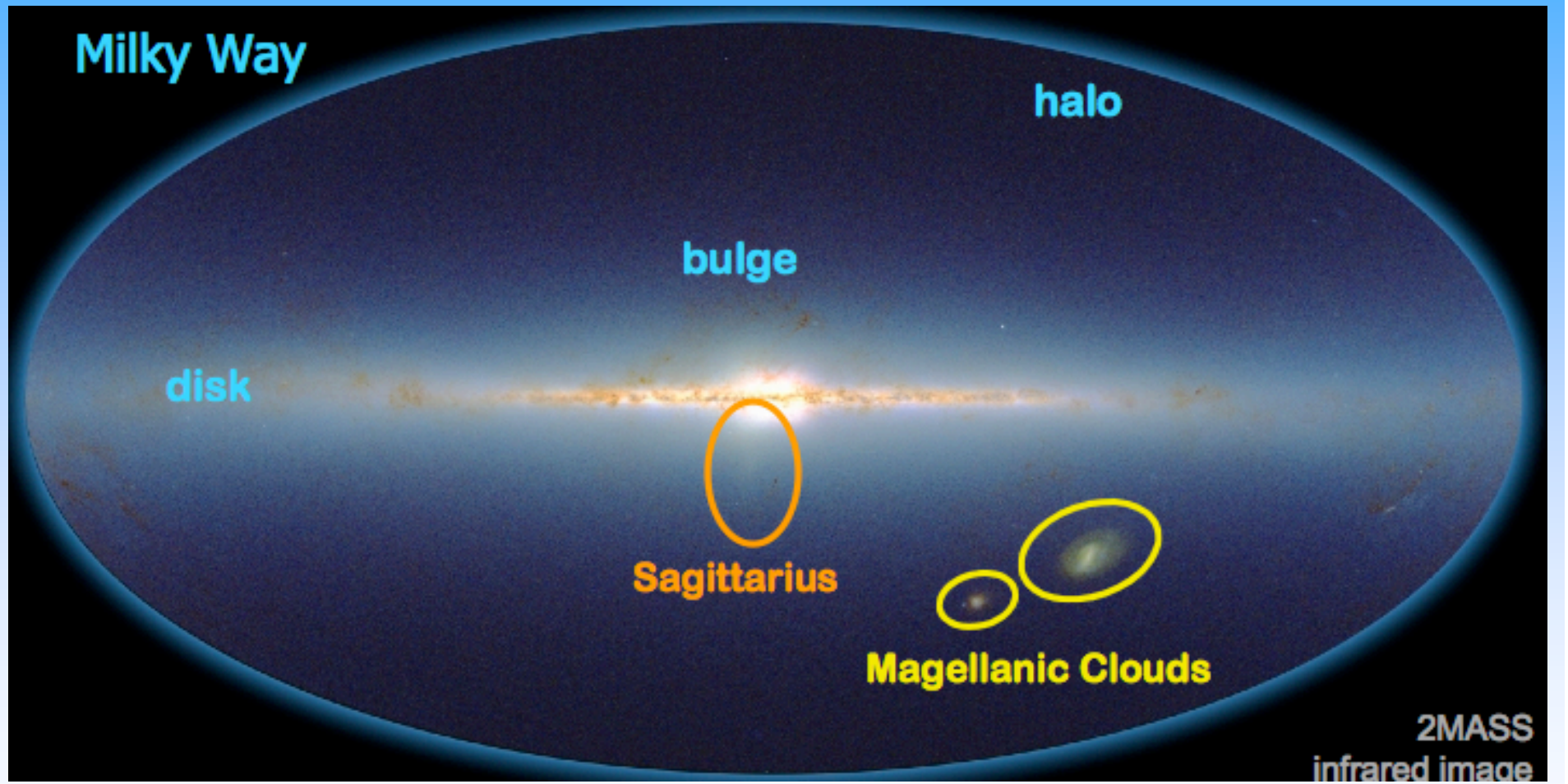
The Milky Way Halo

Direct Evidence for Accretion

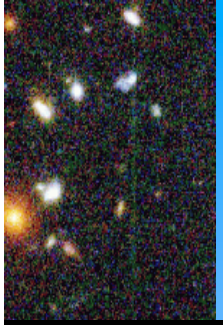
Sagittarius dwarf galaxy

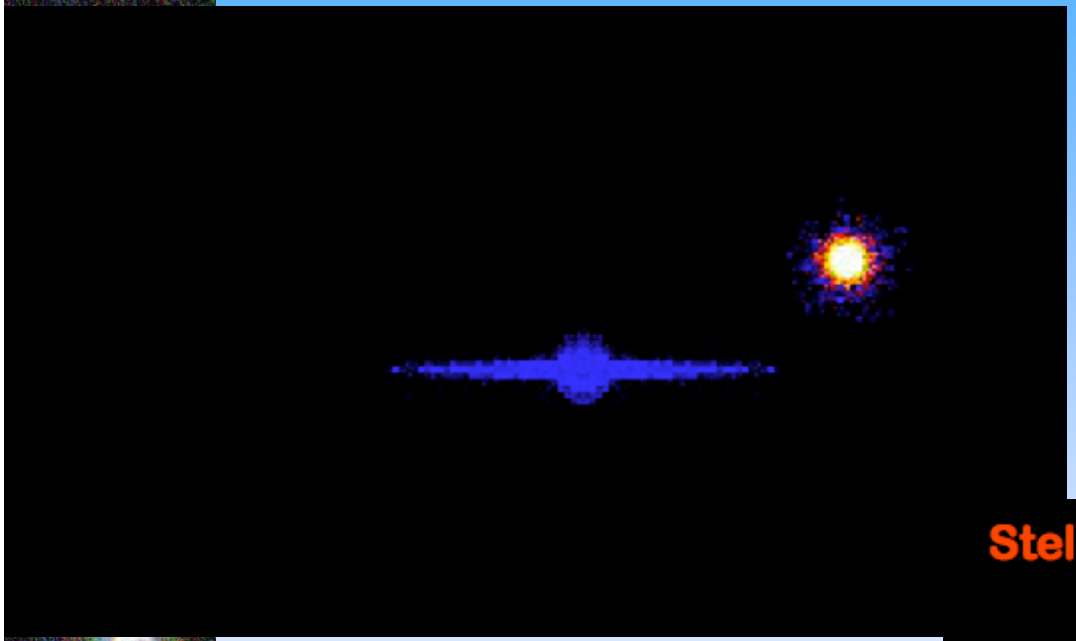
- currently merging with Milky Way
- diameter >20 degrees, with larger tidal streamer
- $L = 1\text{-}2 \times 10^7 L_\odot$
- $M \sim 10^8 M_\odot$
- includes 5 globular clusters

Ibata et al. 1997, A.J. 113, 634

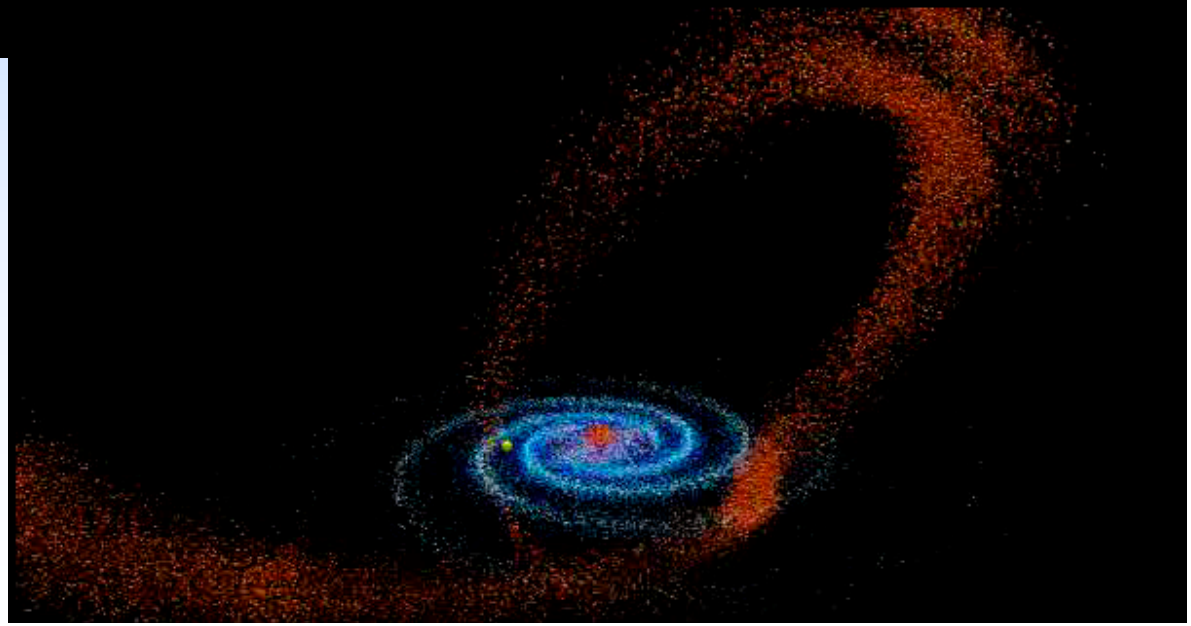

Milky Way
halo
bulge
disk
Sagittarius
Magellanic Clouds
2MASS
infrared image

Sag A : Disruption of a Satellite in the Milky Way Halo



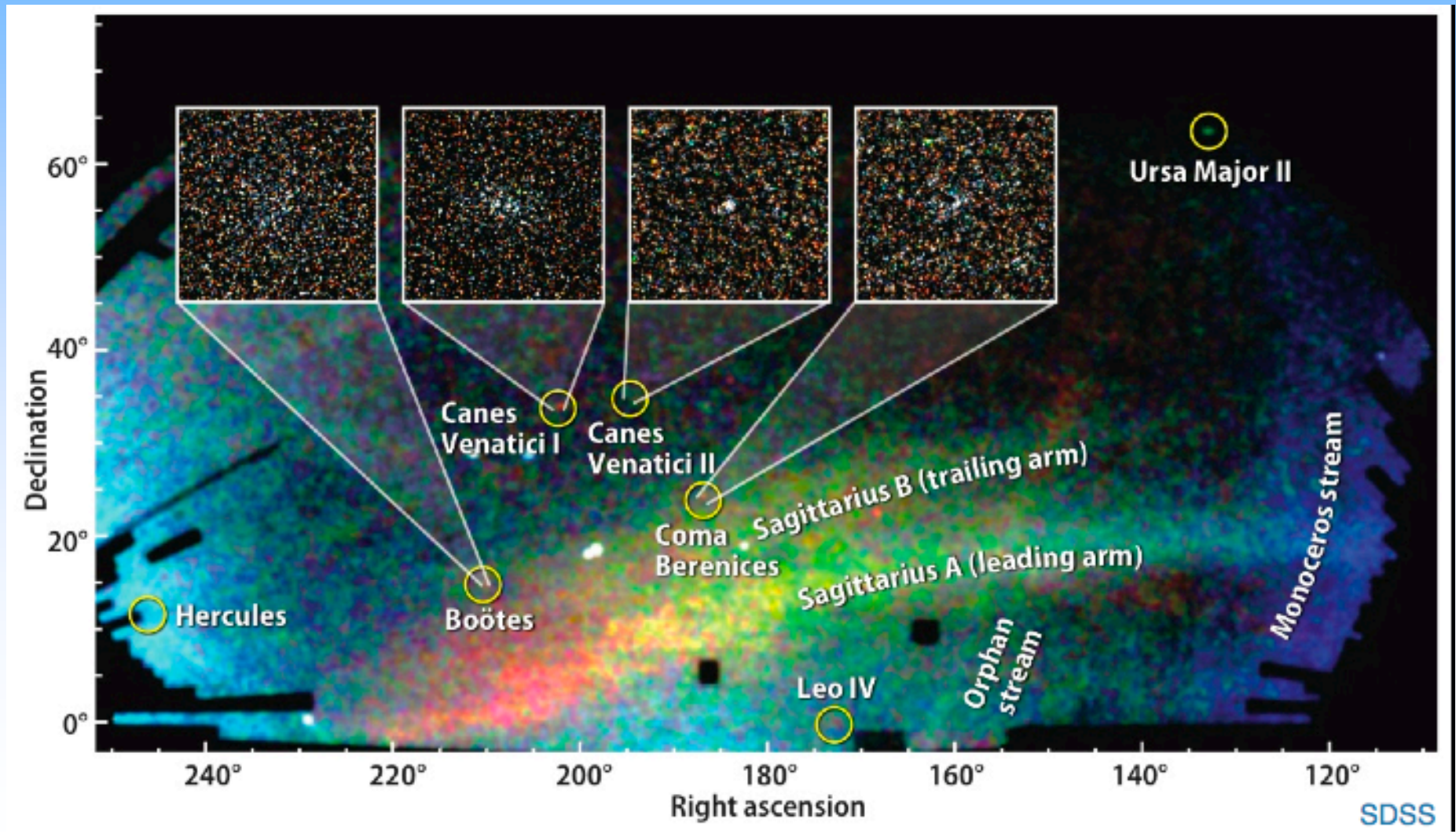


Stellar streams – remnants of a galaxy torn apart



More Satellites to the Milky Way ?

