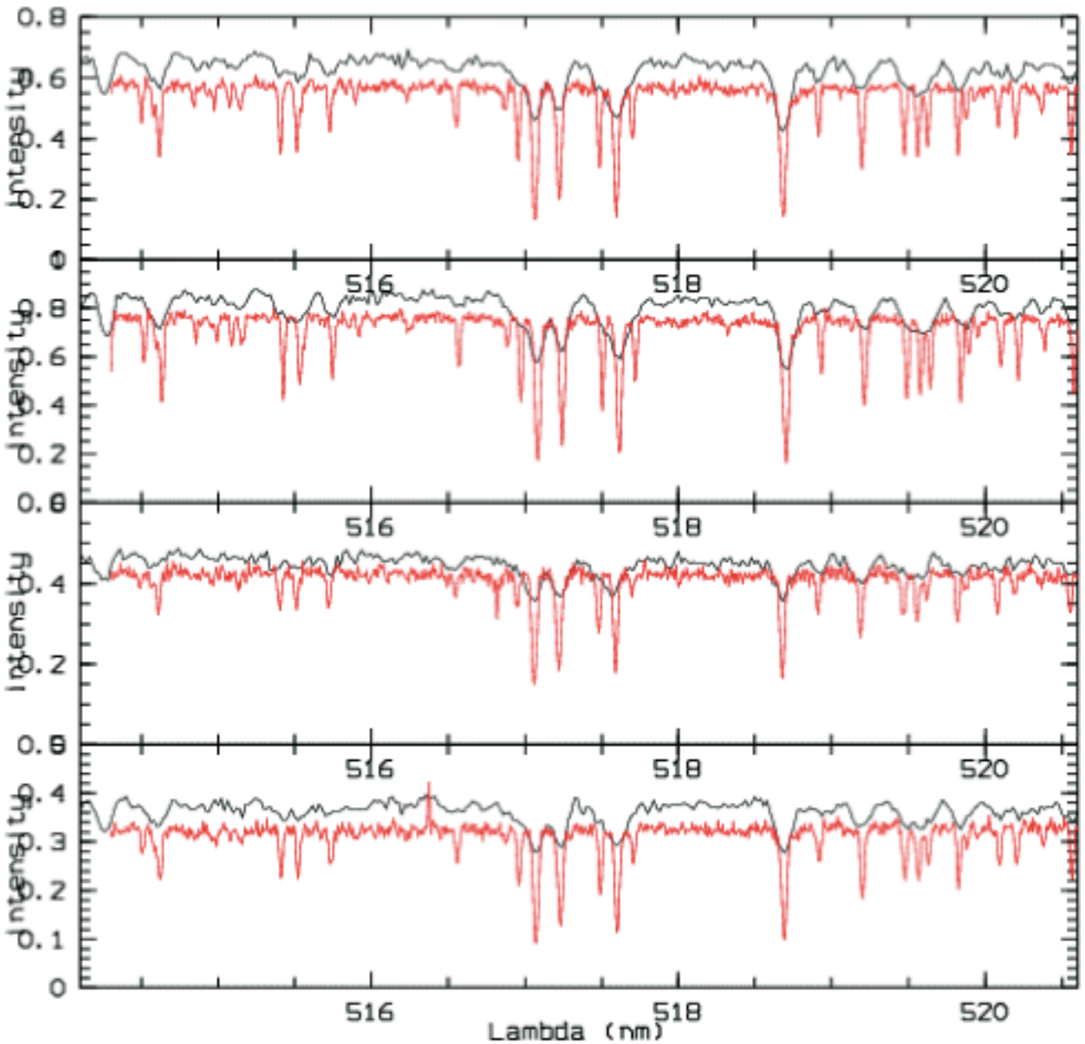


Figure15: GIRAFFE Low (L4, black lines) and High (H9, red lines) resolution spectra of 4 giants belonging to the Globular Cluster NGC 6809

H9, R~26000

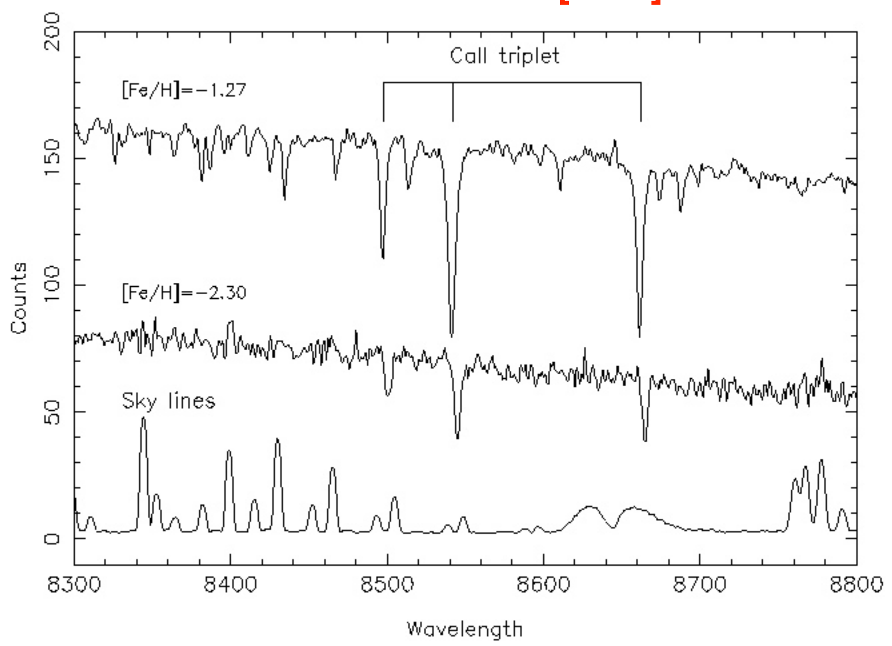
L4, R~6000

Integration time twice as long for H9

Pasquini et al. 2002 ESO Messenger, 110, 1

Low Resolution Stellar Spectroscopy: the Ca II Triplet

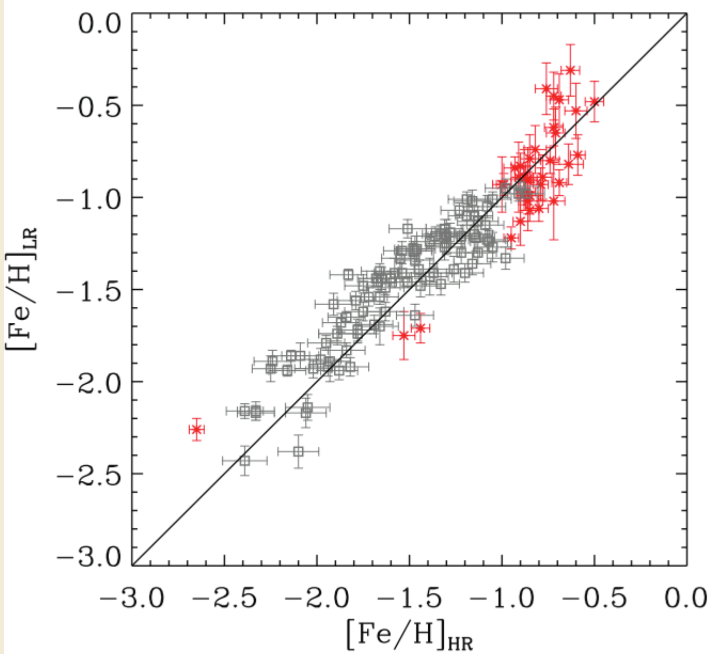
EWs trace [Fe/H]



FORS / FLAMES

λλ820-920nm

R~6 000



Also MgB region λλ440-550nm

Battaglia et al. 2008

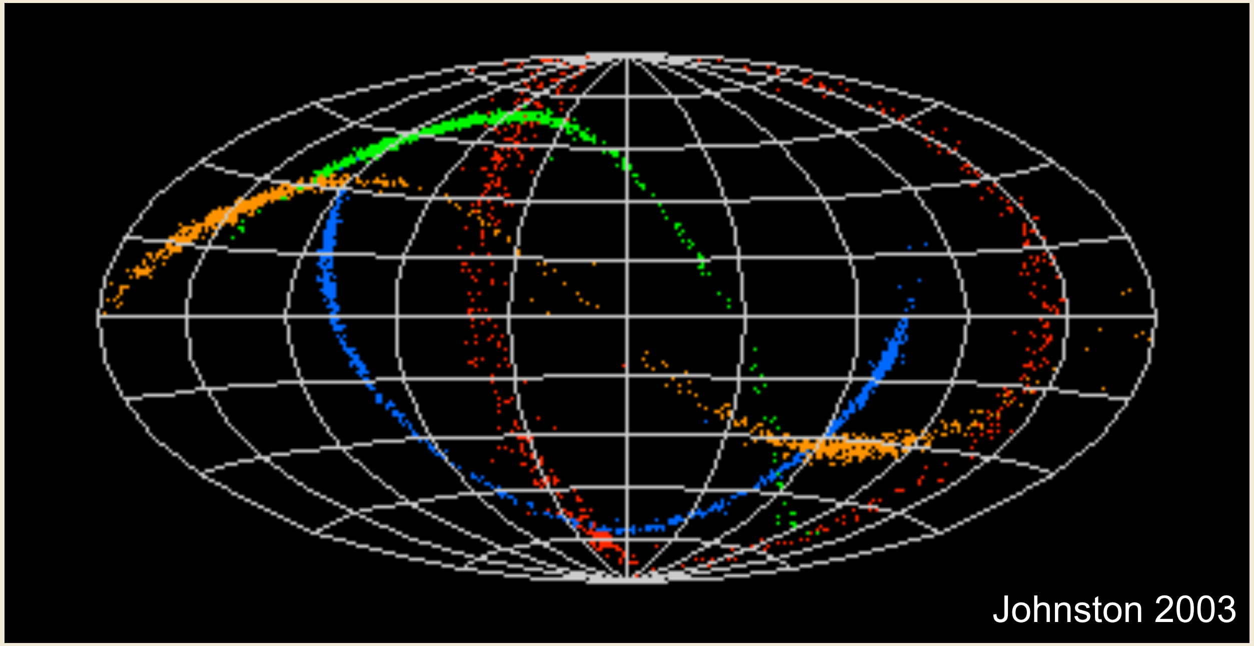
LOW RESOLUTION SPECTROSCOPY:

Stars trace kinematics (mass) & chemical evolution

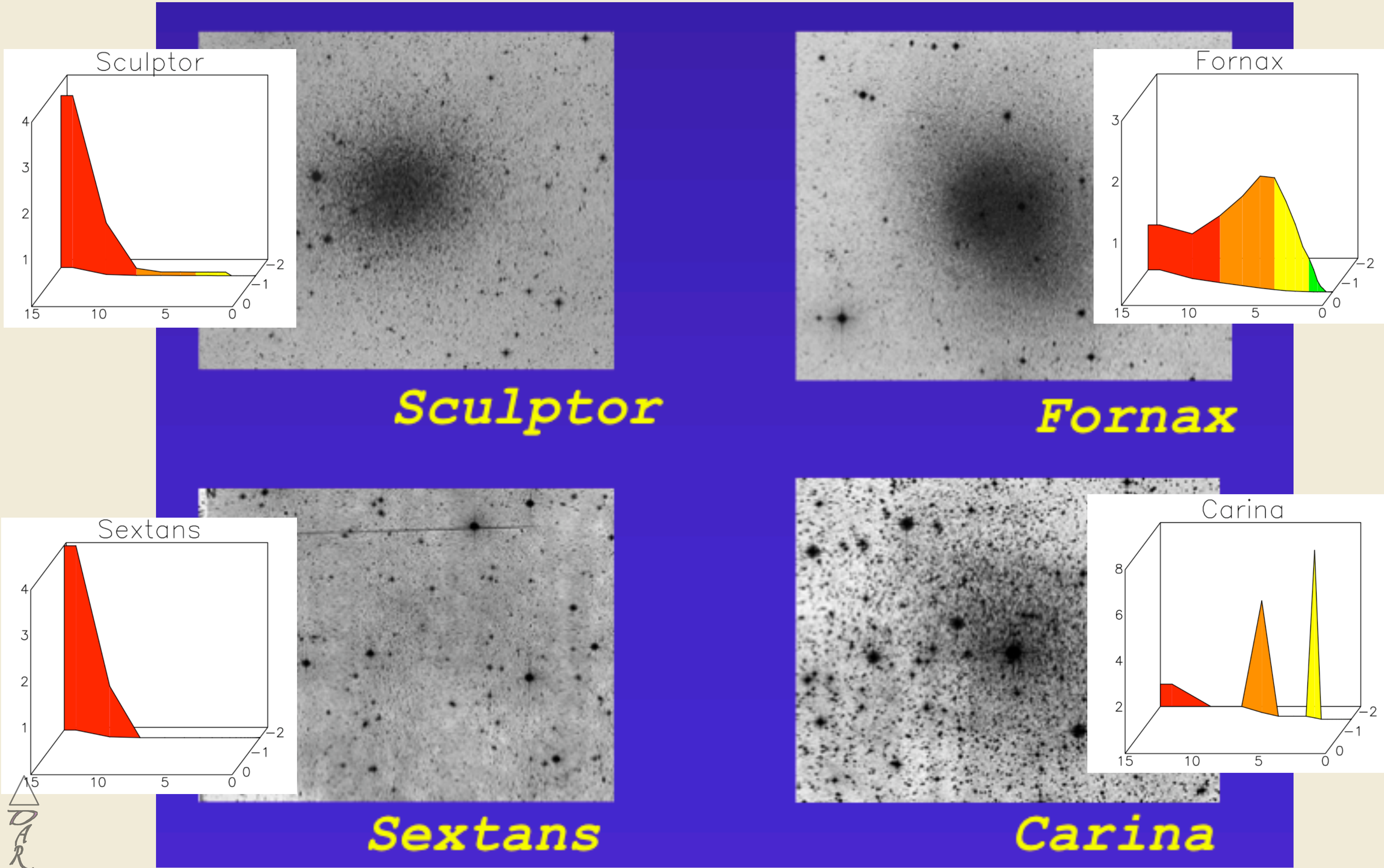
Looking for Evidence on small scales...