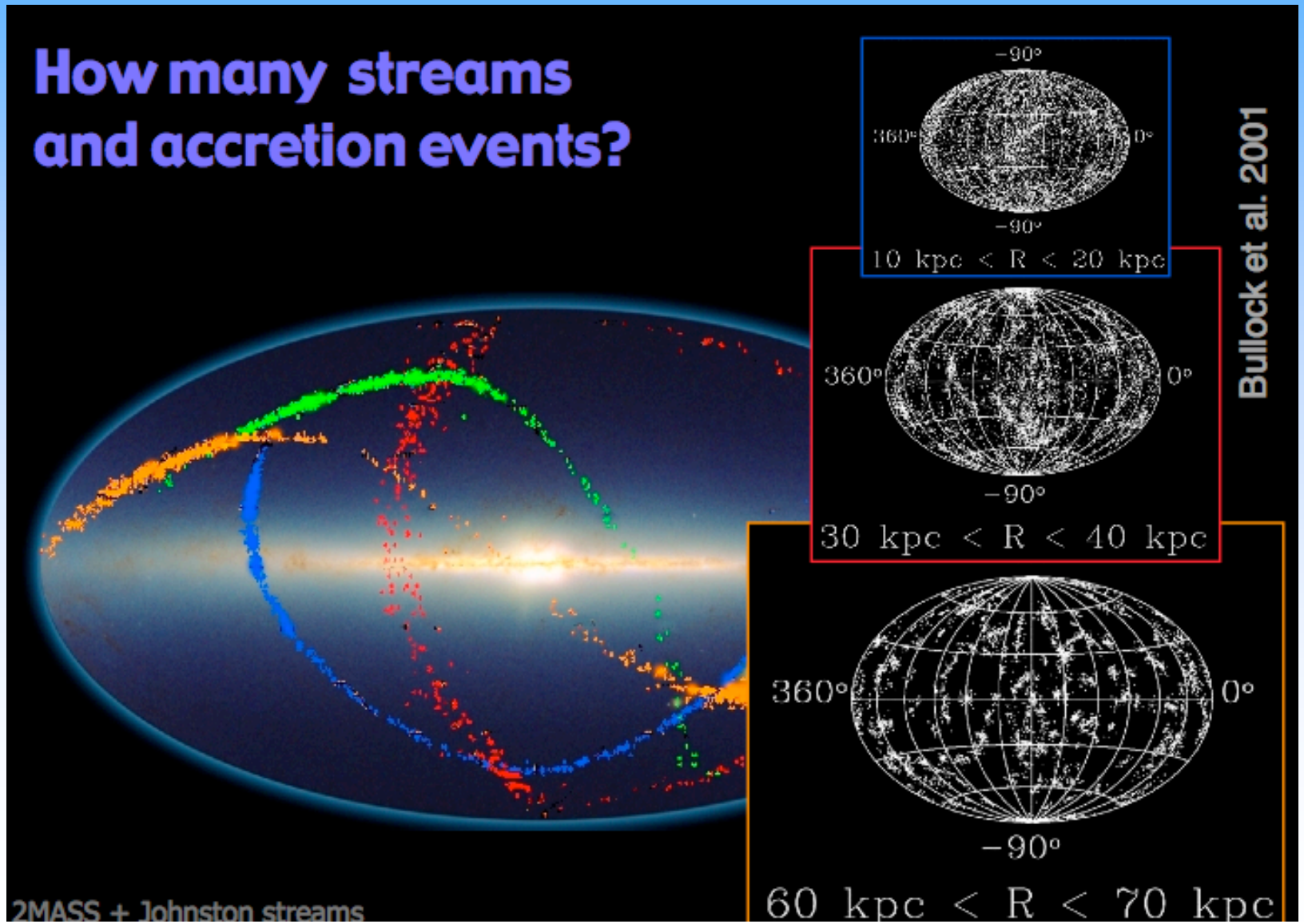
New very faint dSphs are being discovered … how many are we still missing ? Not enough to solve the missing satellite problem! How faint/low mass can they go ? Empty DM halos ?



More Satellites to the Milky Way ?

How many satellites has the Milky Way swallowed already ?

New streams are being discovered …



More Satellites to the Milky Way ?

How many satellites has the Milky Way swallowed already ?

New streams are being discovered … Outlook :

RAVE
RADIAL VELOCITY EXPERIMENT

The RAdial Velocity Experiment

- 6dF spectrograph at the 1.2m UK Schmidt, AAO.
- R=7500 Ca triplet (841–879 nm) spectra.
- Southern hemisphere stars, 9 < I < 12 mag.
- Radial velocity measurement accuracy < 2 km/s.
- [Fe/H], α, log g, T_{eff}…
- Began 2003, to run until > 2010.
- > 150,000 spectra to date.
- Data releases and more information:
  www.rave-survey.aip.de

More Satellites to the Milky Way ?

How many satellites has the Milky Way swallowed already ?

New streams are being discovered … Outlook :

RAVE
RADIAL VELOCITY EXPERIMENT

Science Goals

- Chemical and kinematic signatures of stellar streams in the halo, outer bulge and thick disk due to satellite accretion.
- Dynamical influence of the local spiral arms and inner bar.
- Ellipticity, warping and lopsidedness of the disk.
- First non-local measurement of surface density in the disk.
- Galactic escape speed
- Detailed structure of the spiral arms and

The Local Group

> 43 galaxies (2007)

35 dwarfs:

17 dSphs, 5 dEs, 13 dIs

50% Local Group gals have $M_{tot}<3\ 10^7\ M_\odot$ (dIs, dSphs)

van den Bergh 2000, PASP, 112, 529

DATA ON LOCAL GROUP GALAXIES

NAME	ALIAS	TYPE	M_v	D (Mpc) Galaxy	D (Mpc) Local Group
WLM	DDO 221	Ir IV–V	−14.4	0.95	0.81
IC 10	UGC 192	Ir IV:	−16.3	0.66	0.27
Cetus		dSph	−10.1	0.78	0.62
NGC 147	UGC 328	Sph	−15.1	0.66	0.22
And III	A0032+36	dSph	−10.2	0.76	0.31
NGC 185	UGC 396	Sph	−15.6	0.66	0.22
NGC 205	M110	Sph	−16.4	0.76	0.31
M32	NGC 221	E2	−16.5	0.76	0.31
M31	NGC 224	Sb I–II	−21.2	0.76	0.30
And I	A0043+37	dSph	−11.8	0.81	0.36
SMC		Ir IV/IV–V	−17.1	0.06	0.48
Sculptor		dSph	− 9.8	0.09	0.44
Pisces	LGS 3	dIr/dSph	−10.4	0.81	0.42
IC 1613		Ir V	−15.3	0.72	0.47
And V		dSph	− 9.1	0.81	0.37
And II		dSph	−11.8	0.68	0.26
M33	NGC 598	Sc II–III	−18.9	0.79	0.37
Phoenix		dIr/dSph	− 9.8	0.40	0.59
Fornax		dSph	−13.1	0.14	0.45
LMC		Ir III–IV	−18.5	0.05	0.48
Carina		dSph	− 9.4	0.10	0.51
Leo A	DDO 69	Ir V	−11.5	0.69	0.88
Leo I	Regulus	dSph	−11.9	0.25	0.61
Sextans		dSph	− 9.5	0.09	0.51
Leo II	DDO 93	dSph	−10.1	0.21	0.57
Ursa Minor	DDO 199	dSph	− 8.9	0.06	0.43
Draco	DDO 208	dSph	− 8.6	0.08	0.43
Milky Way	Galaxy	S(B)bc I–II	−20.9:	0.01	0.46
Sagittarius		dSph(t)	−13.8::	0.03	0.46
SagDIG		Ir V	−12.0	1.18	1.29
NGC 6822		Ir IV–V	−16.0	0.50	0.67
Aquarius	DDO 210	V	−10.9	0.95	0.95
Tucanae		dSph	− 9.6	0.87	1.10
Cassiopeia	And VII	dSph	−12.0	0.69	0.29
Pegasus	DDO 216	Ir V	−12.3	0.76	0.44
Pegasus II	And VI	dSph	−11.3	0.78	0.38

The Local Group

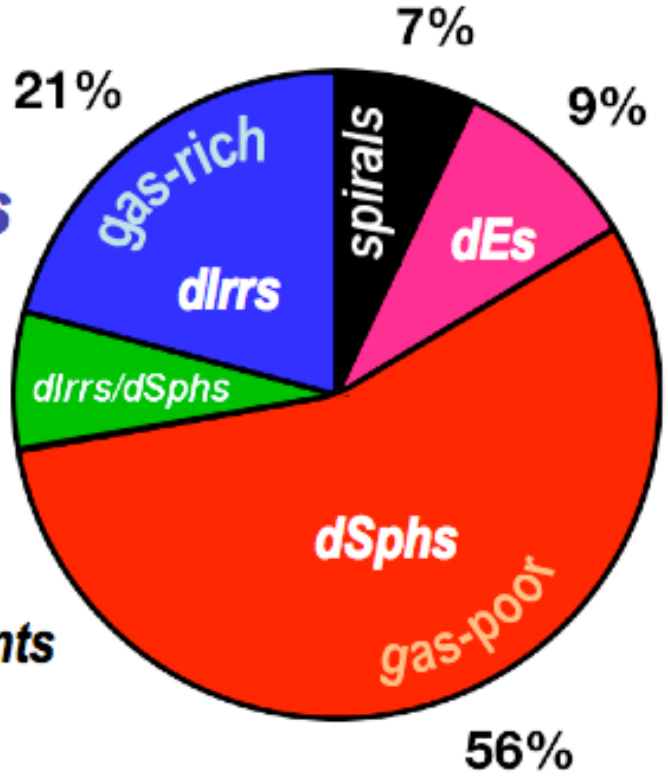
The Local Group (E. Grebel 2007, Saas-Fee Course)

Local Group: Wide range of galaxy properties

Certain or probable members:

- ≥ 43 galaxies (R_0 ~ 1 Mpc)
- 40 satellites and dwarfs ($M_V \geq -18$ mag); + tidal remnants

→ galaxy assembly in action

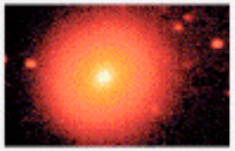


3 Spirals

Massive, luminous; cont. star formation

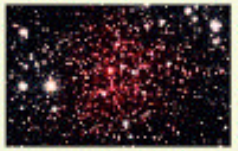
3 dIrr/dSphs

3 dEs, 1 cE



Compact, bright; old/intermed. age; some gas

24 dSphs



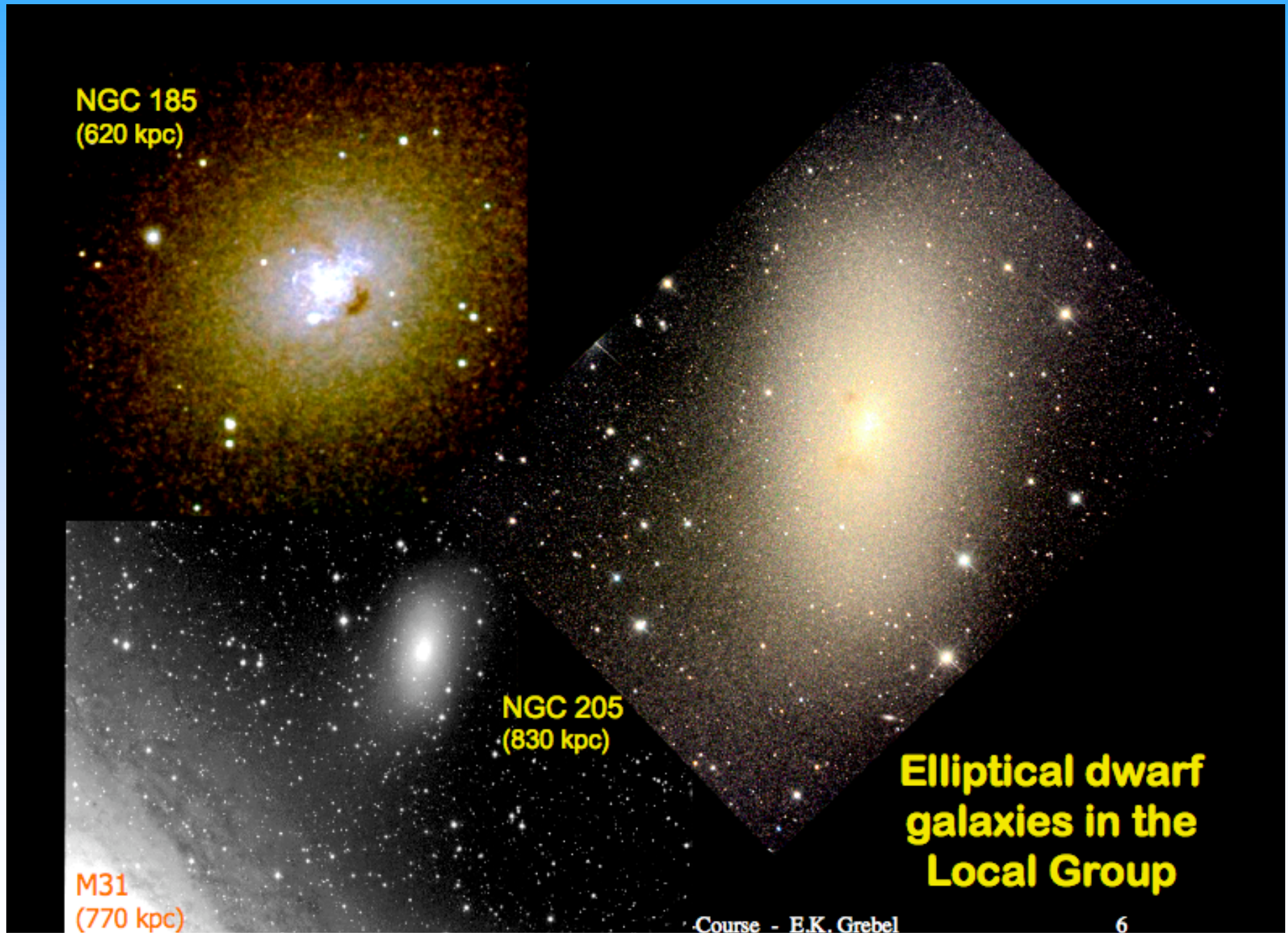
Diffuse, faint, low mass, old/ intermed. age