Is the outer halo filled with tidal streams from disrupted dwarf galaxies that remain coherent in phase space?

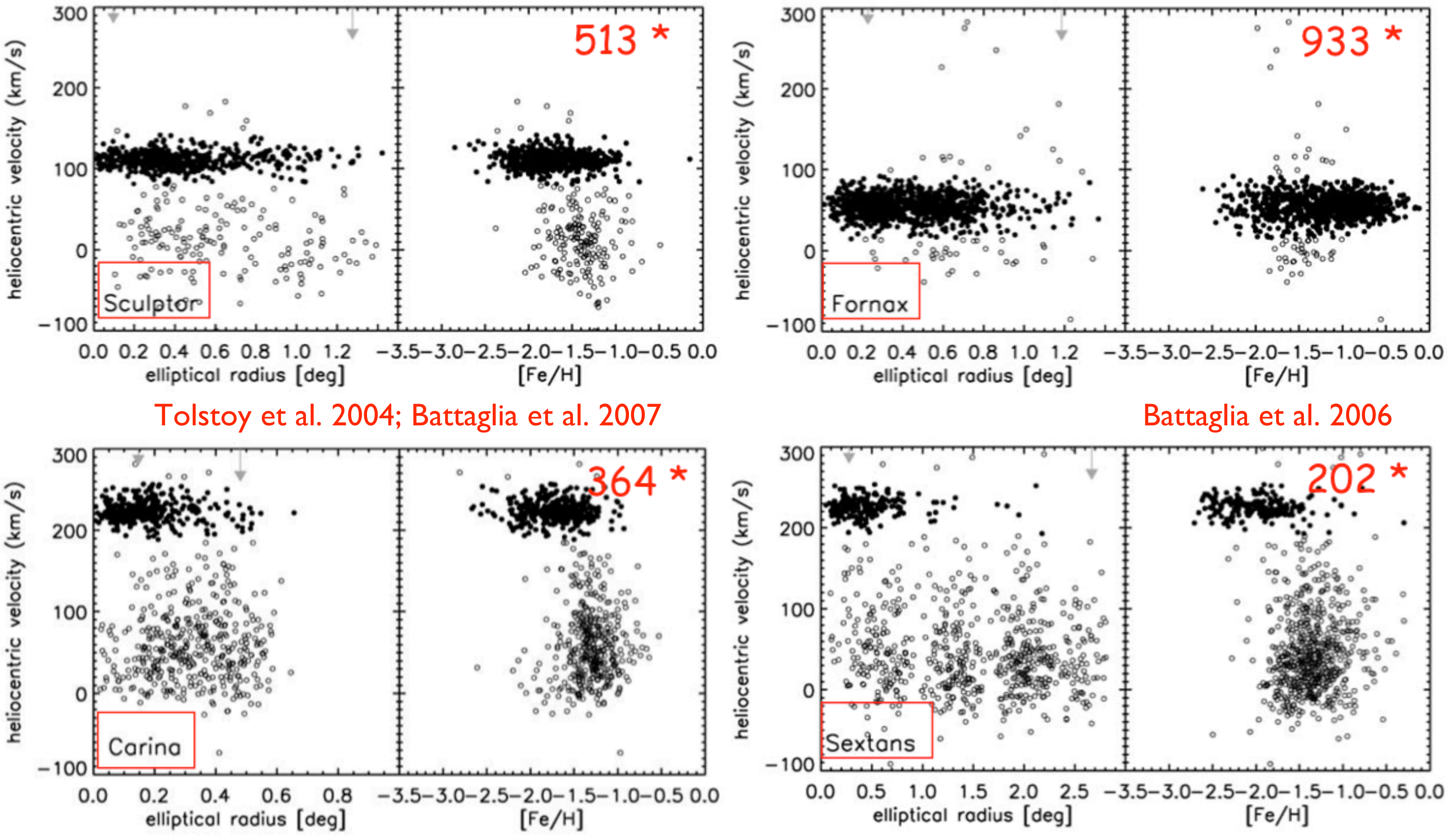
(Johnston et al. 1996; Helmi & White 1999 etc...)



Local dSph studied with FLAMES



VLT/FLAMES results



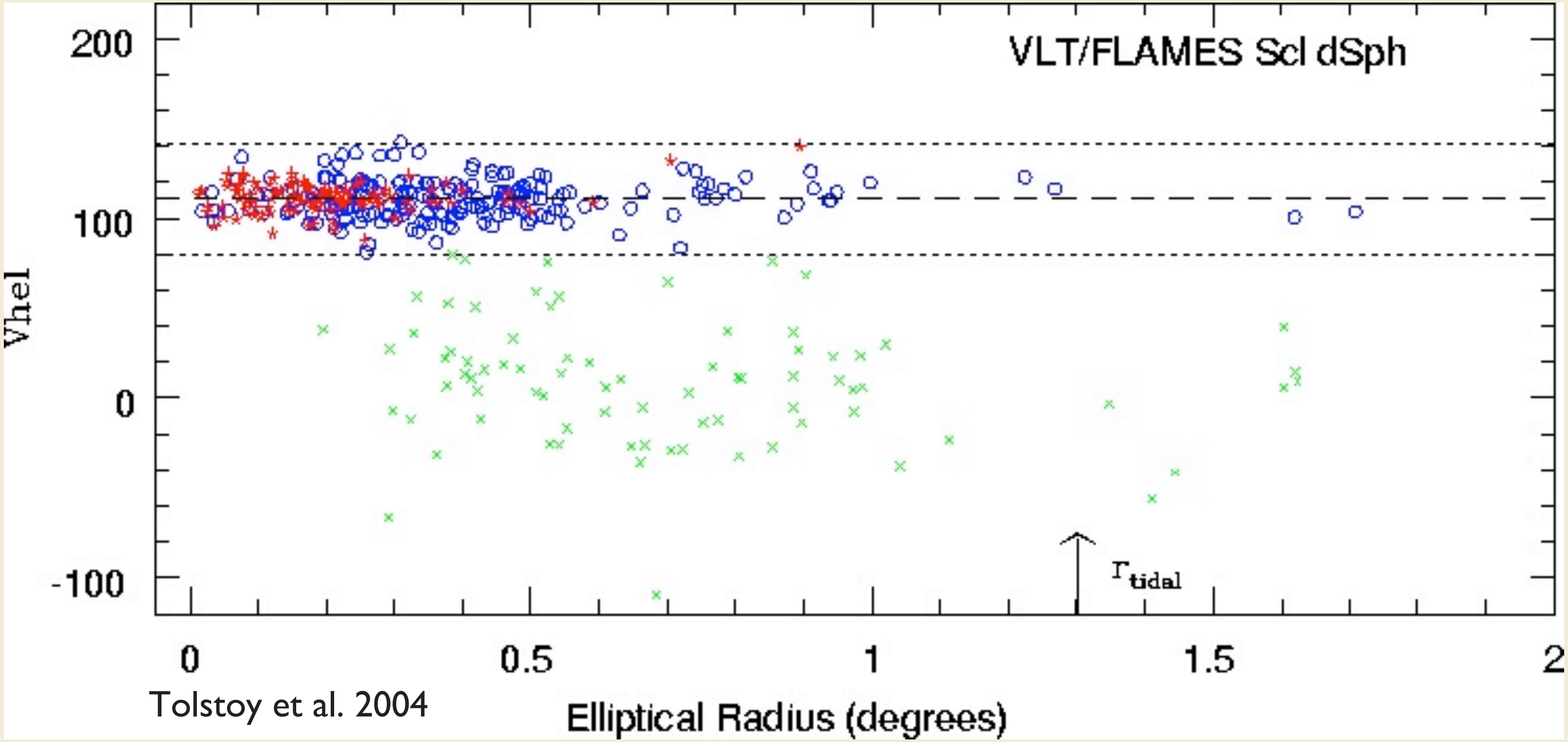
Tolstoy et al. 2004; Battaglia et al. 2007

Battaglia et al. 2006

Koch et al. 2006

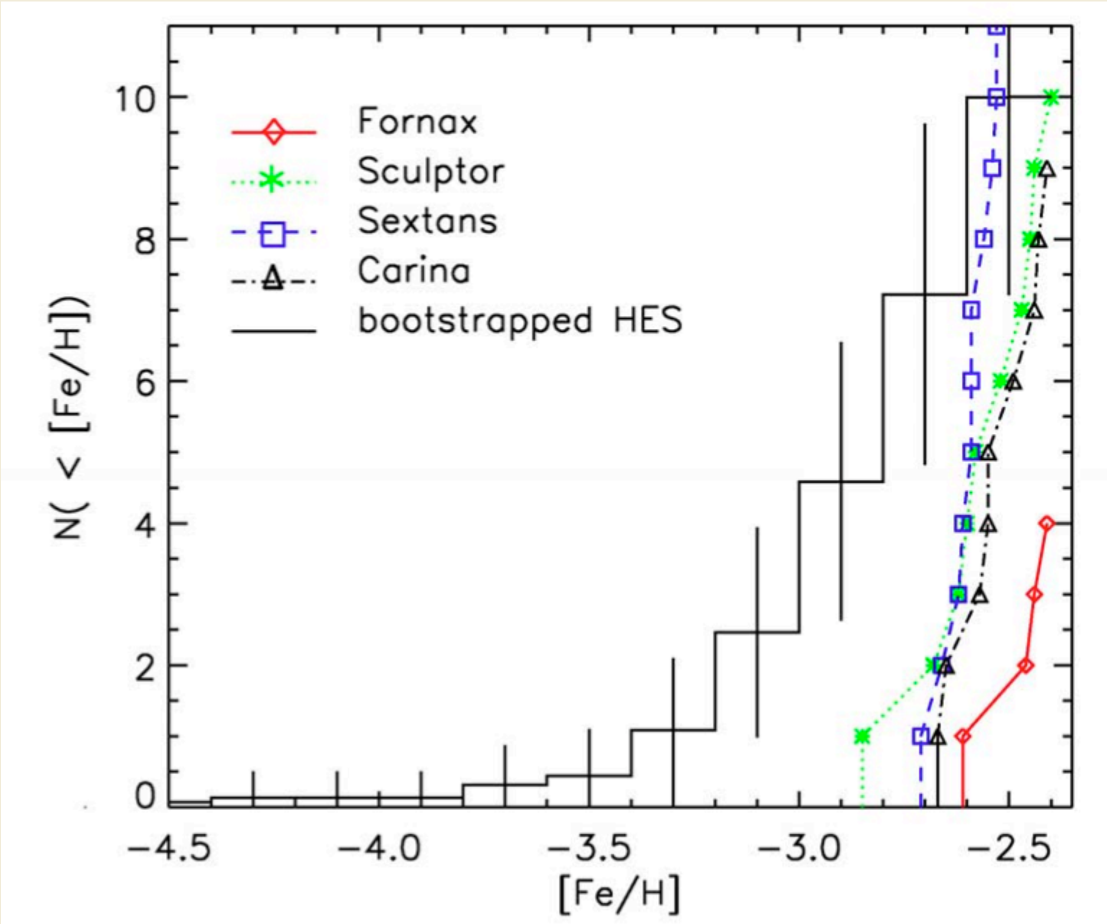
Battaglia et al. 2007

Kinematics & Metallicity



Tolstoy et al. 2004

No Low Metallicity Tail...



Halo & dSph distributions significantly different

If drawn from the same population would expect 25% of the metal poor stars in dSph to have [Fe/H] < -3 i.e. 35/135

We find no stars [Fe/H] < -3 (so far)

Helmi et al. 2006, ApJL

DART

LR spectroscopy cases:

R~5000 resolution spectroscopy in I-band and near-infrared, to measure detailed chemo-dynamical properties in of indvidual stars in galaxies beyond the Local Group.