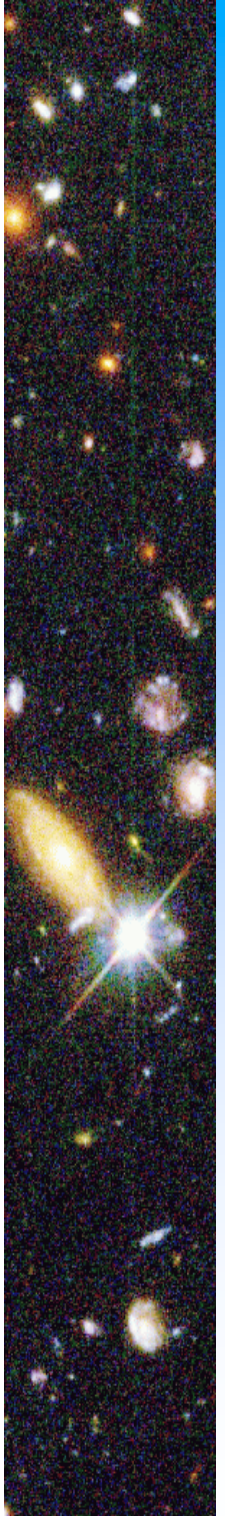
9 Irrs / dIrrs

?

Irregular, gas-rich, active, range of ages

Dwarf Ellipticals

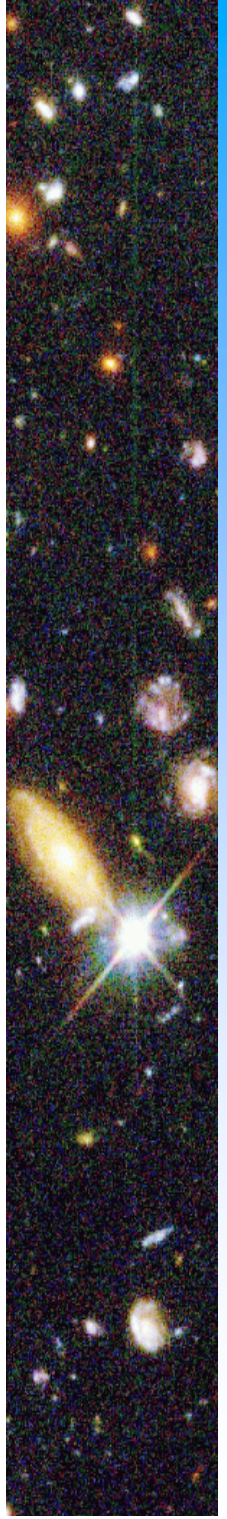


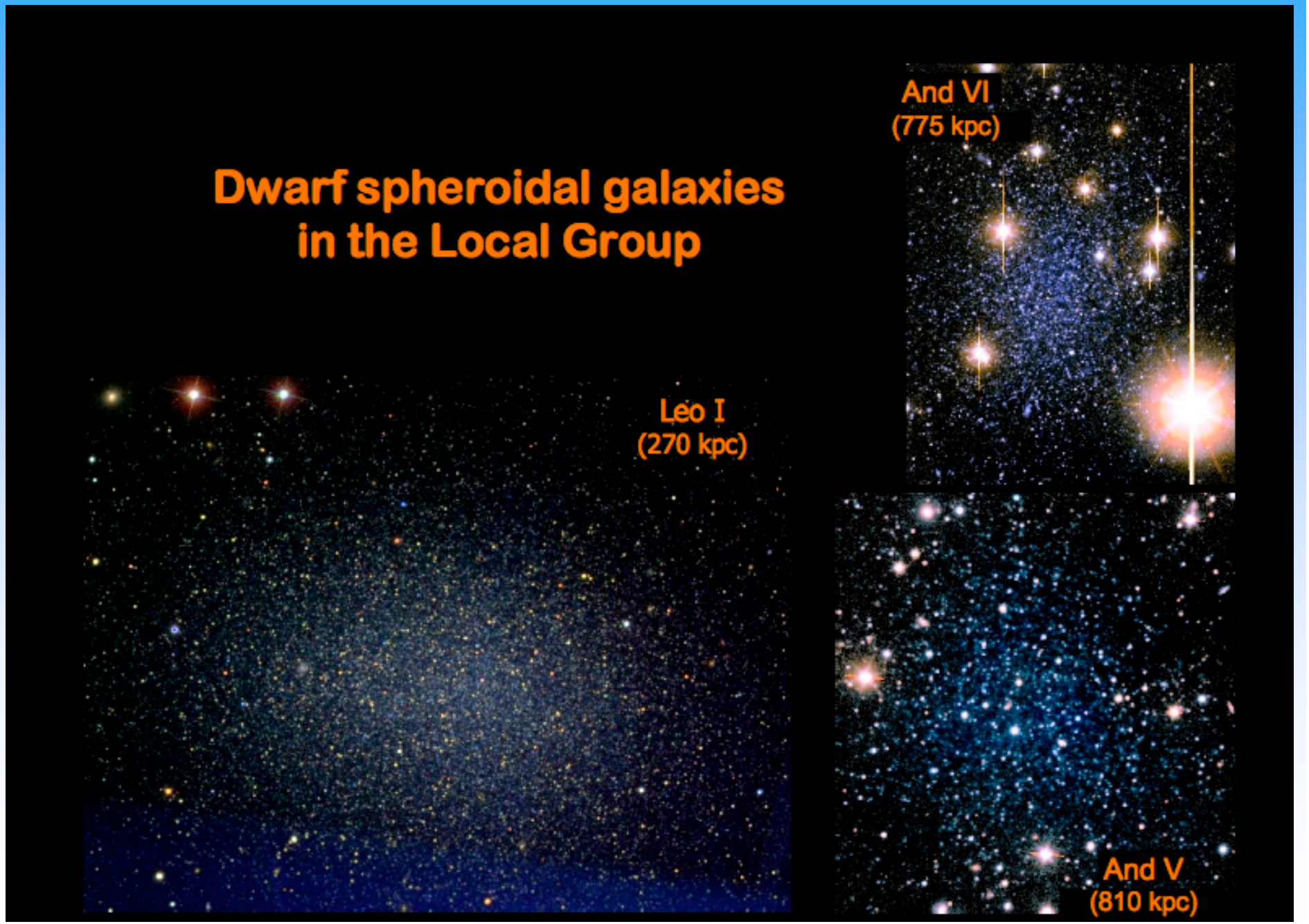


Dwarf Ellipticals

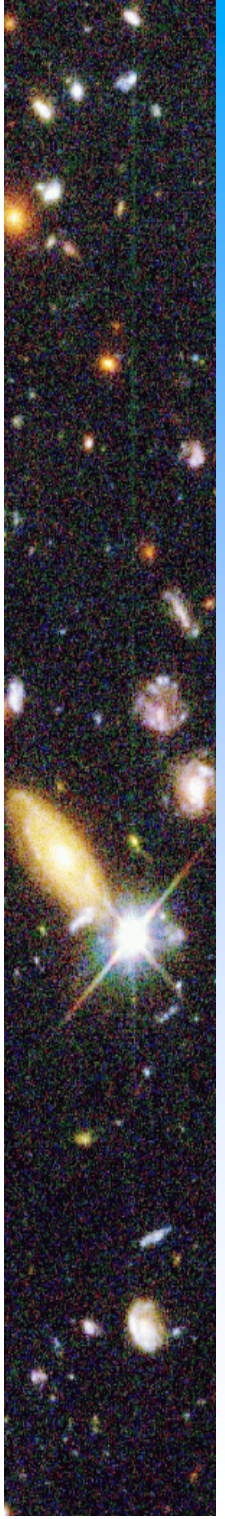
- ☆ spherical - elliptical, exponential light profiles
- ☆ high central stellar densities
- ☆ dEs and dE,Ns with nuclei containing up to 20% light
- ☆ $M_V \geq -17$ mag, $\mu_V \leq 21$ mag arcsec^{-2}
- ☆ $M(HI) \leq 10^8 M_\odot$, some still have ongoing low-level SF
- ☆ $M_{tot} \sim 10^9 M_\odot$
- ☆ long-lasting SF in the past
- ☆ considerable chem. enrichment
- ☆ in high galaxy density regions, mostly satellites

Dwarf Spheroidals





Dwarf Spheroidals

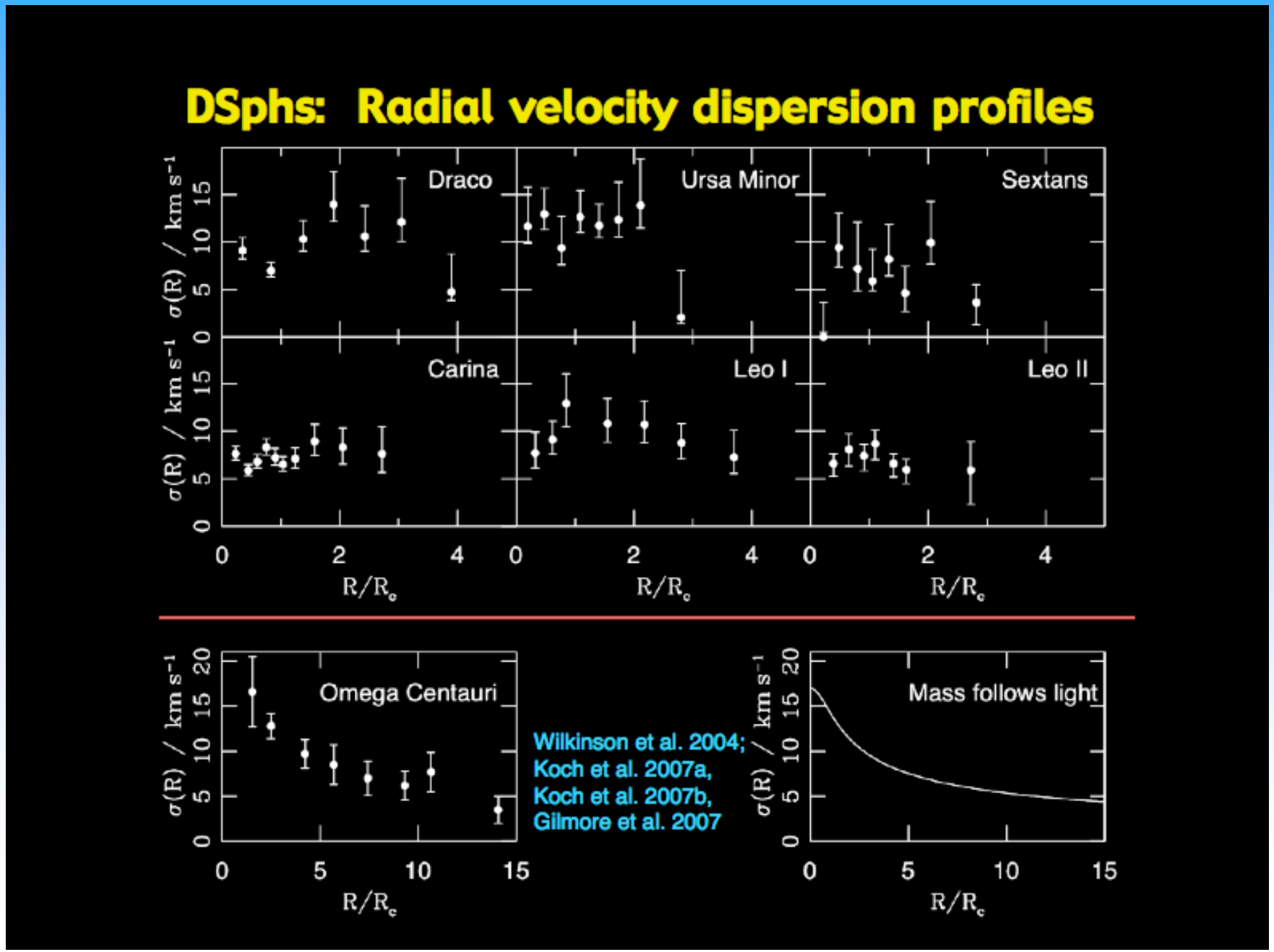


Dwarf Spheroidals dSphs

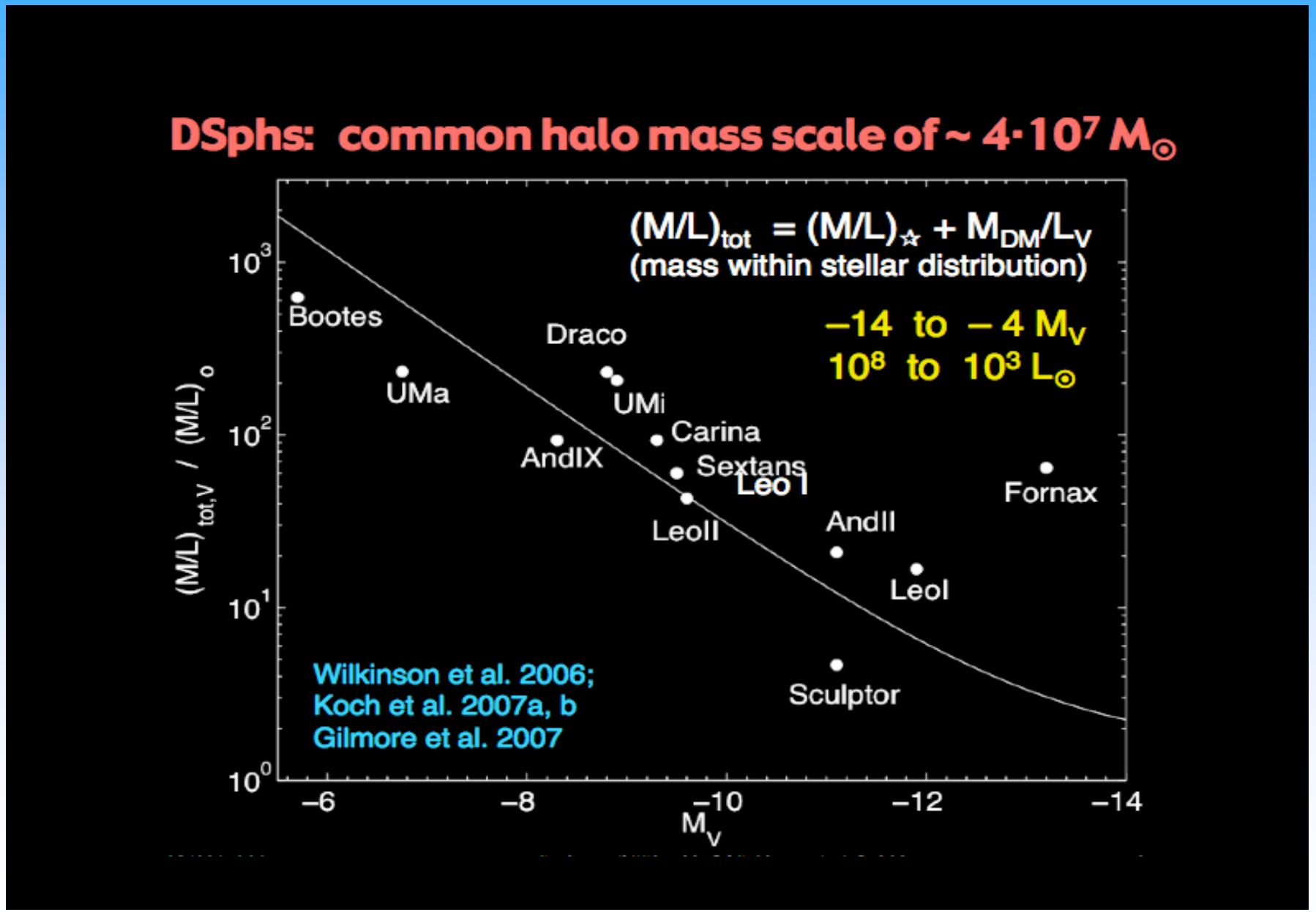
- ☆ diffuse, LSB dwarfs
- ☆ little central concentration
- ☆ younger stellar populations (more centrally concentr.)
- ☆ $M_V \geq -14$ mag, $\mu_V \geq 22$ mag arcsec^{-2} (least lum. gals known)
- ☆ M(HI) $\leq 10^5 M_\odot$, no ongoing SF
- ☆ $M_{tot} \sim 10^7 M_\odot$ (least massive gals known)
- ☆ exponential light profiles, $R_{1/2} > 100\ R_{1/2}$ (GCs@same lum.)
- ☆ long-lasting SF @ early times, all have old stellar pops
  - some stopped SF 10 - 12 Gyr ago,
  - some formed majority of their stars 6 - 8 Gyr ago
  - few had SF 1 - 2 Gyr ago
  - SF influenced by big companion
- ☆ low metallicities but large spread in abundances
- ☆ in high galaxy density regions, mostly satellites
- ☆ high DM fractions or radially varying veloc. dispersion

anisotropy?

Dwarf Spheroidals

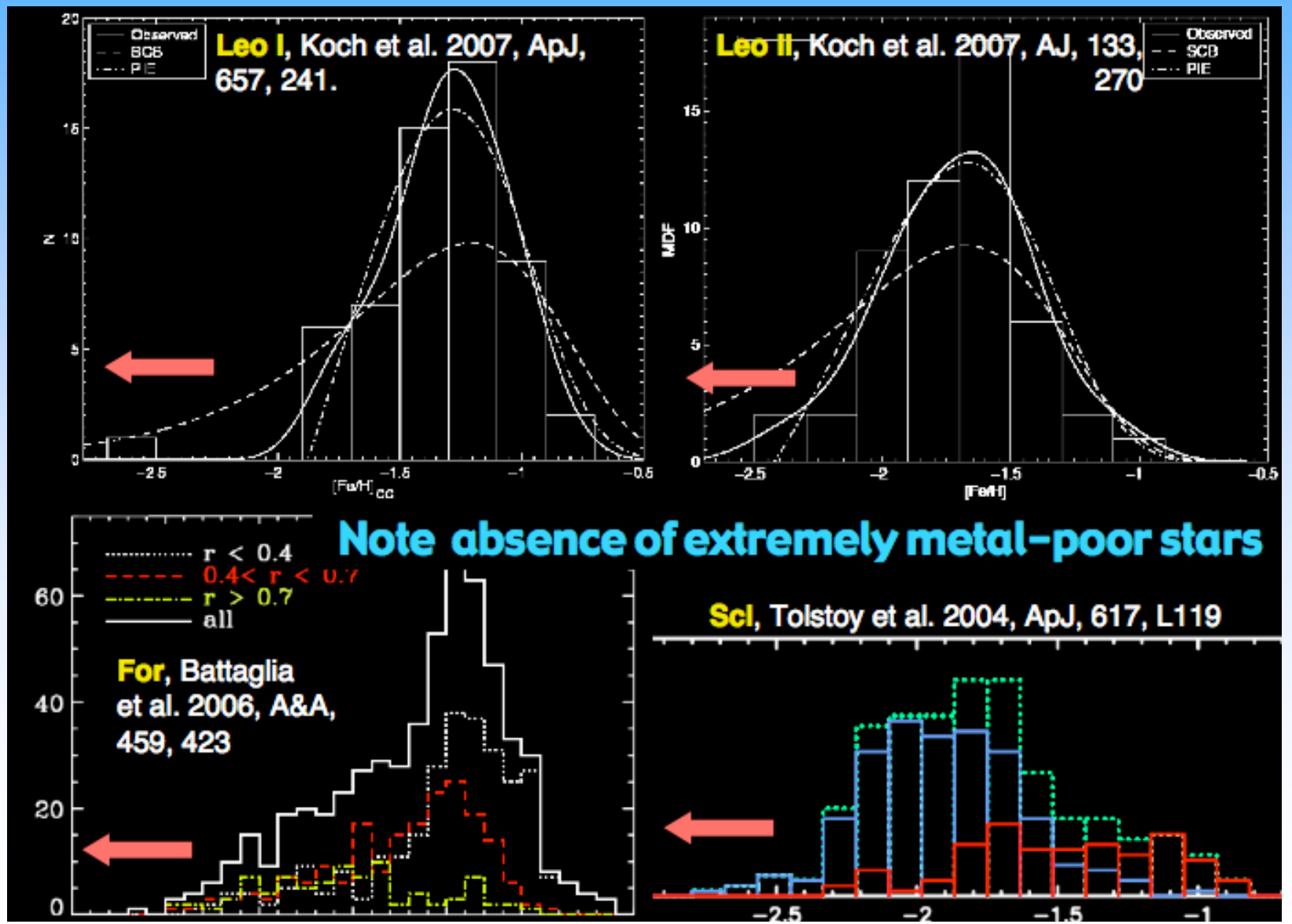


Dwarf Spheroidals

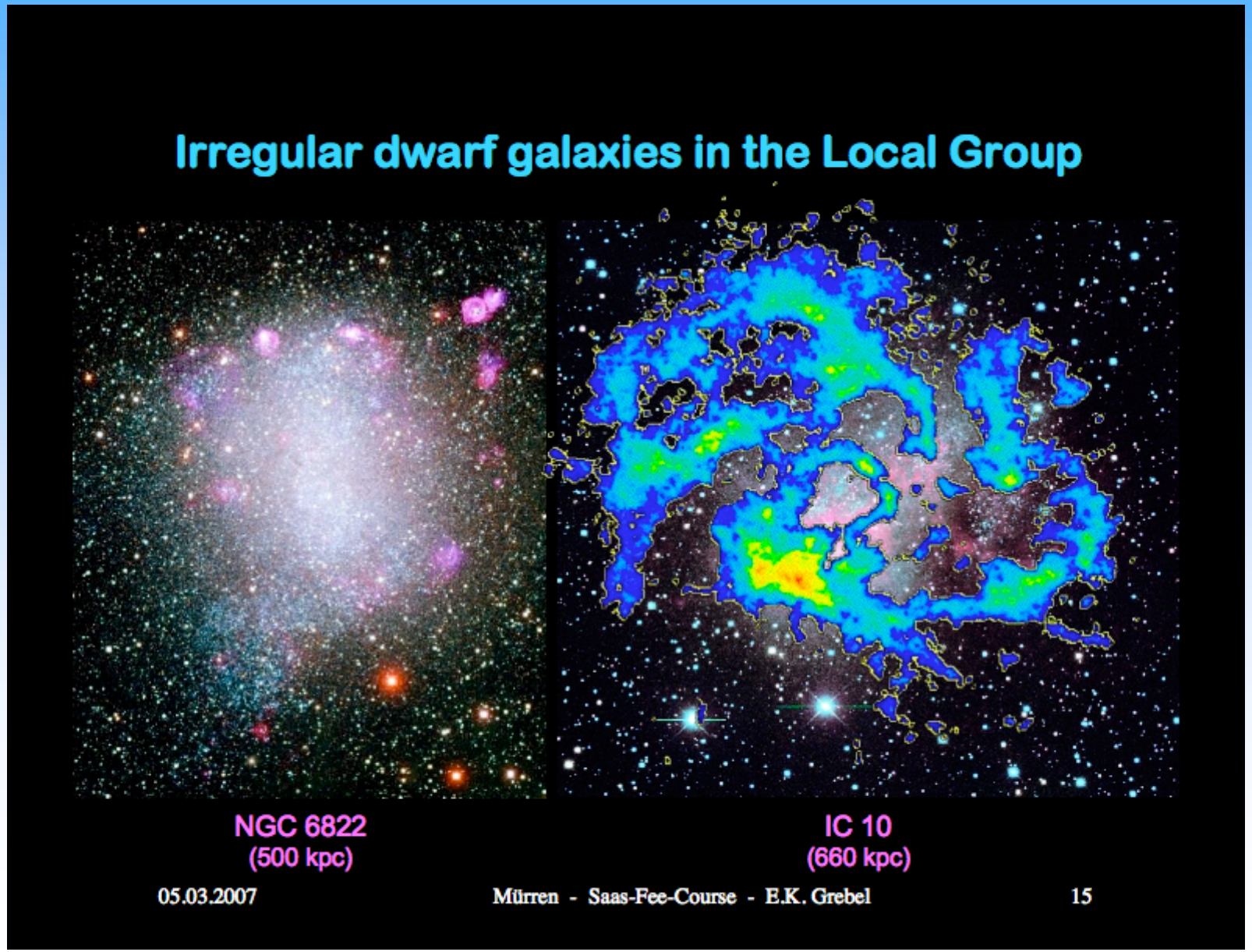


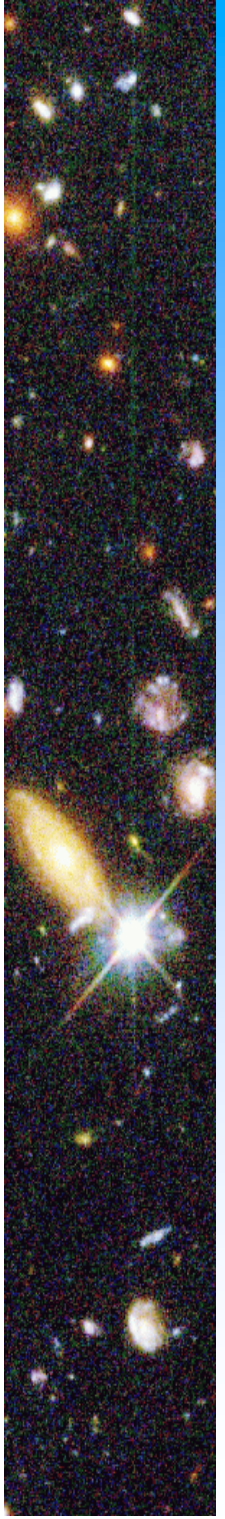
dSphs : Stellar Metallicities

Low but not extremely low stellar abundances.