-Detailed Star Formation Histories: in combination with very deep CMDs, spectroscopic metallicities allow to determine an accurate star formation history of a galaxy and put a time scale on chemical evolution. A wide range of galaxy types, will be within reach: spiral galaxies (e.g., NGC253, NGC300, M81) in nearby galaxy groups, such as Sculptor or M81 (2~Mpc away), the closest Elliptical galaxy (Centaurus A, 3.5Mpc away) and also dwarf elliptical galaxies.

-Chemo-dynamical analyses: combining kinematic and basic metallicity properties of individual stars allows us to disentangle the dynamical state of a galaxy very precisely accurately. On ELT can go deeper into dense regions than ever before.

The most important wavelength range for these cases is 830nm-880nm, where the Ca II triplet can be found. It has been shown to be an excellent indicator of [Fe/H]. Of course kinematic studies can be carried out where ever there are absorption lines, and perhaps a metallicity surrogate can be found at redder wavelengths - but not happened yet.

LR spectroscopy: requirements

MOS: >1000 stars per galaxy; 830-880nm or 480-550nm ; R~5000

$M_I > -4$

IFU and/or multi-fibres ?

Resolved Low Mass Stars

High spatial resolution - sensitivity - photometric accuracy

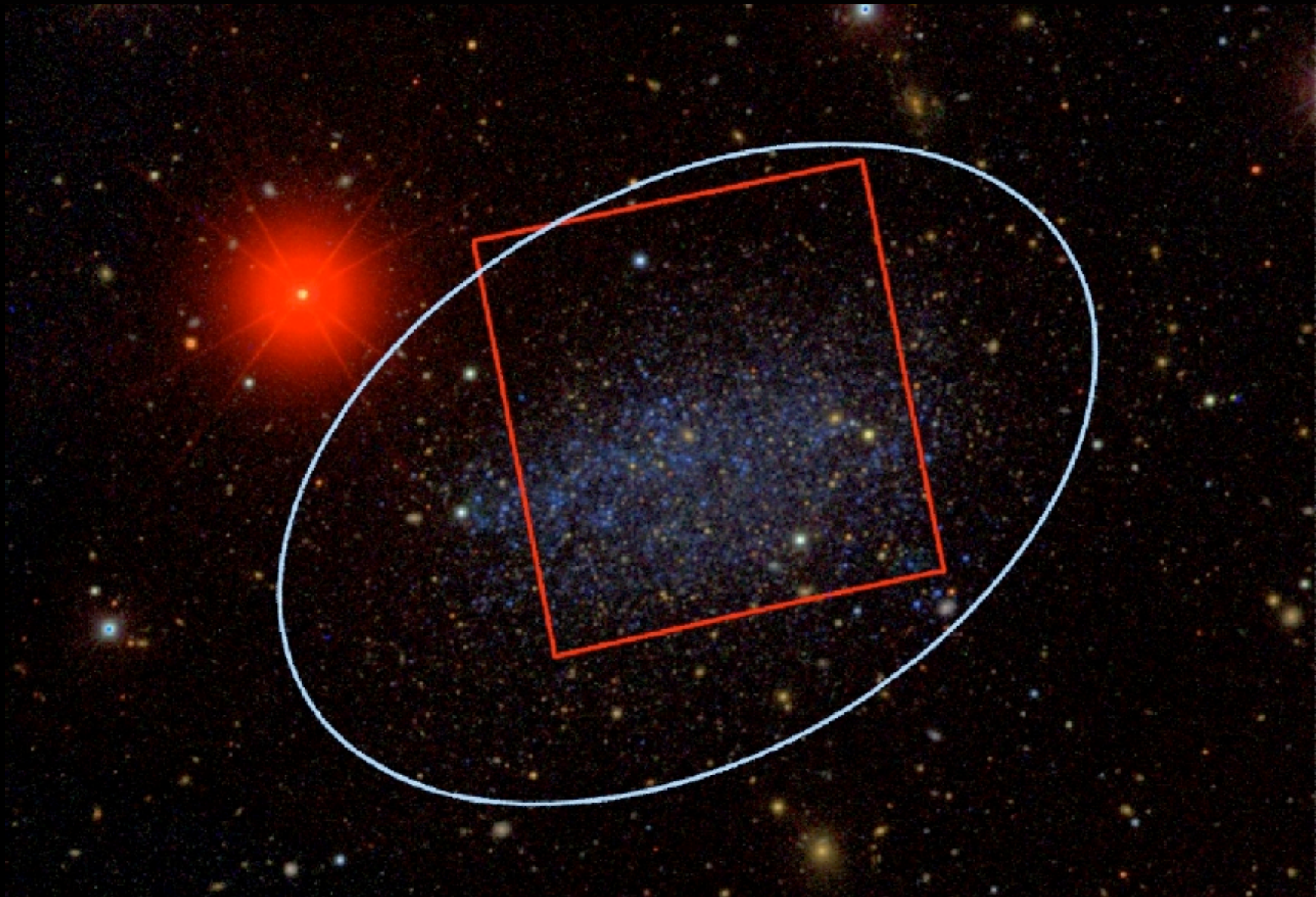
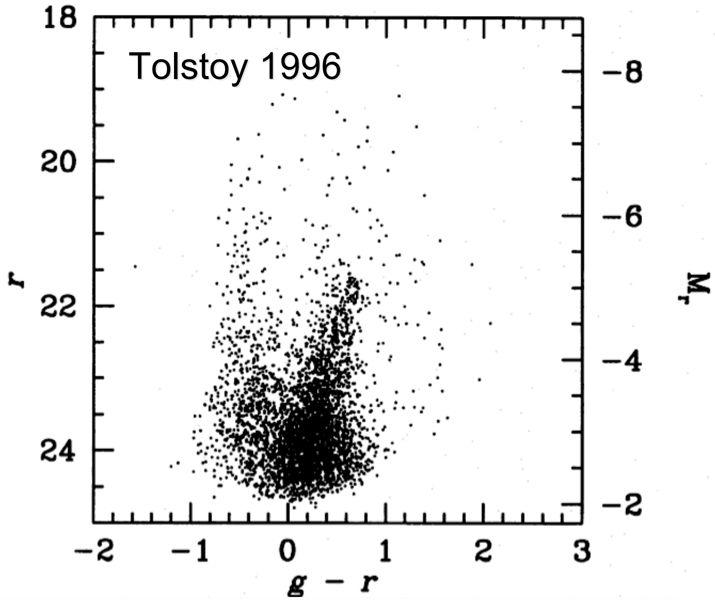
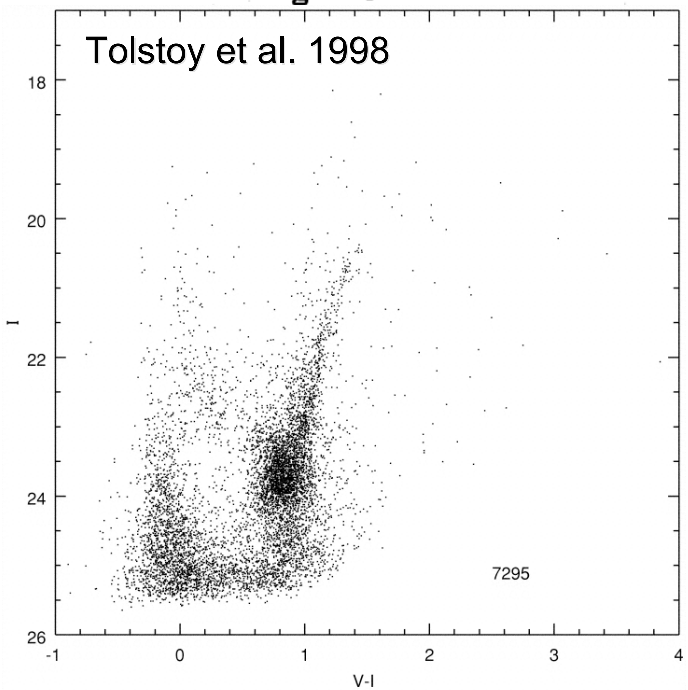


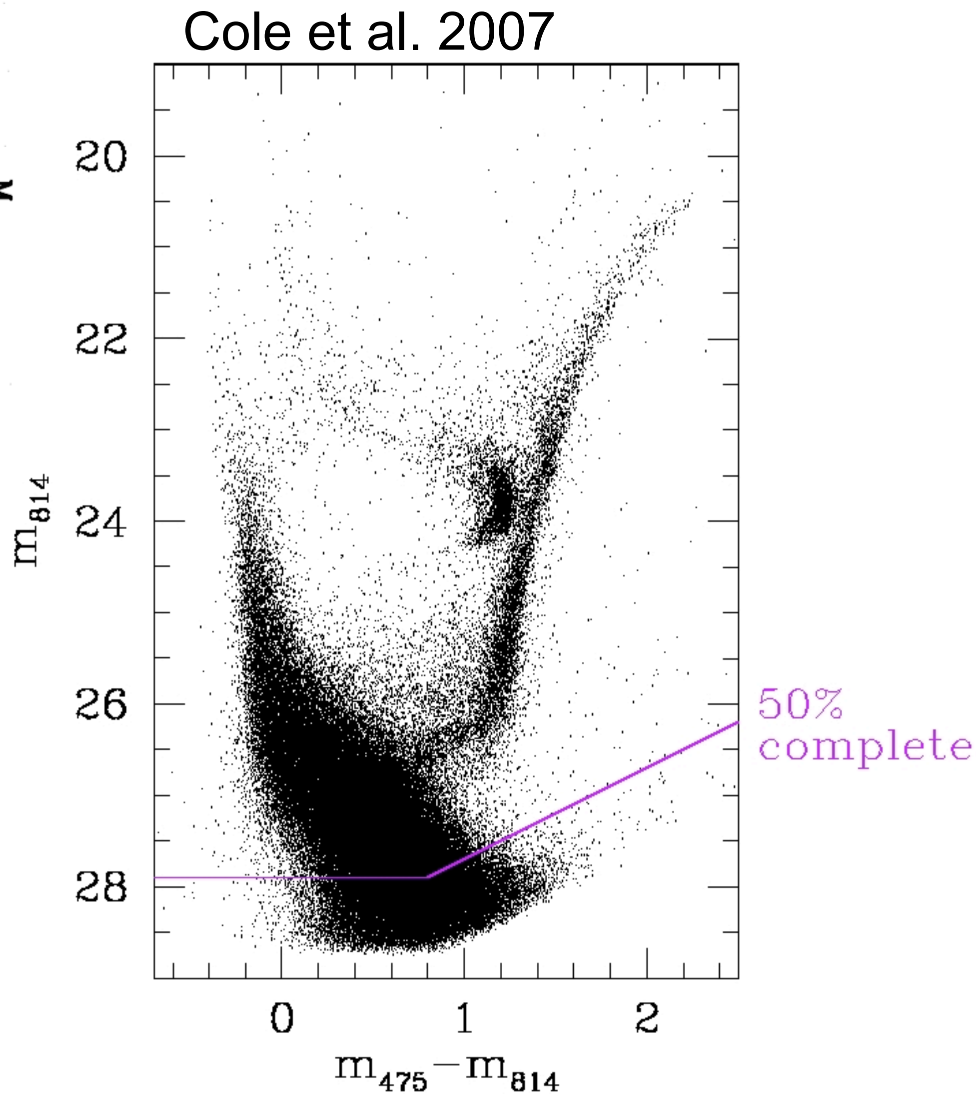
Image: SDSS gri composite. Ellipse: Holmberg dimension. Square: ACS