Dwarf Irregular Galaxies

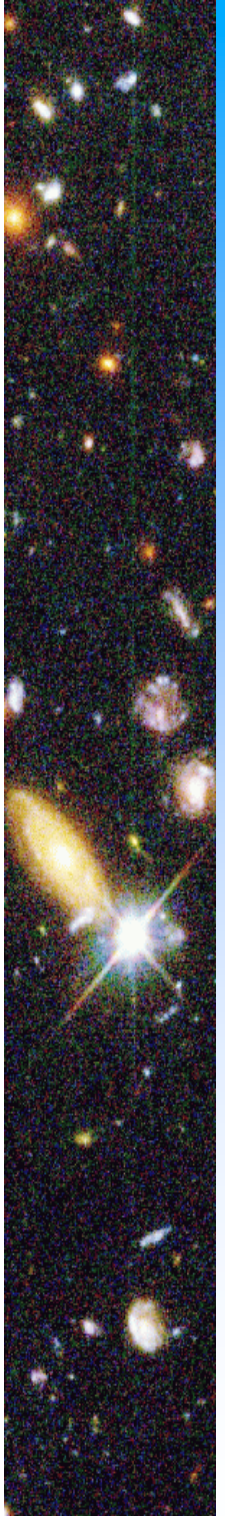




Dwarf Irregulars dIrrs, dIs

- ☆ blue, gas-rich, irregular, dominated by scattered HII regions
- ☆ young stellar populations, active SF
- ☆ $M_V \geq -14$ mag, $\mu_V \leq 23$ mag arcsec^{-2}
- ☆ M(HI) ≤ 10^9 $M_\odot$, clumpy, often more extended than stellar comp.
- ☆ $M_{tot} \sim 10^{10}$ $M_\odot$
- ☆ stochastic SF, no spiral arms/density waves
- ☆ low metallicities but large spread in abundances ratios
- ☆ in low galaxy density regions
- ☆ do all dIrrs have old stellar populations ?

if dI stops SF, it will resemble a dSph after few 100 Myr



CMD Analyses of Local Group Galaxies

HST WFPC2 imaging

observational limit depends on distance D

detect Giant Branch & (upper) Main Sequence

stochastic effects (small star number statistics)

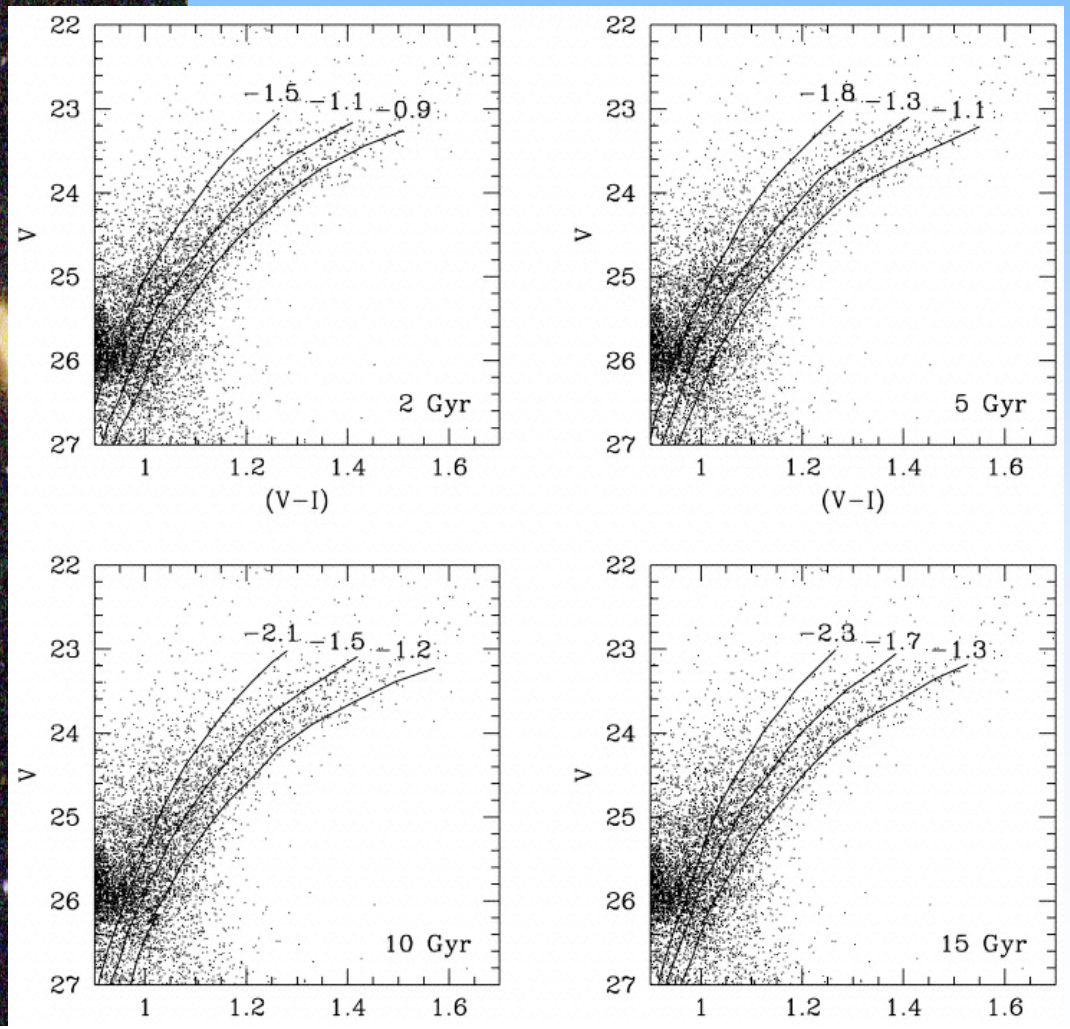
SF history entangled with chemical enrichment history

CMD Analyses of Local Group Galaxies

SF history entangled with chemical enrichment history :

age - metallicity (- dust) degeneracy for optical colours

disentangled with optical + NIR colours !