Tolstoy 1996
18
20
22
24
−8
−6
−4
−2
−2
−1
0
1
2
3
g − r

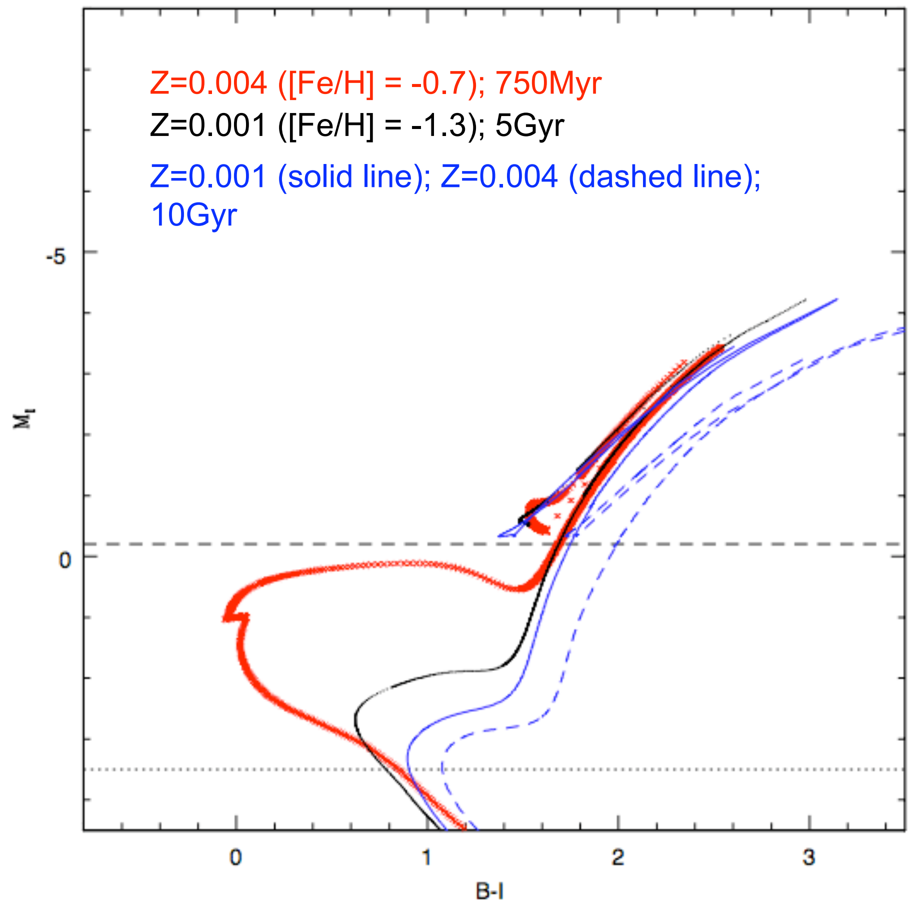


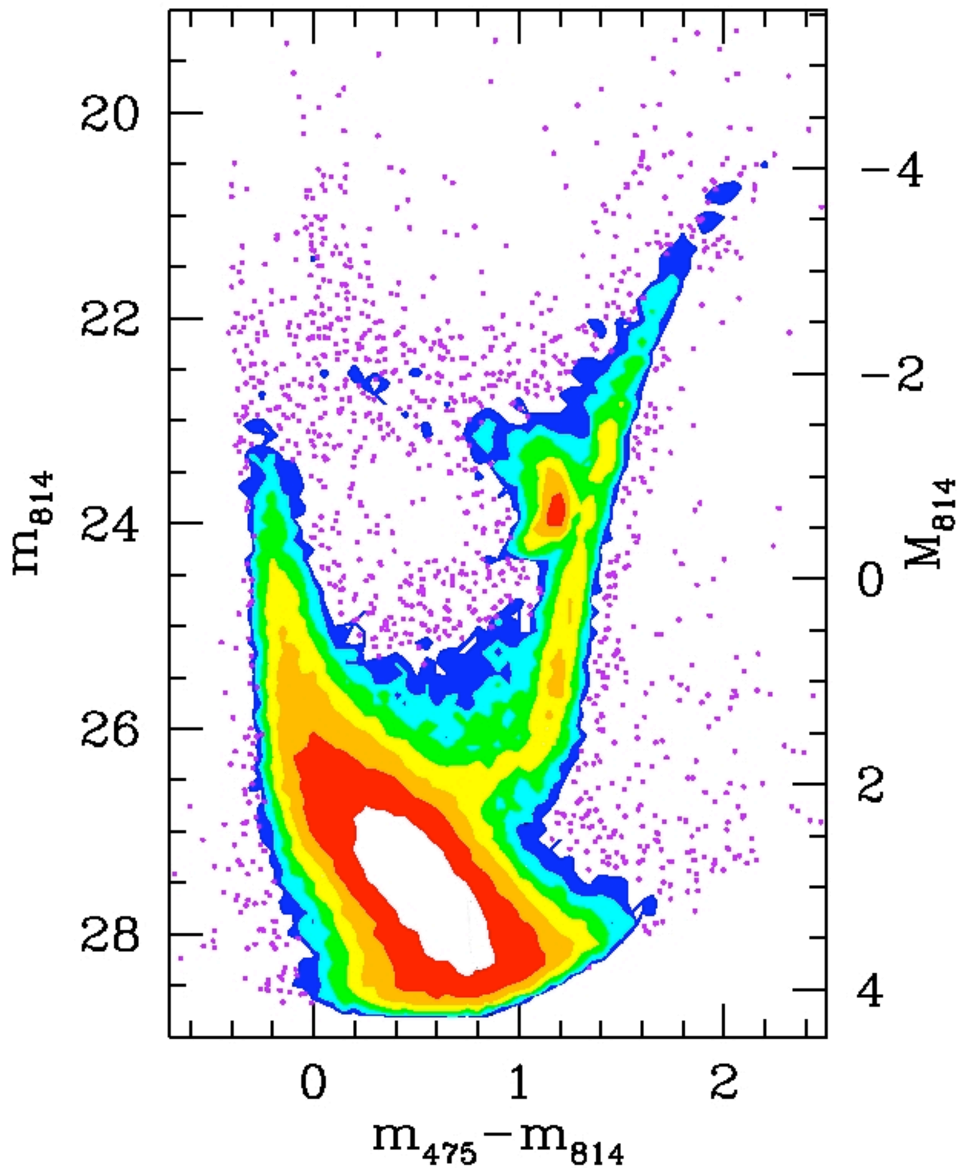
Tolstoy et al. 1998
18
20
22
24
26
-1
0
1
2
3
4
V-I
7295



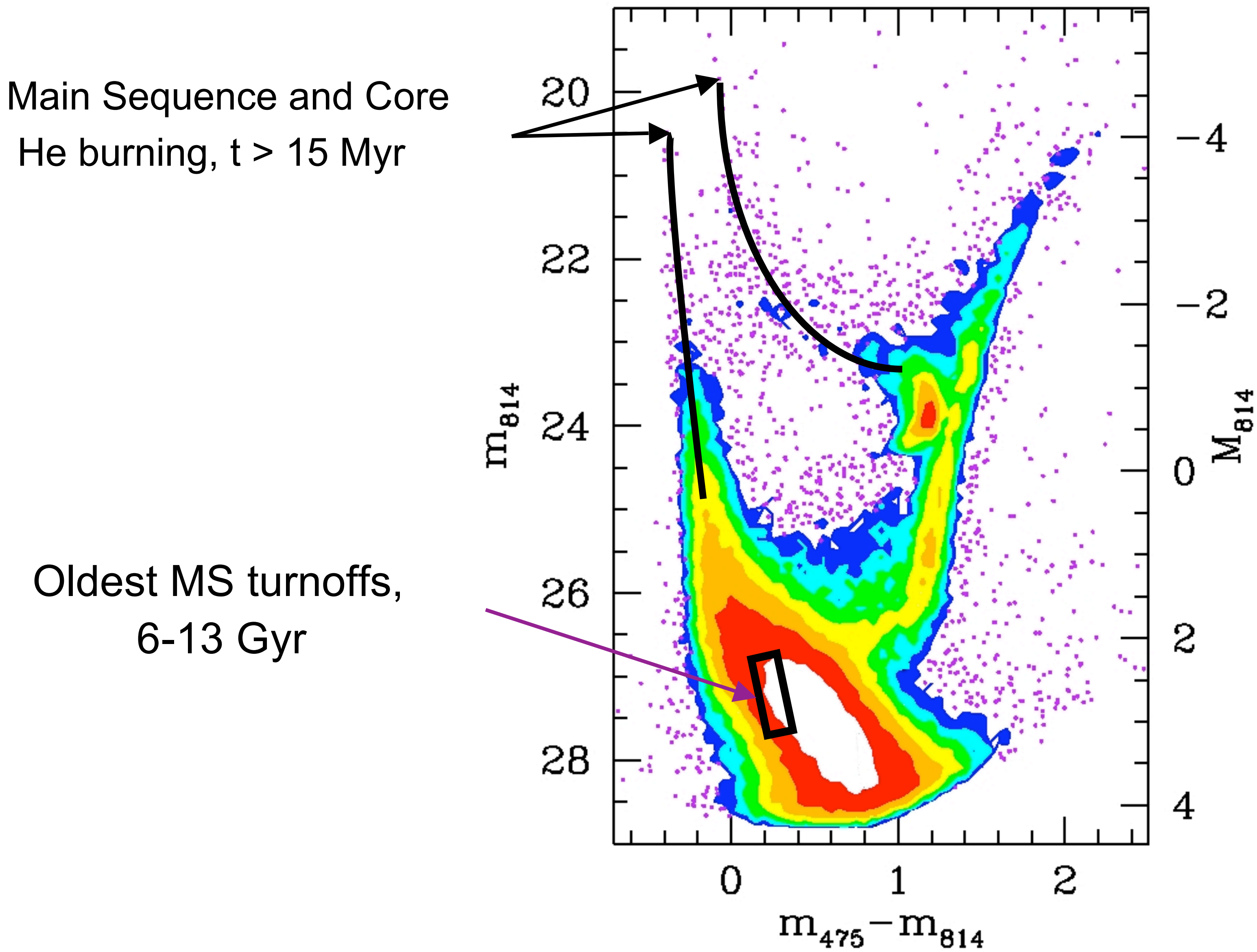
Cole et al. 2007
20
22
24
26
28
0
1
2
m475−m814
50%
complete

Age-Metallicity Degeneracy





20
22
24
26
28
−4
−2
0
2
4
0
1
2
m814
M814
m475−m814

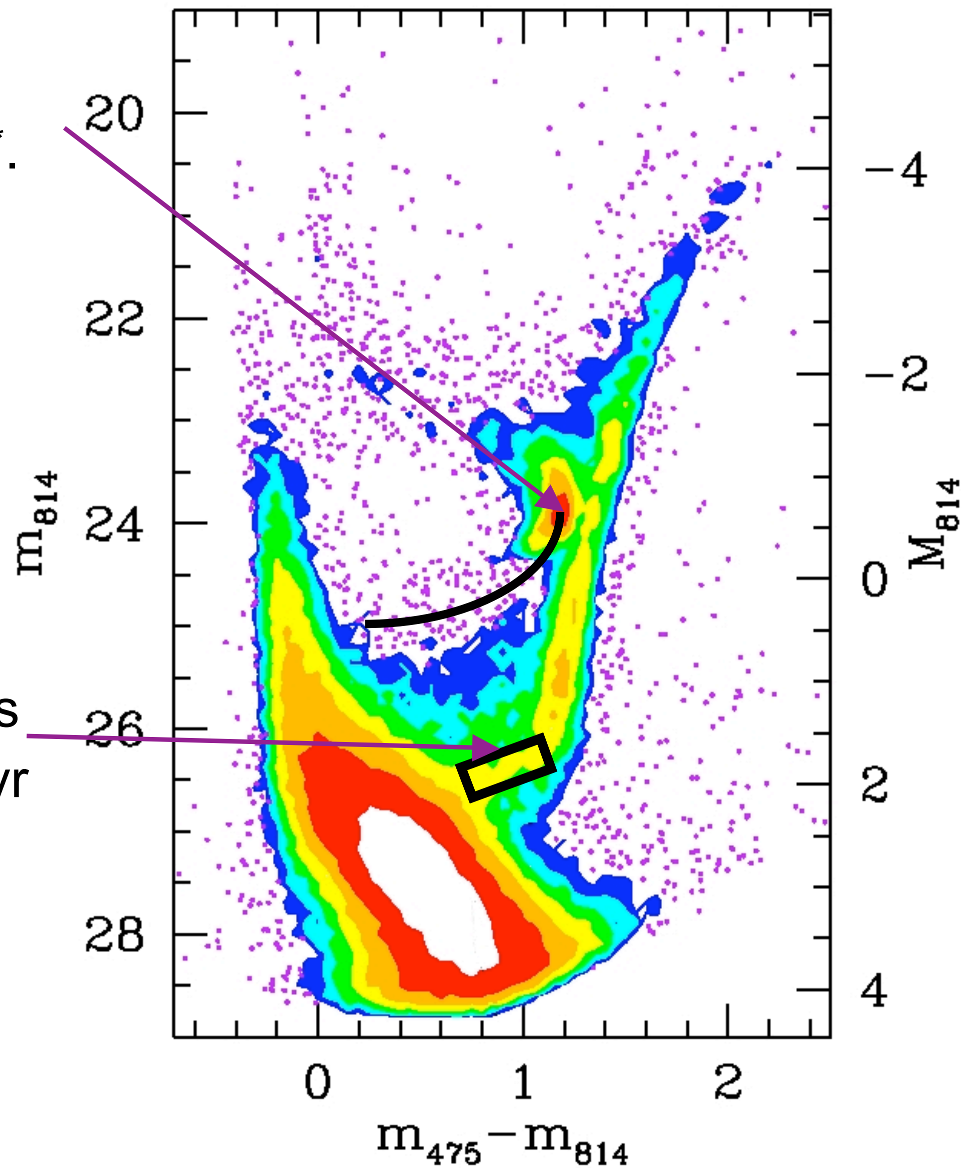


Main Sequence and Core
He burning, t > 15 Myr
Oldest MS turnoffs,
6-13 Gyr
20
22
24
26
28
m_{814}
-4
-2
0
2
4
M_{814}
0
1
2
$m_{475}-m_{814}$

Strong red clump, no serious horizontal branch*.

* 8 candidate RR Lyraes have been found (Dolphin et al. 2002); we hope to find more in our data.

Peak density of subgiants at similar M_I as in 2-6 Gyr old Small Magellanic Cloud star clusters.