RGB region of CMD

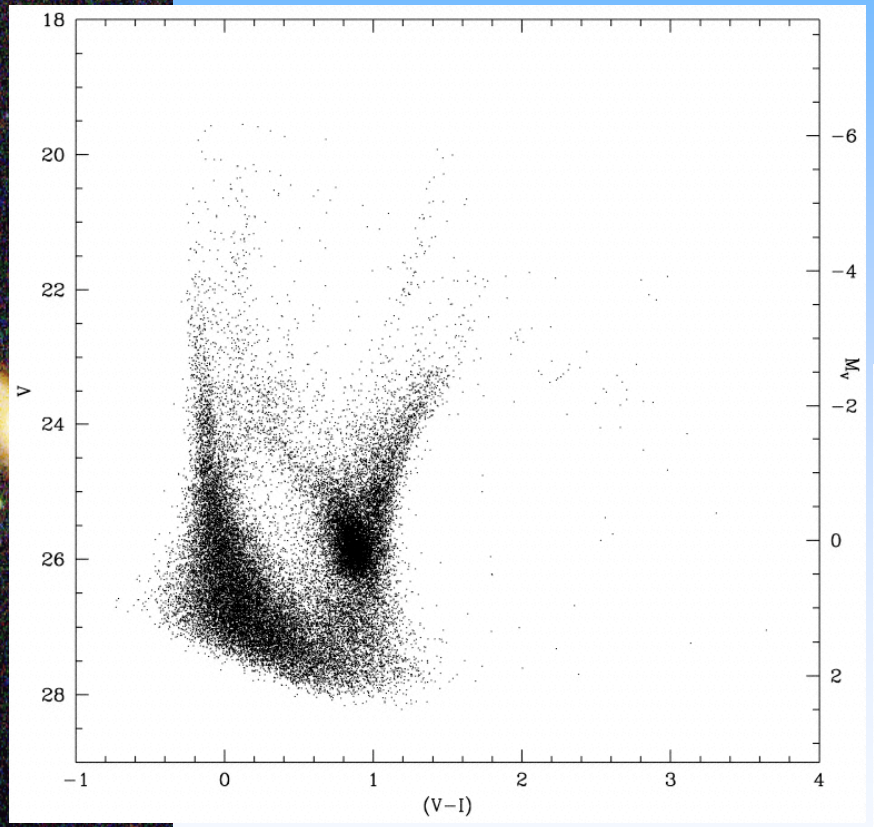
4 different ages

3 different [Fe/H] in each panel

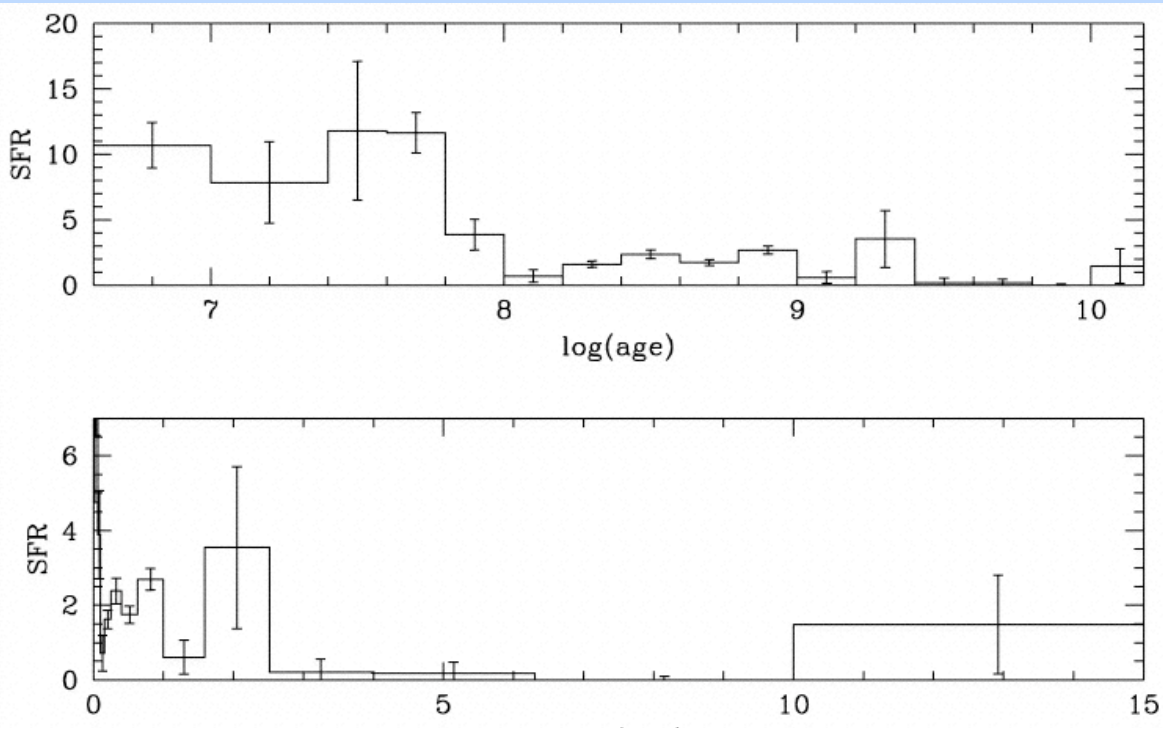
isochrones at similar positions

CMD Analysis of dSph Sextans A, D=1.32 Mpc

Dolphin et al. 03:
HST WFPC2 imaging 50% complete to V=27.5, I=27.0



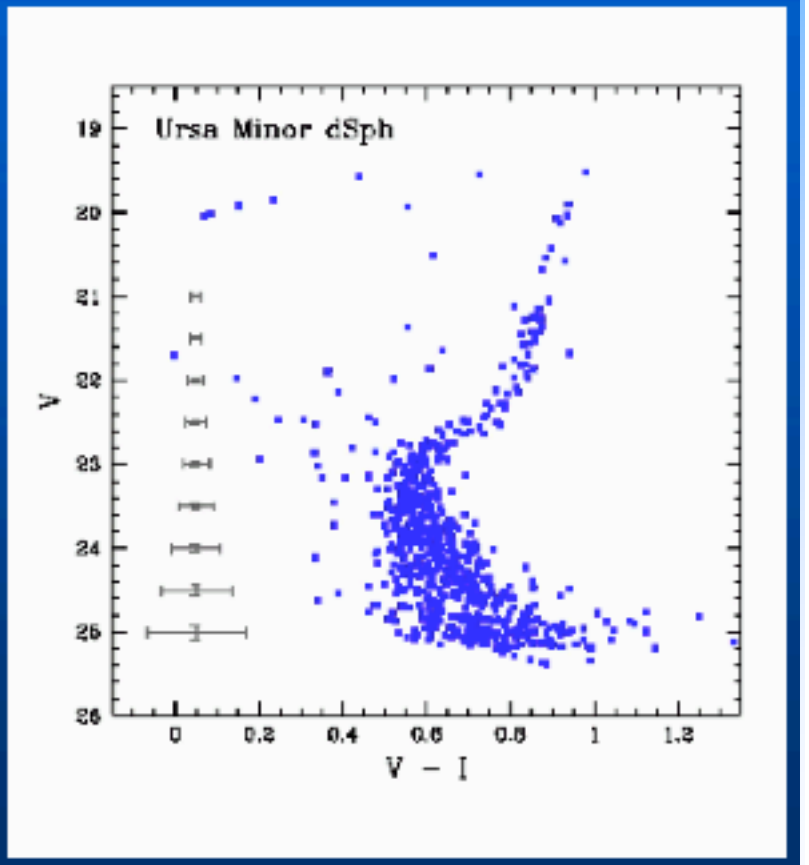
- ☆ high SFR 2.5 Gyr ago
- ☆ recent increase in SFR since ~0.1 Gyr ago
- ☆ stars older than 2.5 Gyr
- ☆ [Fe/H] = - 1.4



CMD Analysis of dSphs

Dwarf Spheroidal Galaxies

- SF history from HST CMDs
- young population is absent (by definition)
- old population ubiquitous
  - at least one purely old galaxy (Ursa Minor) -------->
- intermediate-age population varies from 0% --> >90%



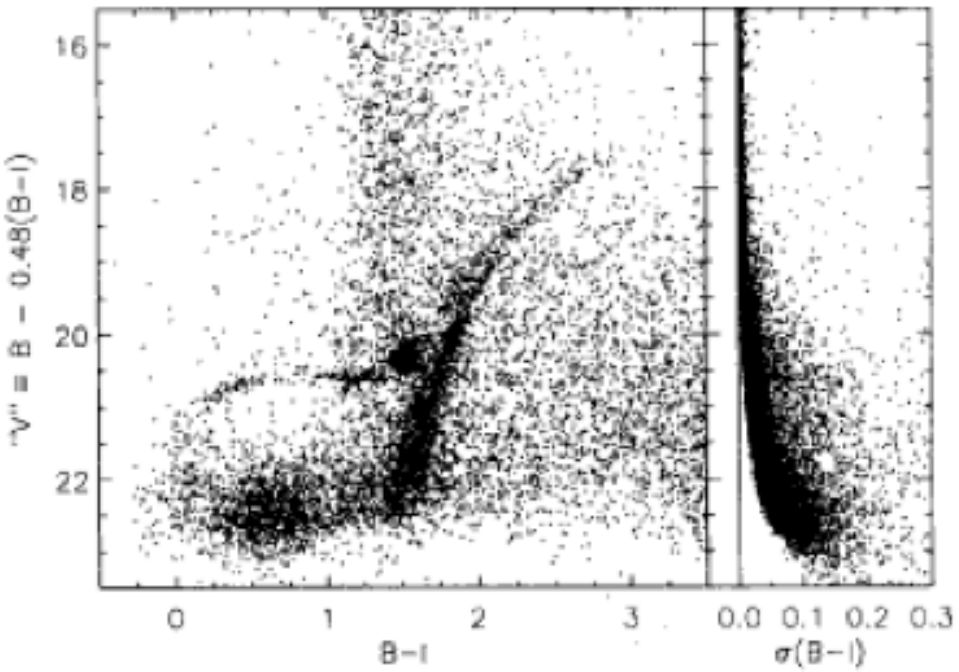
Mighell, Burke 1999, AJ, 118, 366

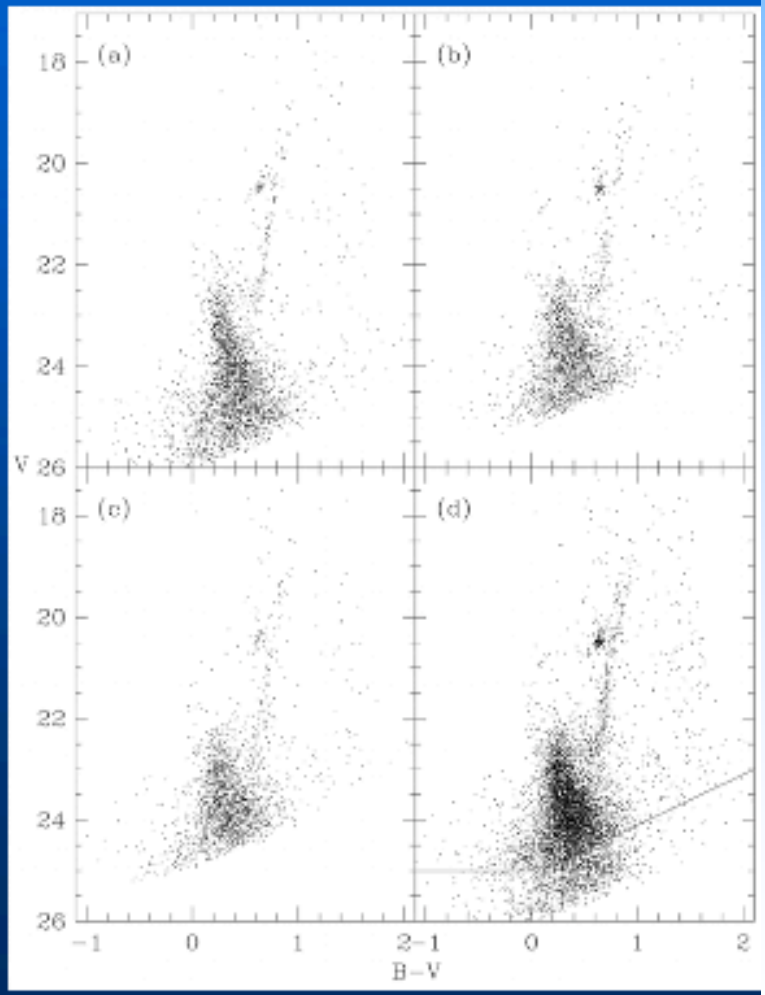
CMD Analysis of dSph

Carina

- 10-13 Gyr old population: 10-20%
- ~7 Gyr old population: 80-90%

Smecker-Hane et al. 1994, AJ, 108, 507

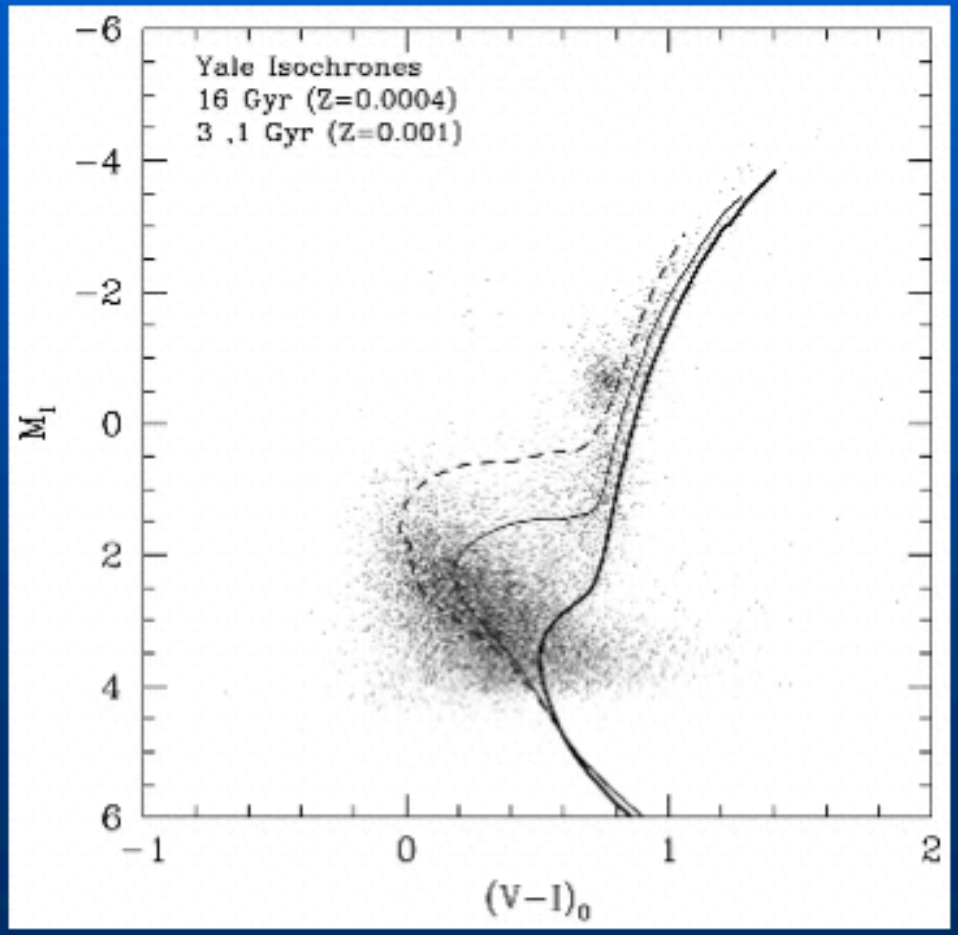


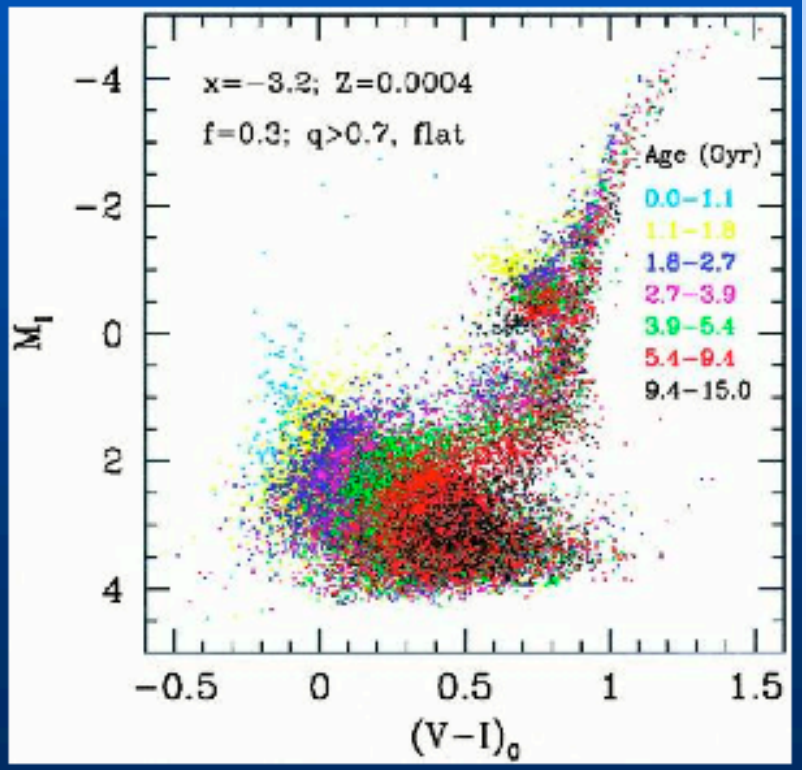


CMD Analysis of dSph

Leo I

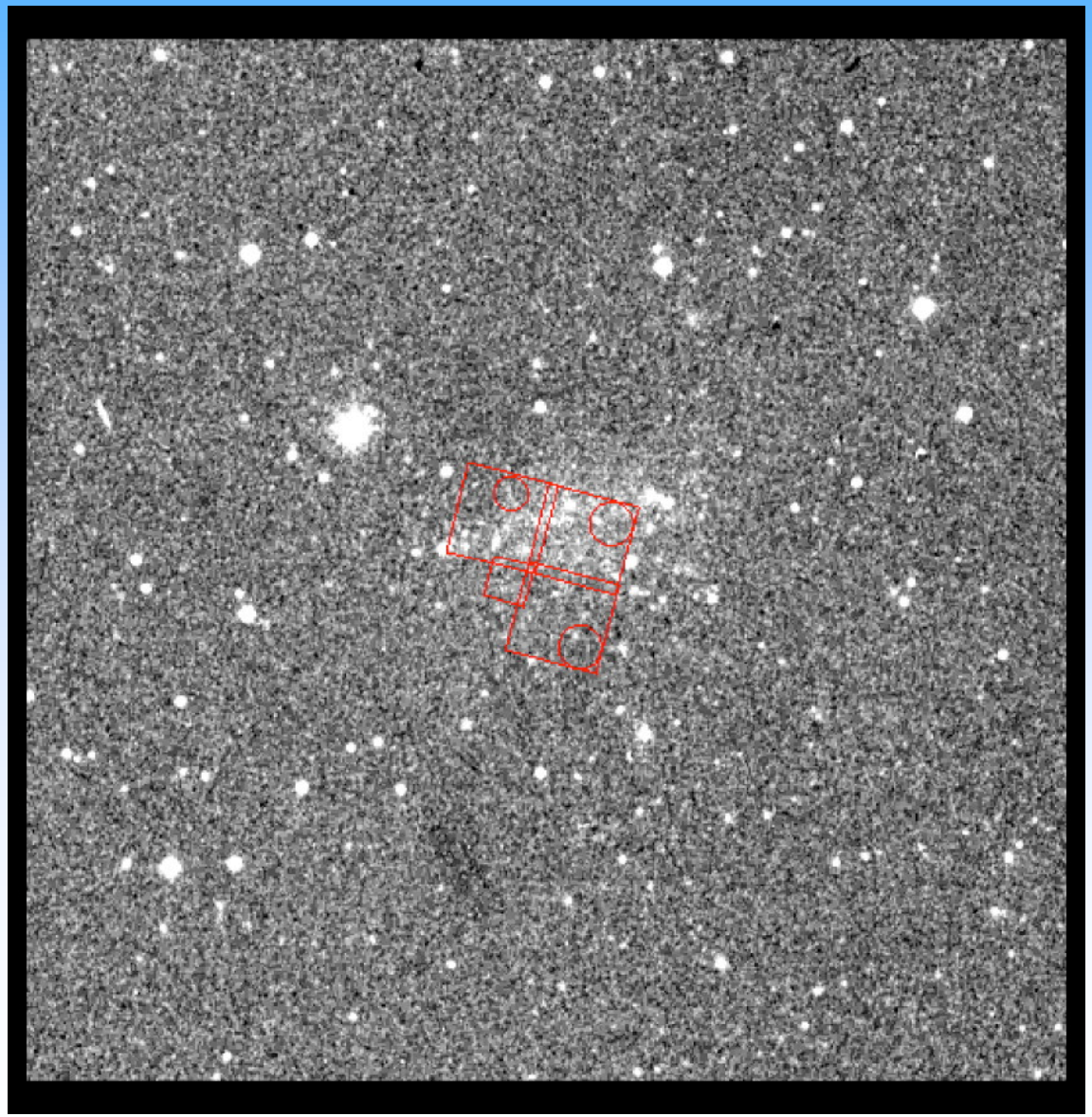
Relatively steady SF from
10-13 Gyr to ~1 Gyr ago





CMD Analyses of dIrrs

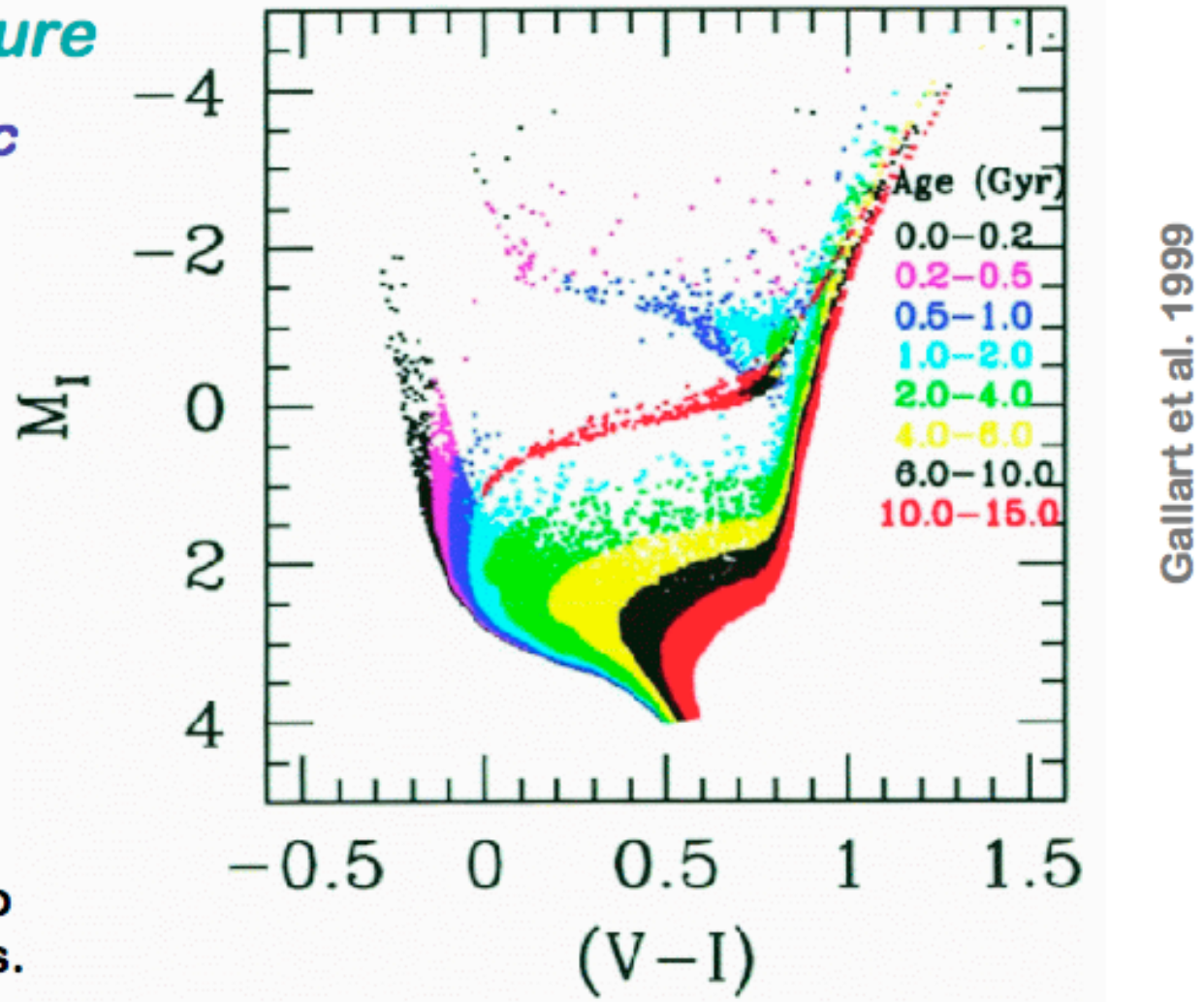
Tolstoy et al. 98: HST WFPC2 imaging of LeoA



The SFHs of Dwarf Galaxies

Age structure

in a synthetic color-magnitude diagram



Gallart et al. 1999

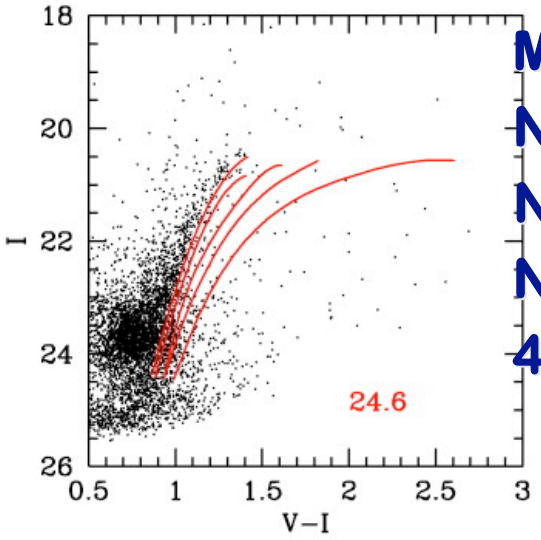
Shown: Constant star formation rate from 15 Gyr to the present, no photom. errors.

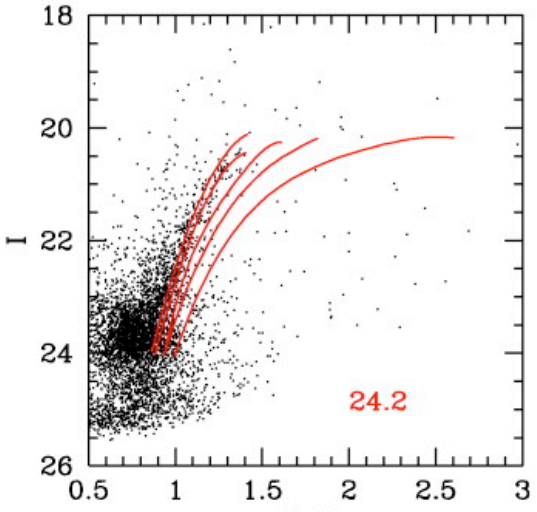
CMD Analyses of dIrrs

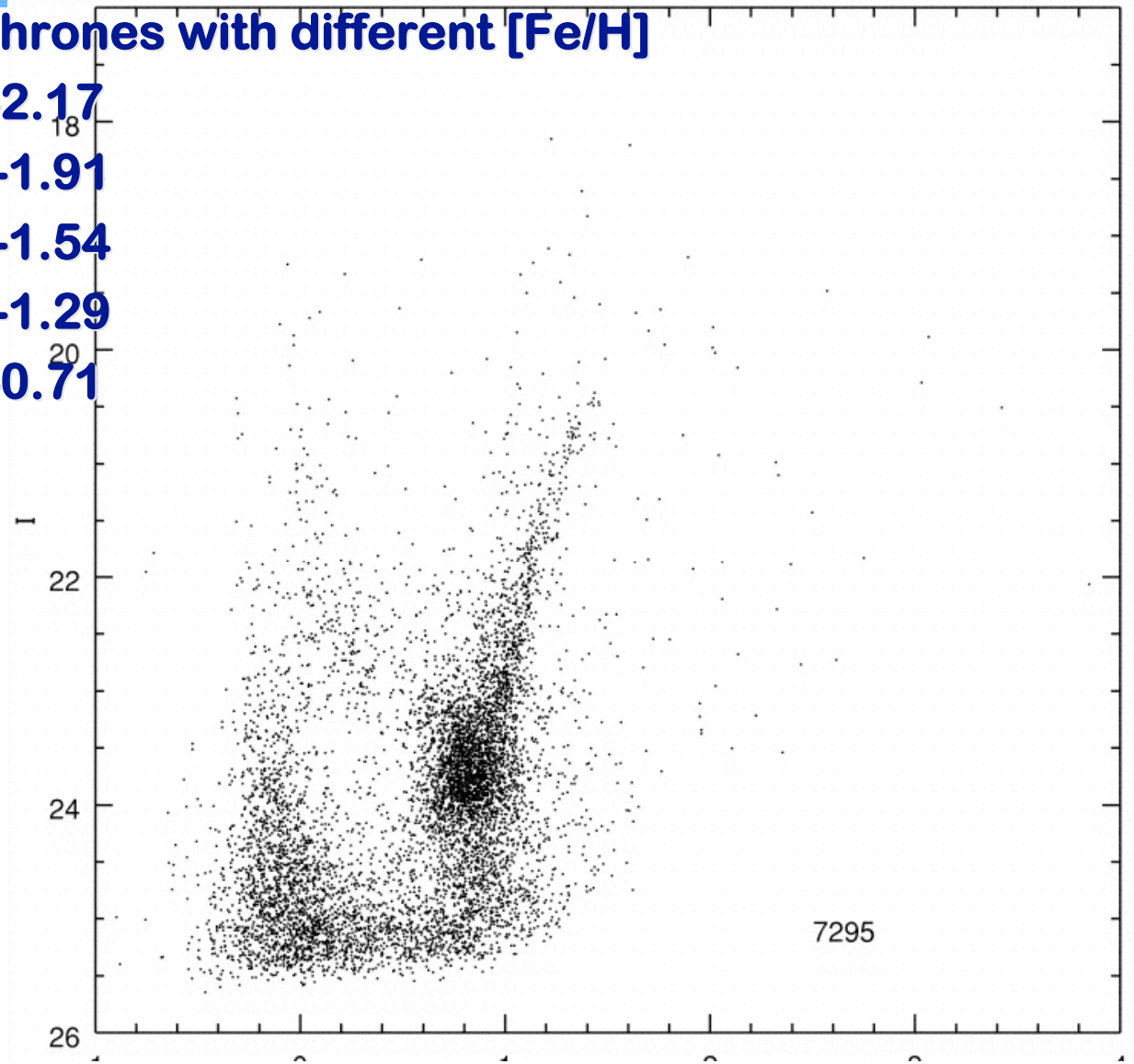
Tolstoy et al. 98: HST WFPC2 imaging of LeoA, D=?