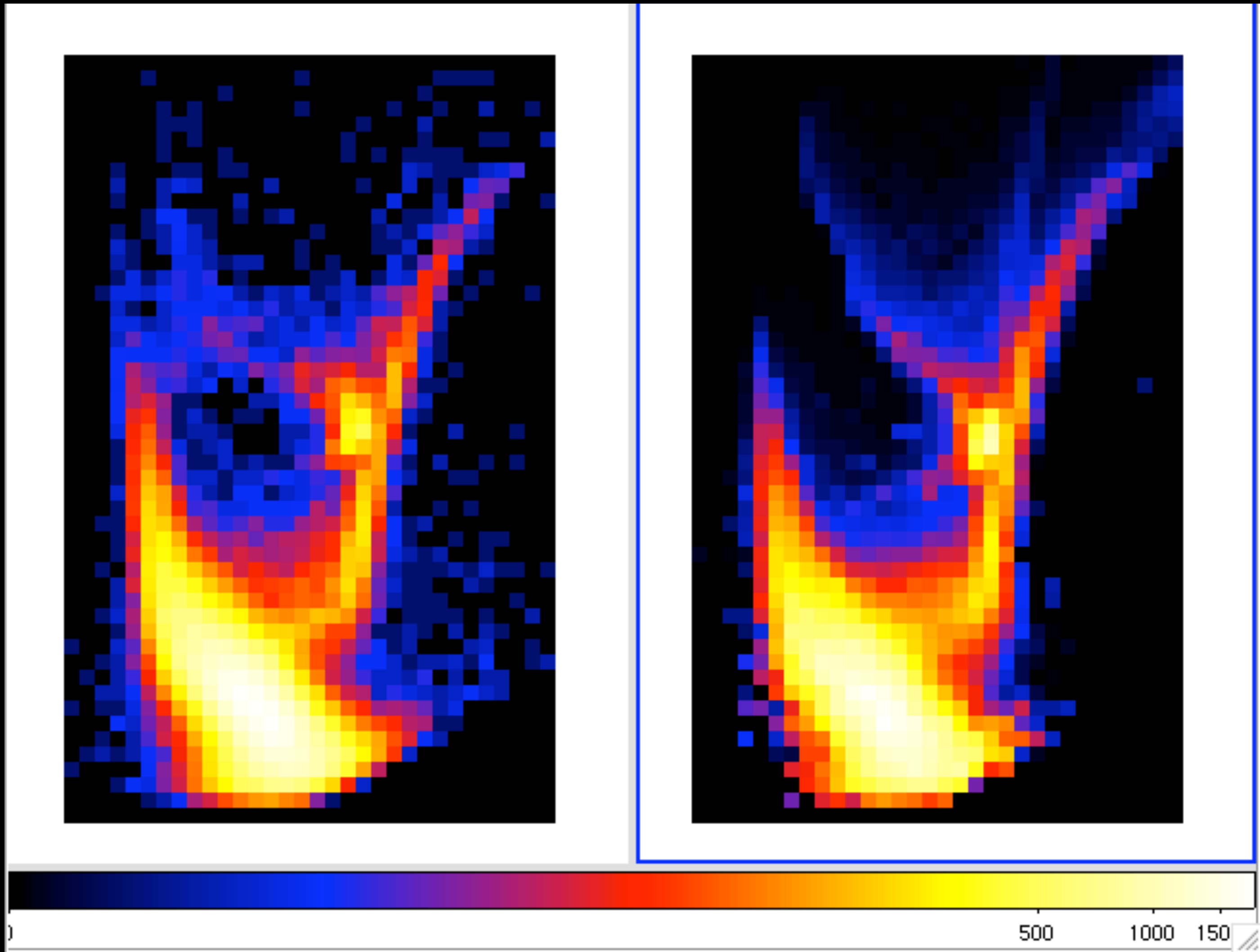


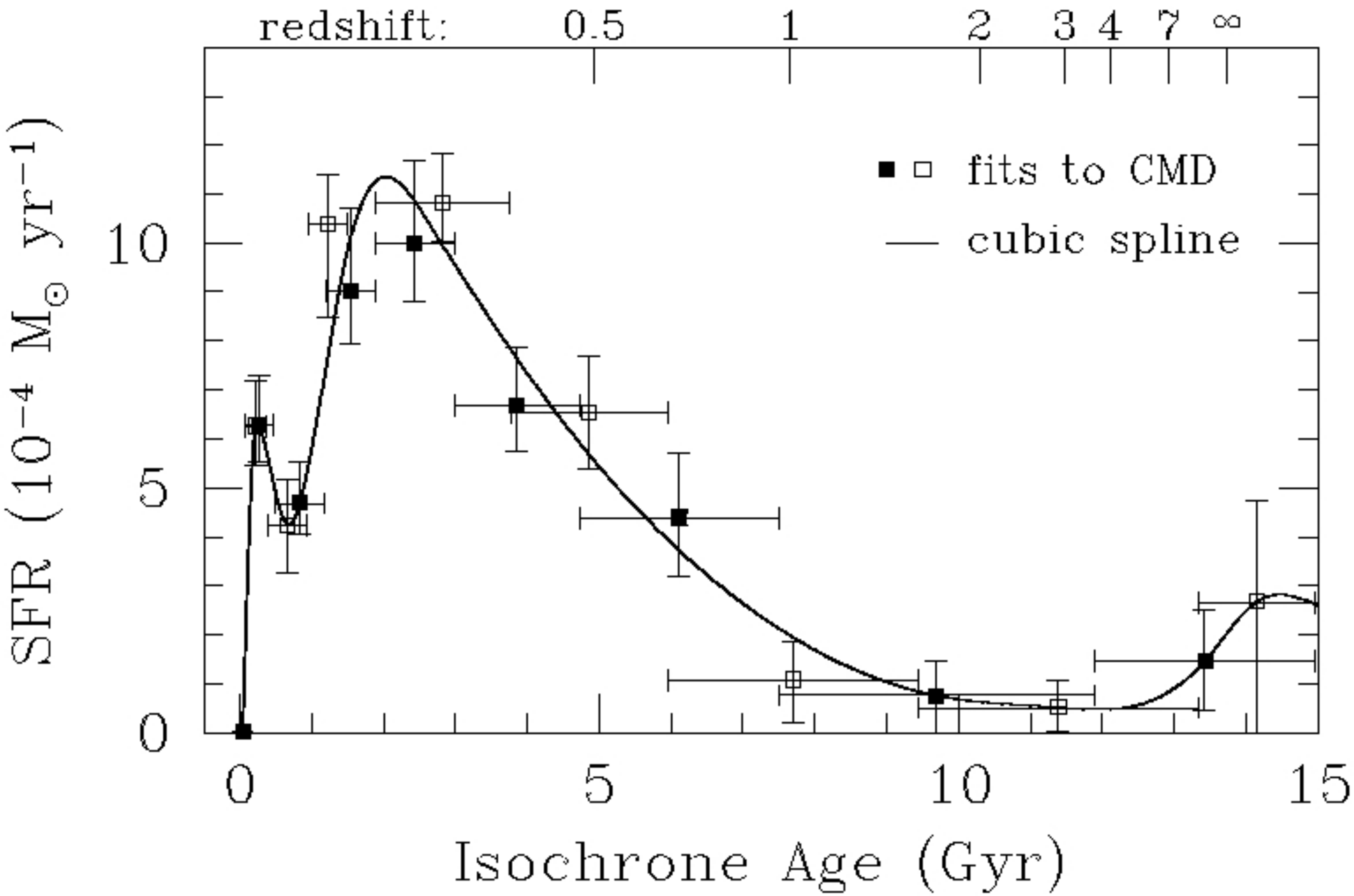
Analysis: Quantifying the Star Formation History

- Compare the photometry to the positions of stellar isochrones at given distance, reddening, IMF, binary star fraction, etc.

- Use a maximum-likelihood technique to determine the distributions in age and metallicity that best recreate the observed CMD.

Observed CMDs Synthetic





Results for 2 age binnings, with 1σ random errors on SFR

Choosing filter combinations

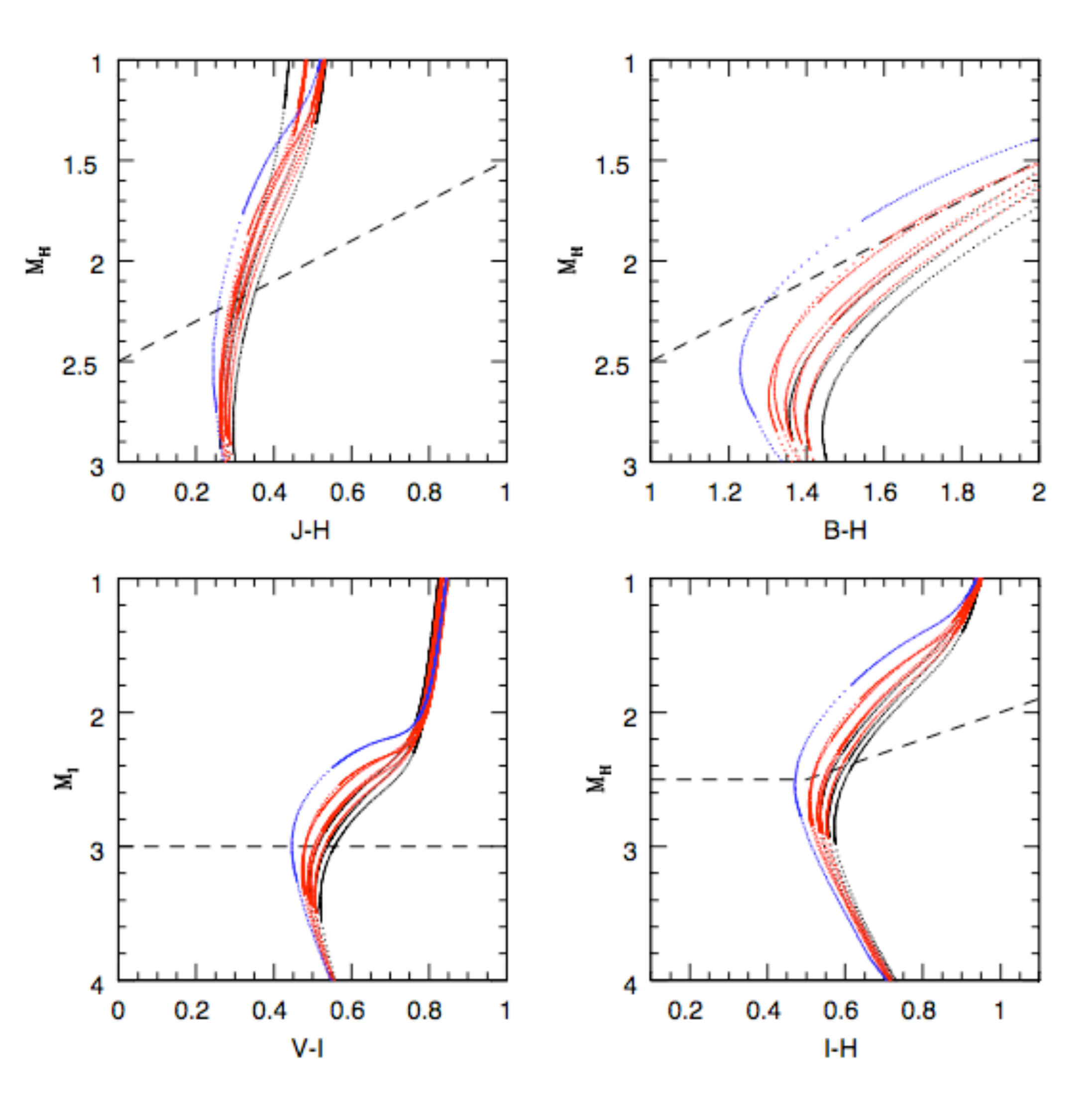
ngc55 m-M= 26.3   (1.8Mpc)

NGC3379 m-M= 30.   (10Mpc)

M81/Scl m-M= 27.7 (3.5Mpc)

M31   m-M= 25.   (1Mpc)

Depth in 10hrs of integration at S/N~5
at a distance of 1.7Mpc (HST)

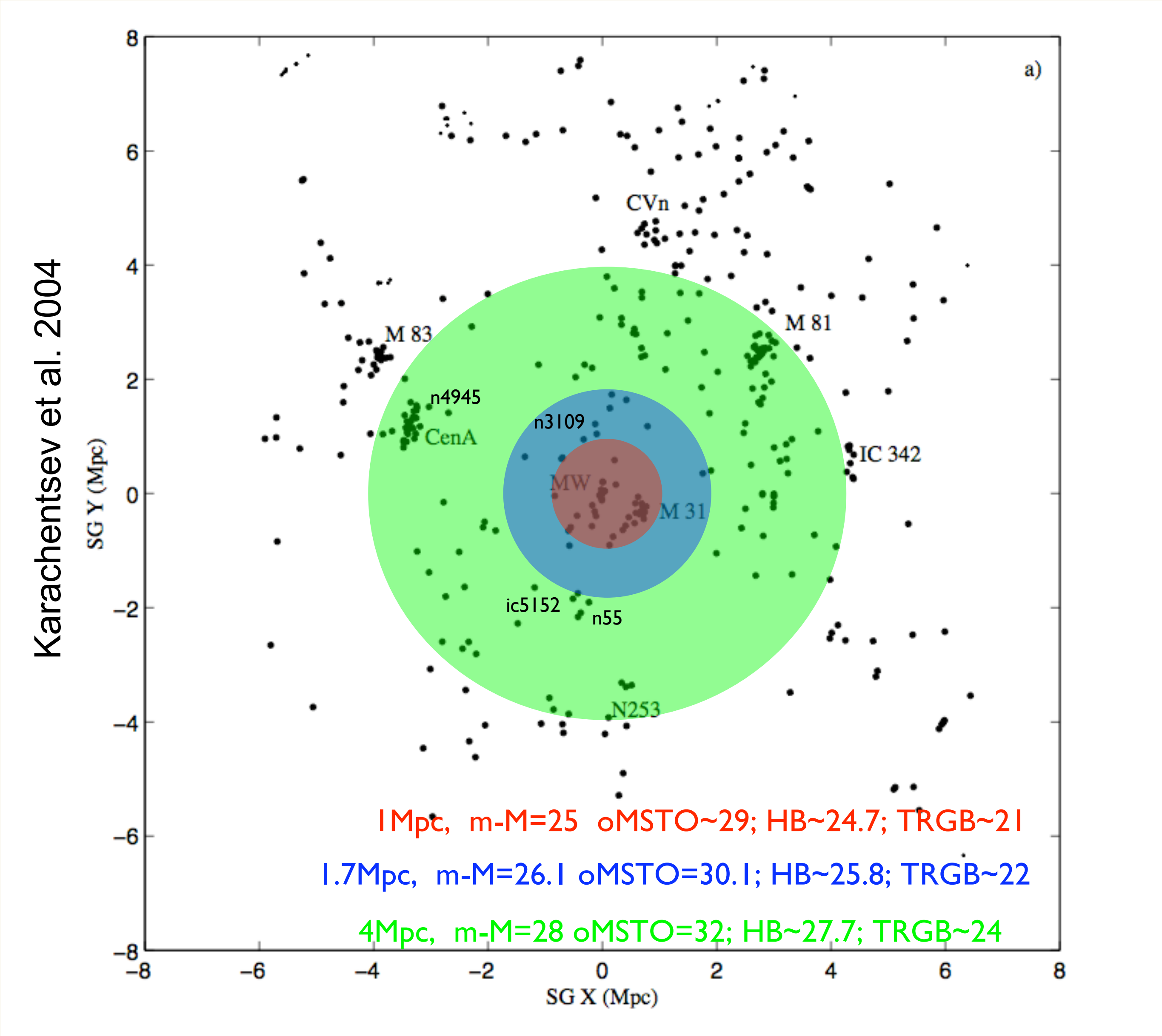


Teramo Isochrones for an low metallicity dwarf-type galaxy, range of age (>8Gyr) and Z ([Fe/H] = -1.3 ⇒ -2.3)

10’’ at 17Mpc (m-M=31.2), is 820pc (equiv. to 4’ fov in LG)

Need at least 100 stars per region of the CMD that needs to be modeled, e.g., to get 100 RGB stars need to look at a surface brightness of ~27 with a 10’’ fov at virgo.

Local Group out to 8Mpc



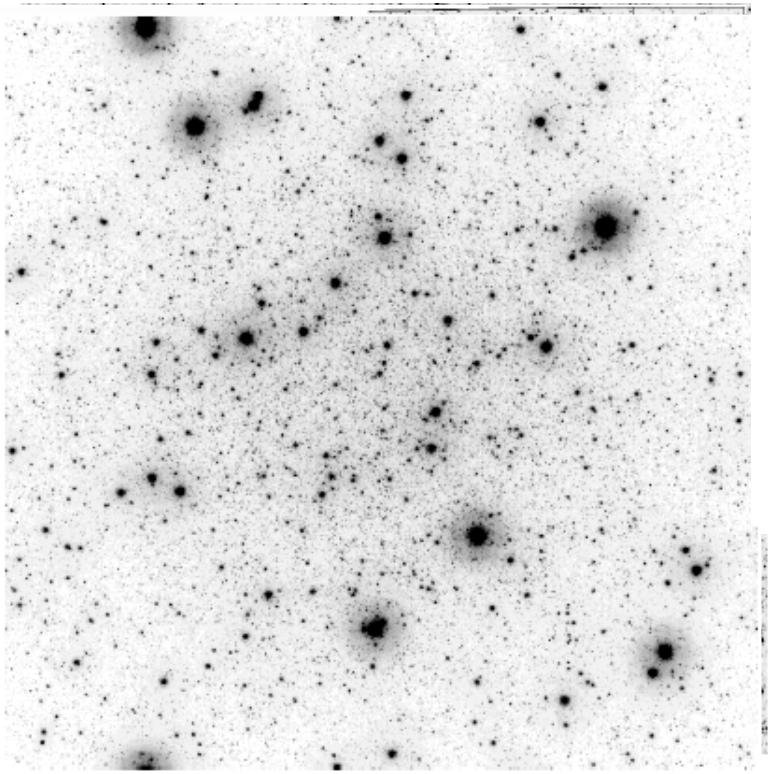
Trade-Offs

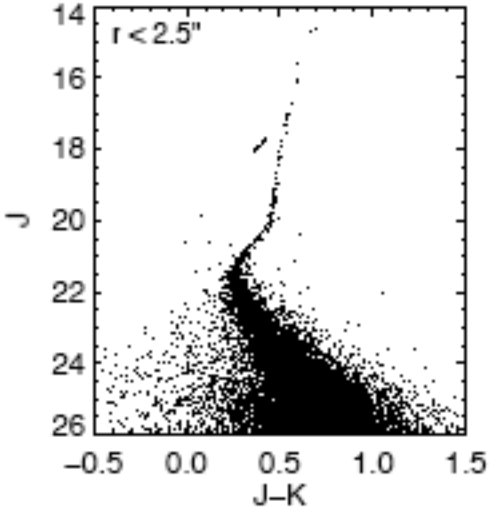
Field of View (fraction of galaxy; size of detector)

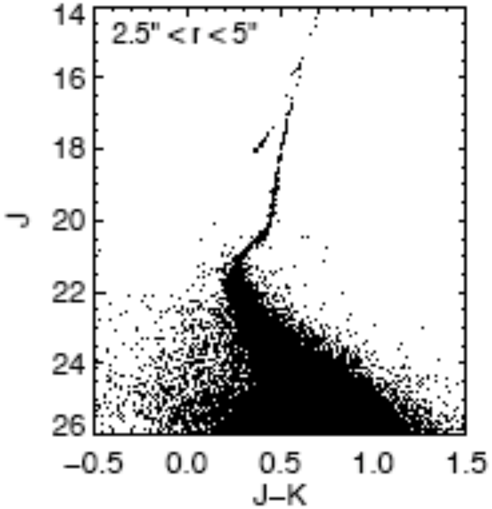
Pixel Size (resolution; diffraction limit; surface brightness limit)

Sensitivity (MSTO, HB, TRGB, E-AGB, young massive stars)

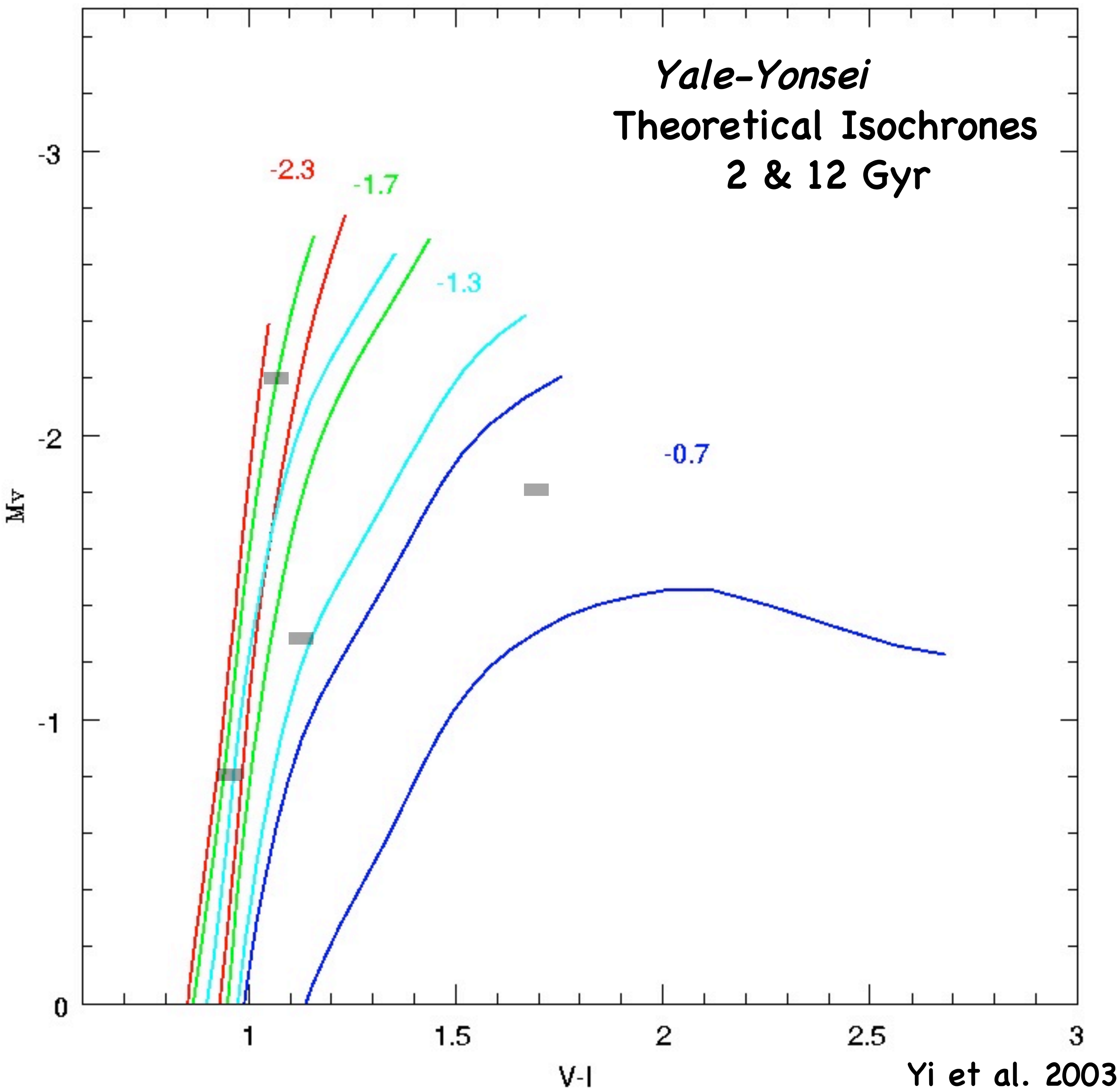
Crowding







Olsen, Blum & Rigaut 2003

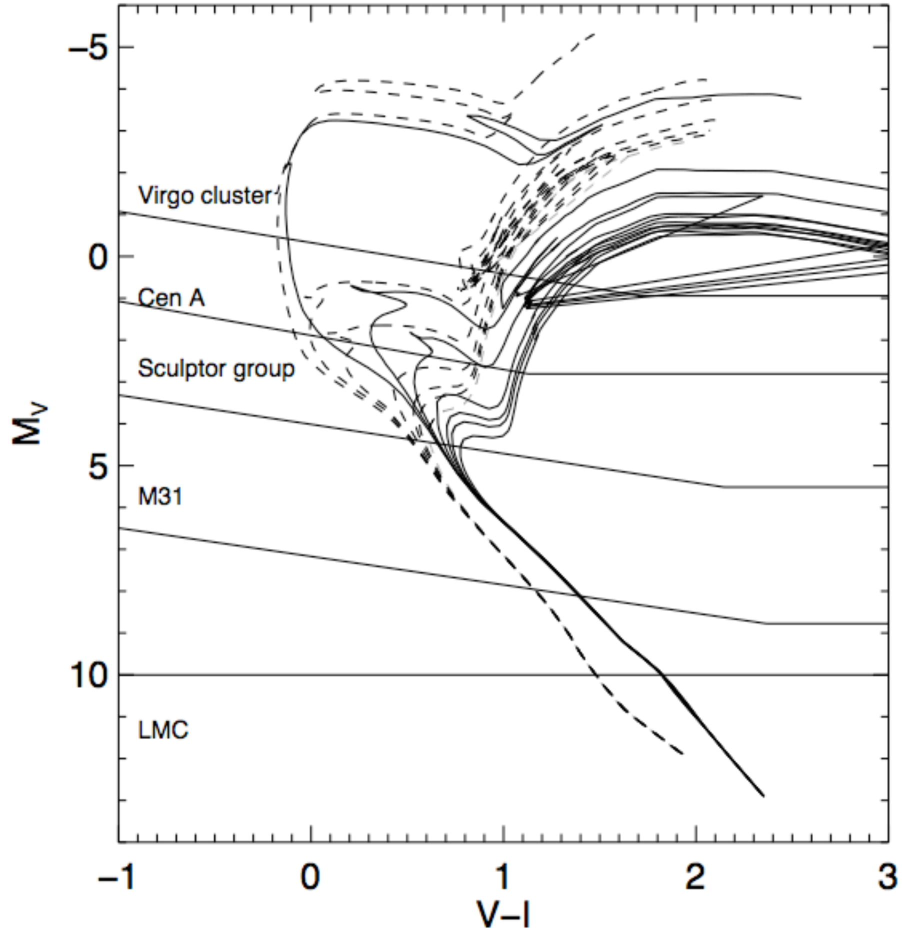

Yale-Yonsei
Theoretical Isochrones
2 & 12 Gyr
-2.3
-1.7
-1.3
-0.7
-3
-2
-1
0
Mv
1
1.5
2
2.5
3
V-I
Yi et al. 2003

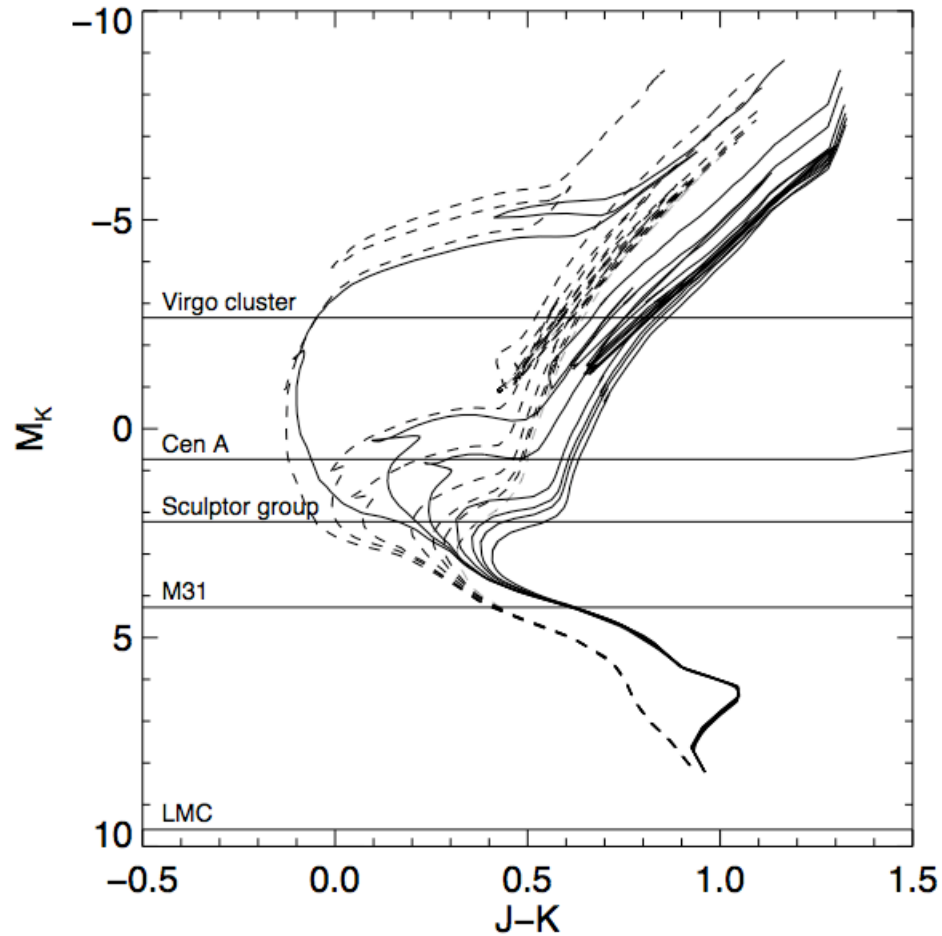
Optical vs. Infra-Red

30m, diffraction limited telescope

100m, diffraction limited telescope

lines at which σ ≤ 0.1photometry is possible at distances given



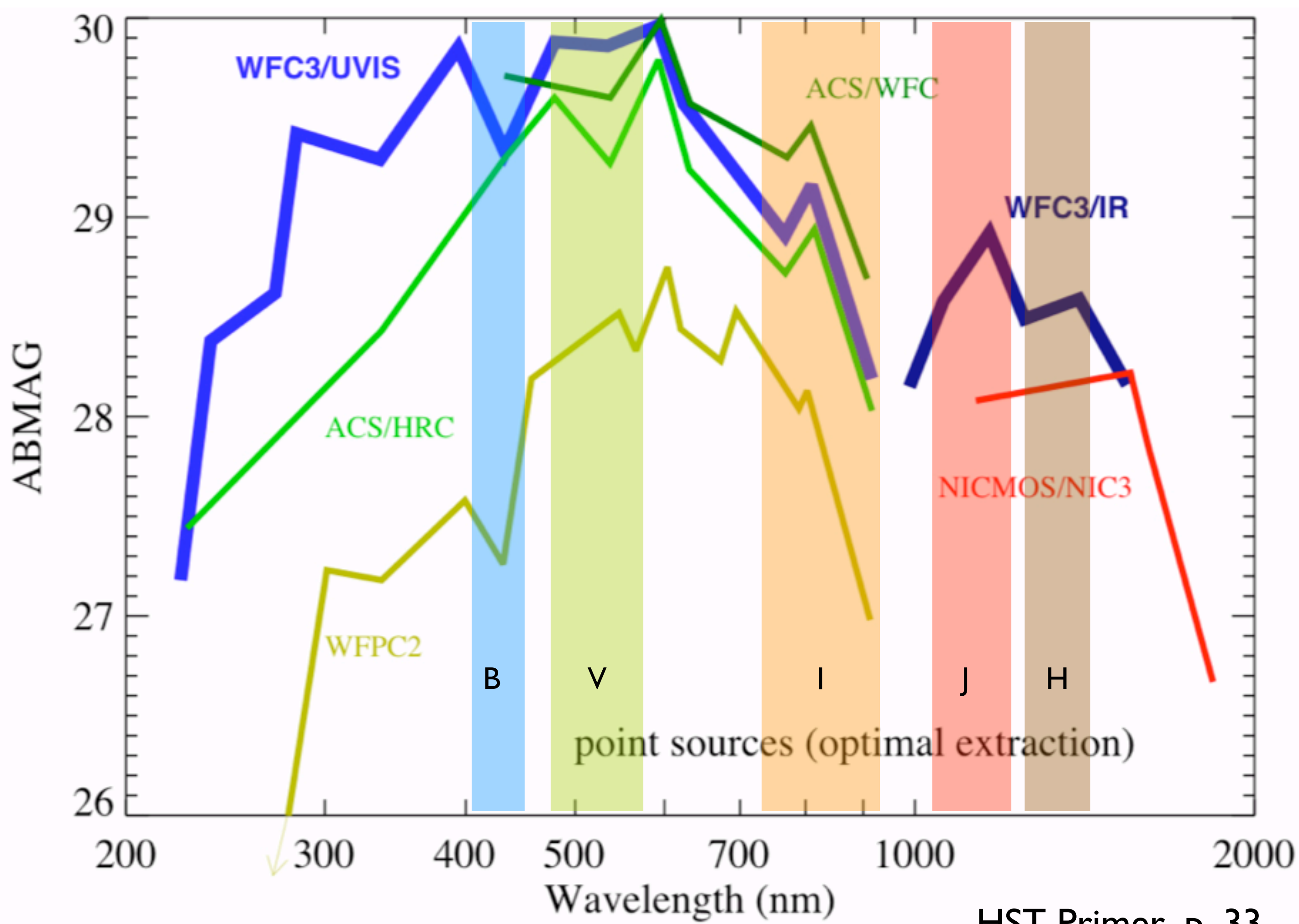


Σ_V=22; Σ_K=19; 14Gyr old; [Fe/H]= -1

Olsen, Blum & Rigaut 2003

Point Source Limits after SM4

Figure 4.3: Point-Source Limiting Magnitude S/N~5; 10 hr exposure

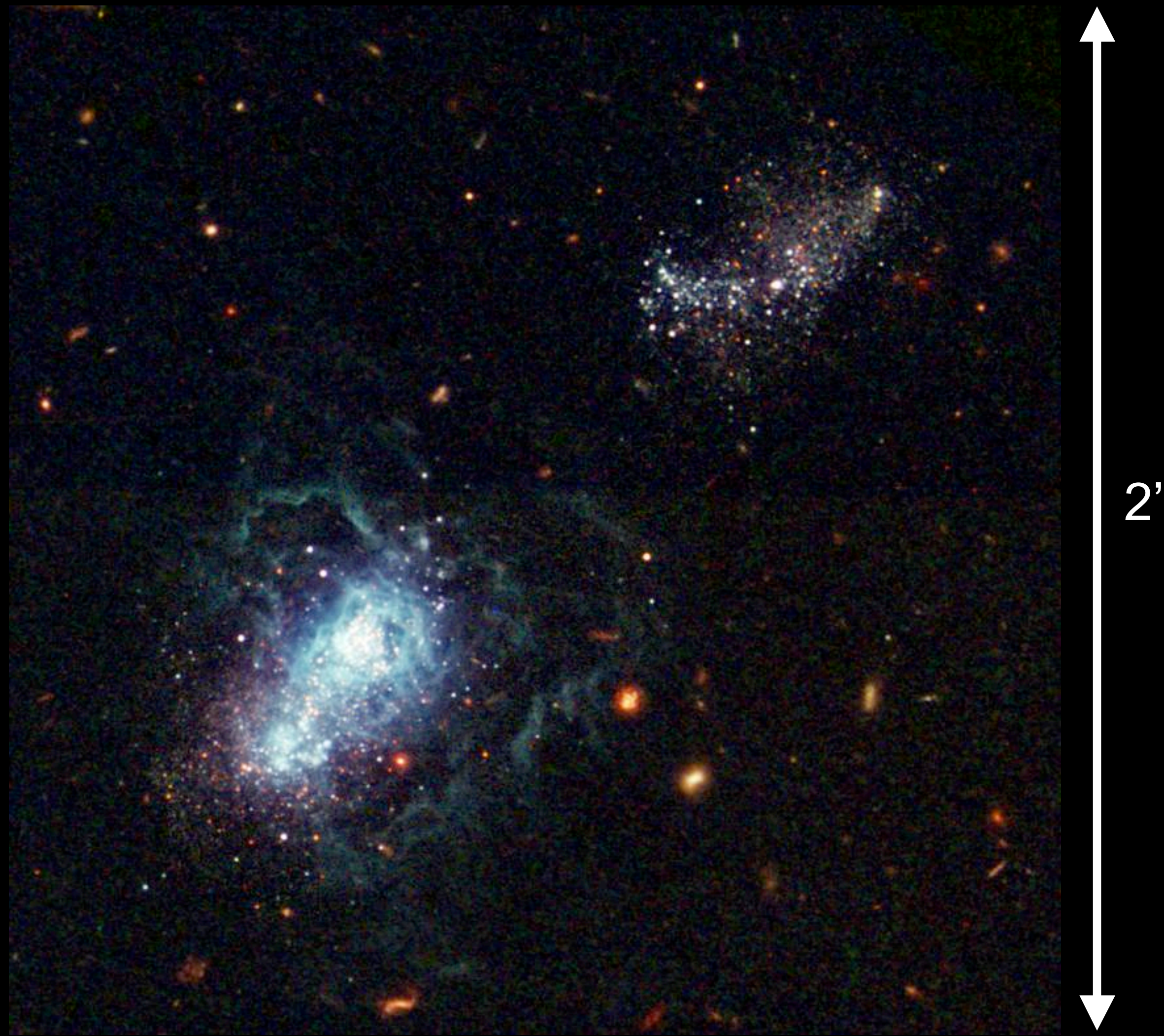


HST Primer, p. 33

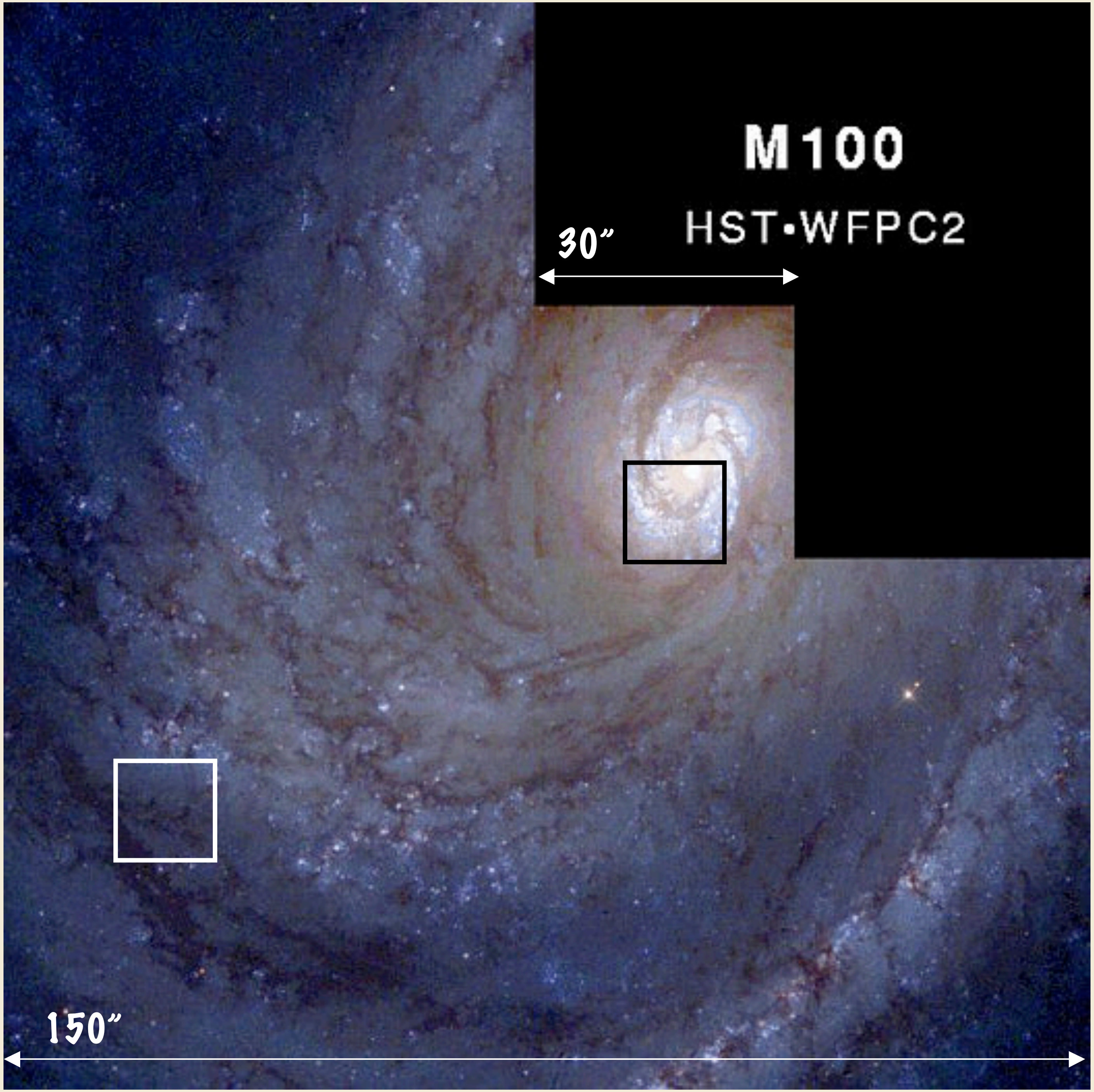
M59

I_0 =15.8 mag arcsec^2
R_e = 39″

I Zw 18

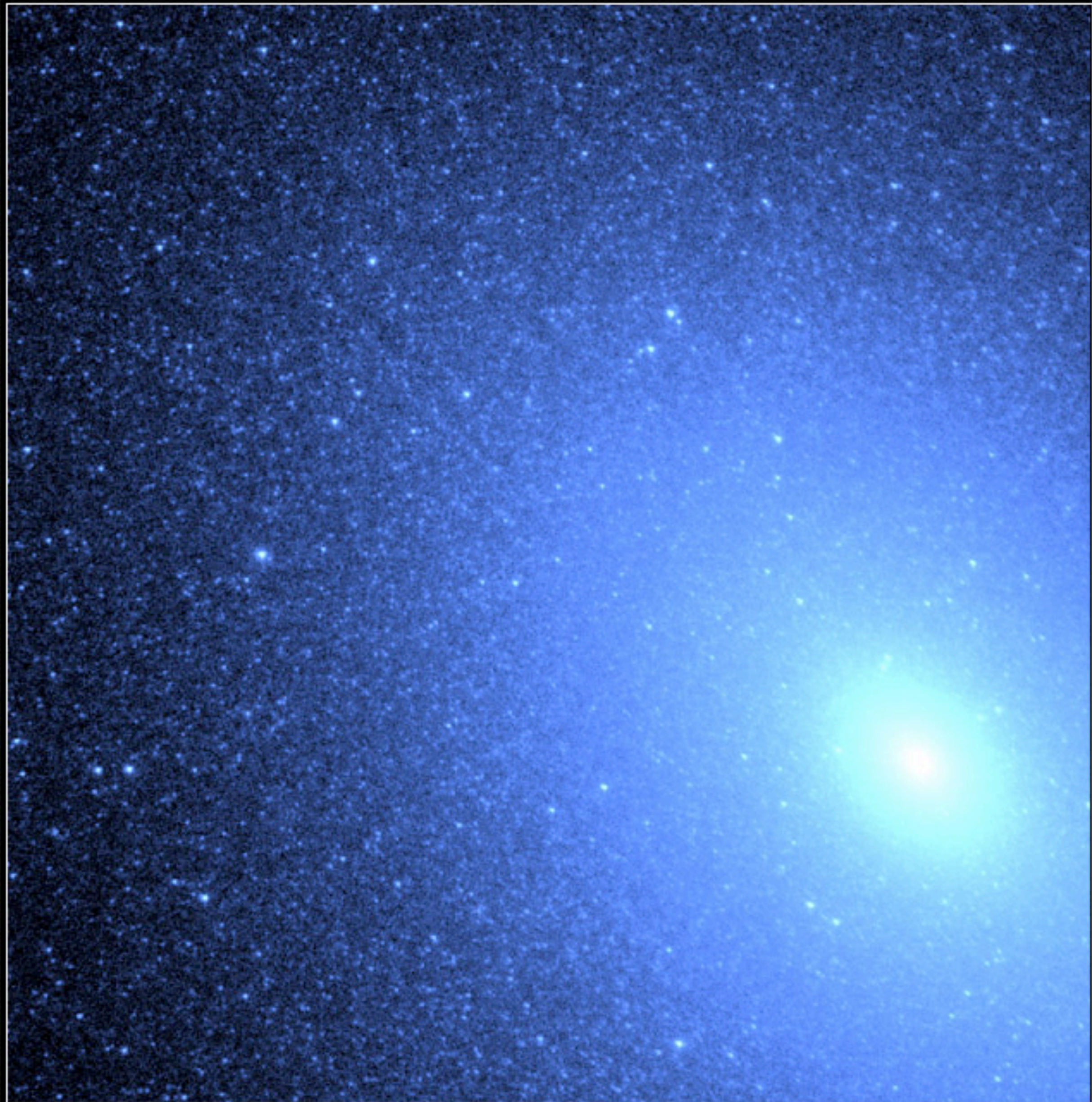


Virgo Spiral

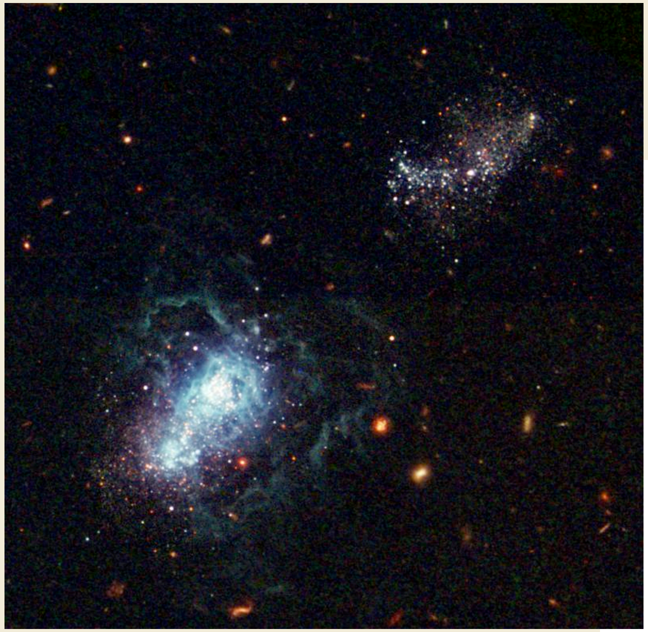


NGC 1569

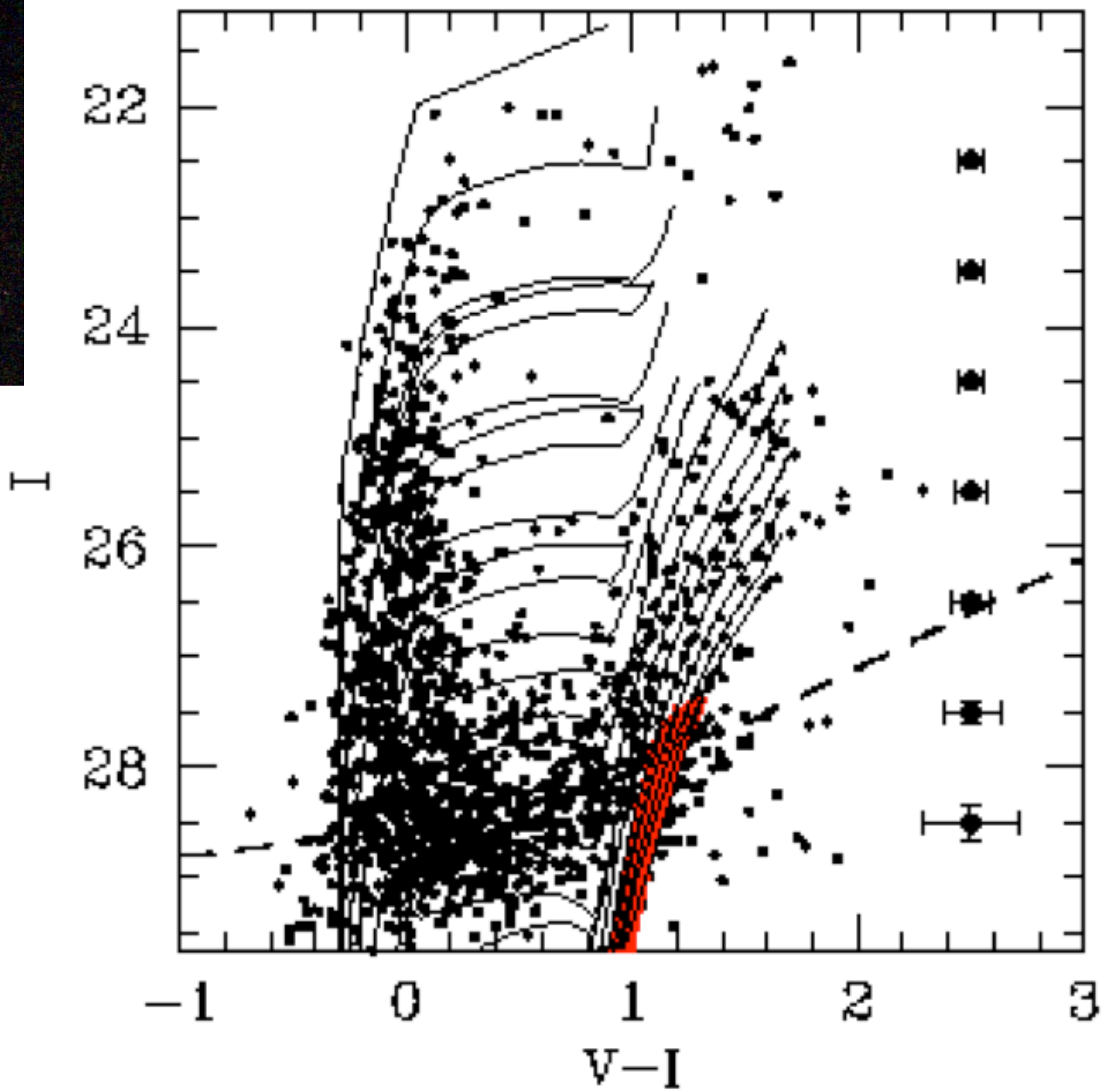
NGC 1569



HST STIS
24" x 24"



I Zw 18



~19Mpc (m-M~31.4)

24orbits ACS time

Table 1. Potential targets for an ELT

Object	$(m-M)_0$	θ(1 pc)	Ra(J2000)	Dec
LMC	18.5	4”	05 23	–69 45
M31	24.3	0.3”	00 43	+41 16
Sculptor Group	26.5	0.1”	00 23	–38 00
M81/82	27.8	0.06”	09 55	+69 40
Cen A	28.5	0.04”	13 25	–43 00
Leo Group	30.0	0.02”	10 48	12 35
Virgo Cluster	31.2	12 mas	12 26	+12 43
Fornax cluster	32.0	11 mas	03 37	-35 37
50Mpc	33.5	4 mas	…	…
Arp220	34.5	2 mas	15 34	+23 30
Perseus Cluster	34.5	2 mas	03 18	+41 31
Stephan’s Quintet	35.0	2 mas	22 36	+33 57
Coma Cluster	35.0	2 mas	13 00	+28 00
Redshift z~0.1	38.5	0.5mas		…
Redshift z~0.3	41	0.2mas		…