- ☆ 2 different distance moduli
- ☆ 5 GC isochrones with different [Fe/H]

M15	-2.17
NGC 6397	-1.91
NGC 6752	-1.54
NGC 1852	-1.29
47 Tuc	-0.71

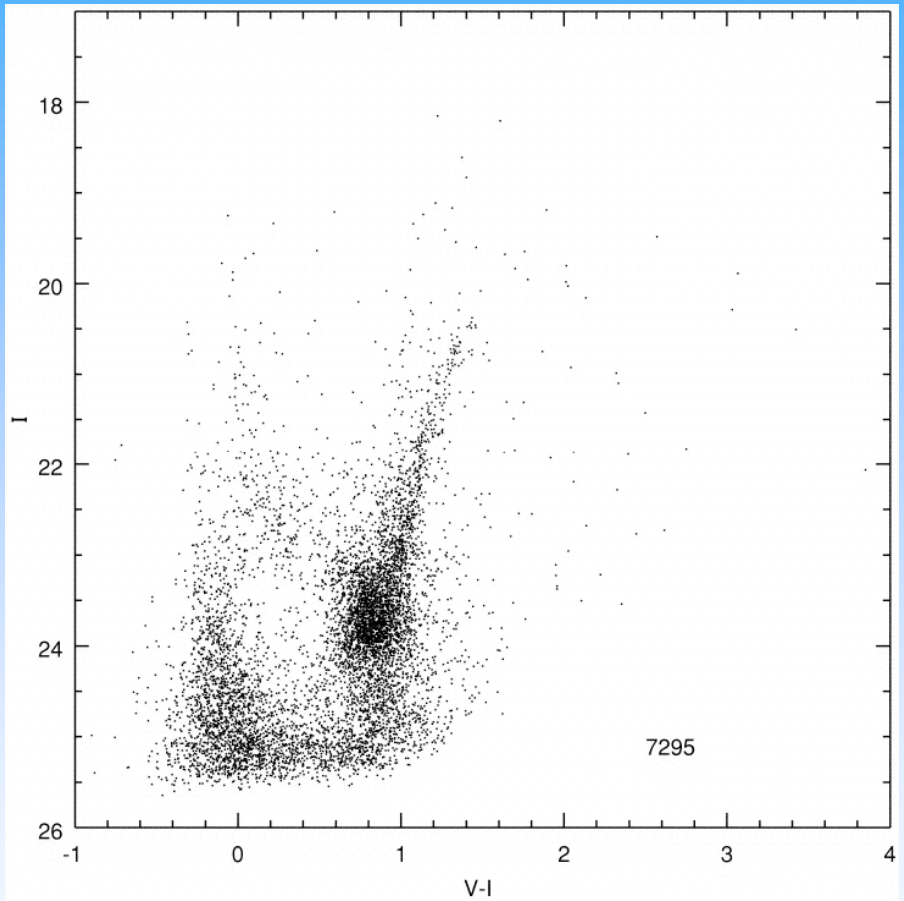


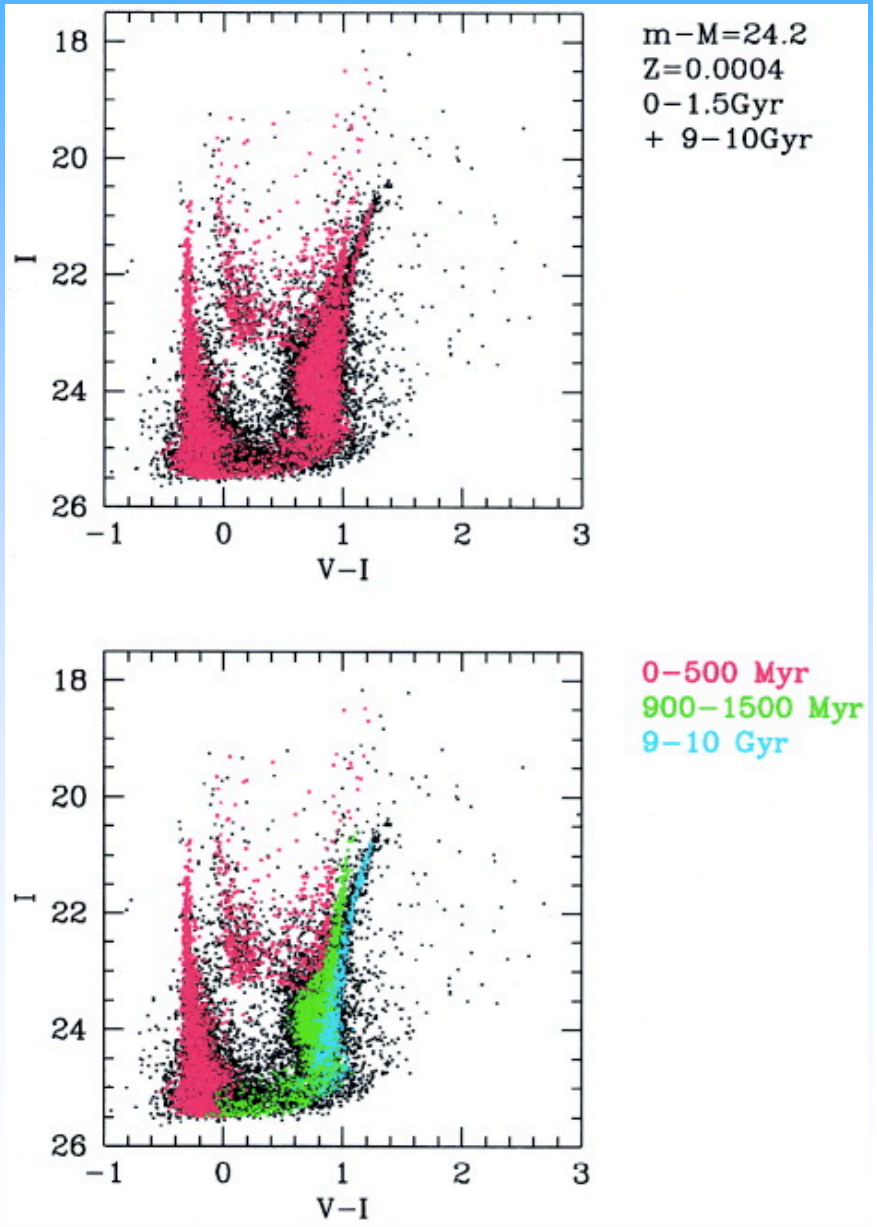




CMD Analyses of dIs

Tolstoy et al. 98: HST WFPC2 imaging of LeoA, D=?



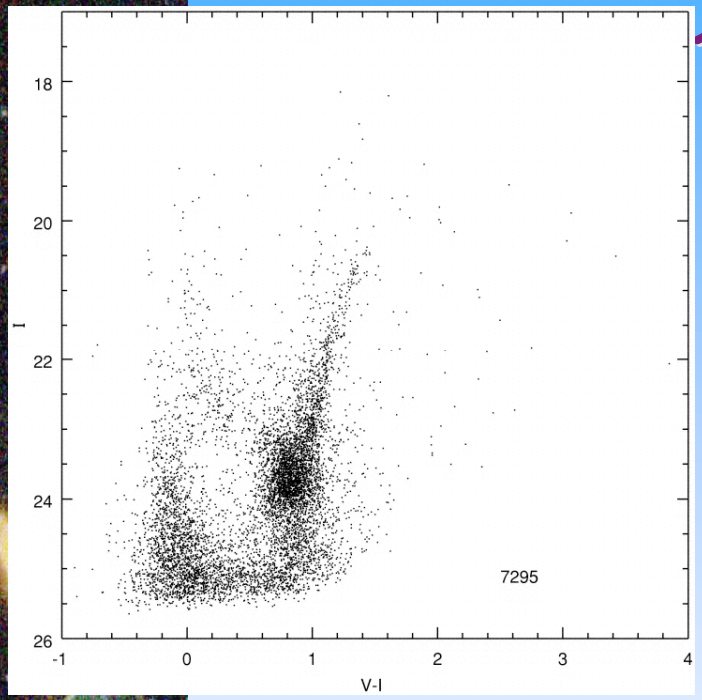


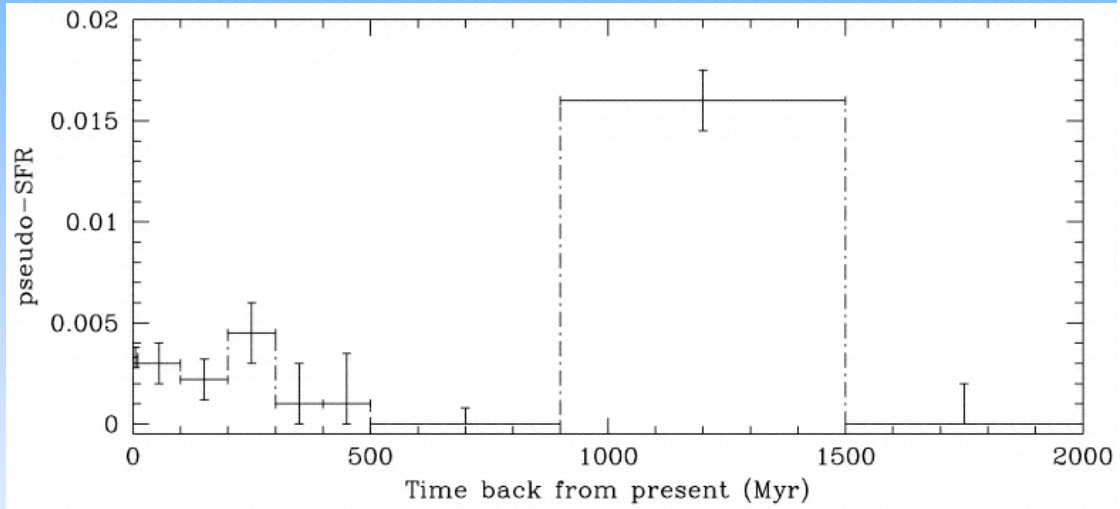
CMD Analyses of dIs

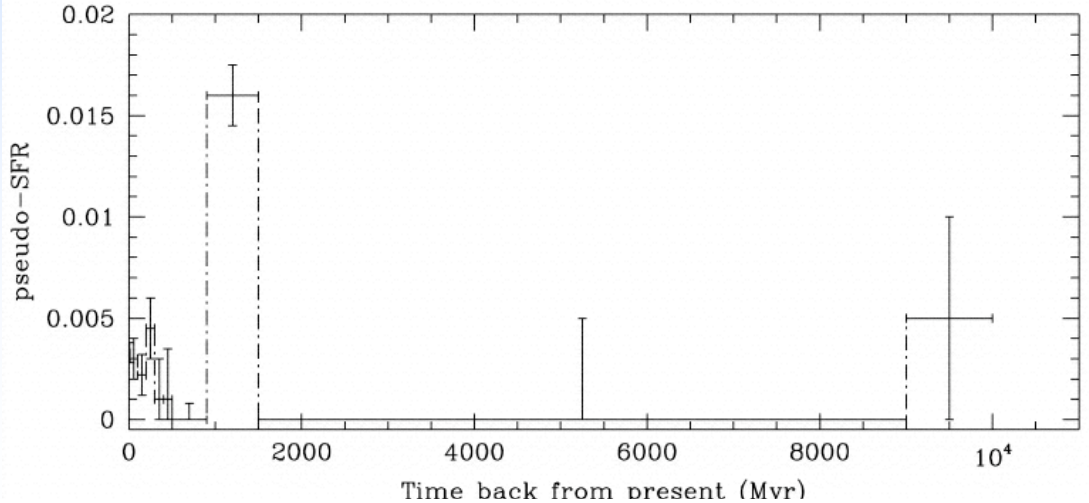
Tolstoy et al. 98: HST WFPC2 imaging of LeoA, BDM=24.2

12 + log (O/H) = 7.3 +/- 0.2 (2.4% solar)

(from Skillman+89, PNe)

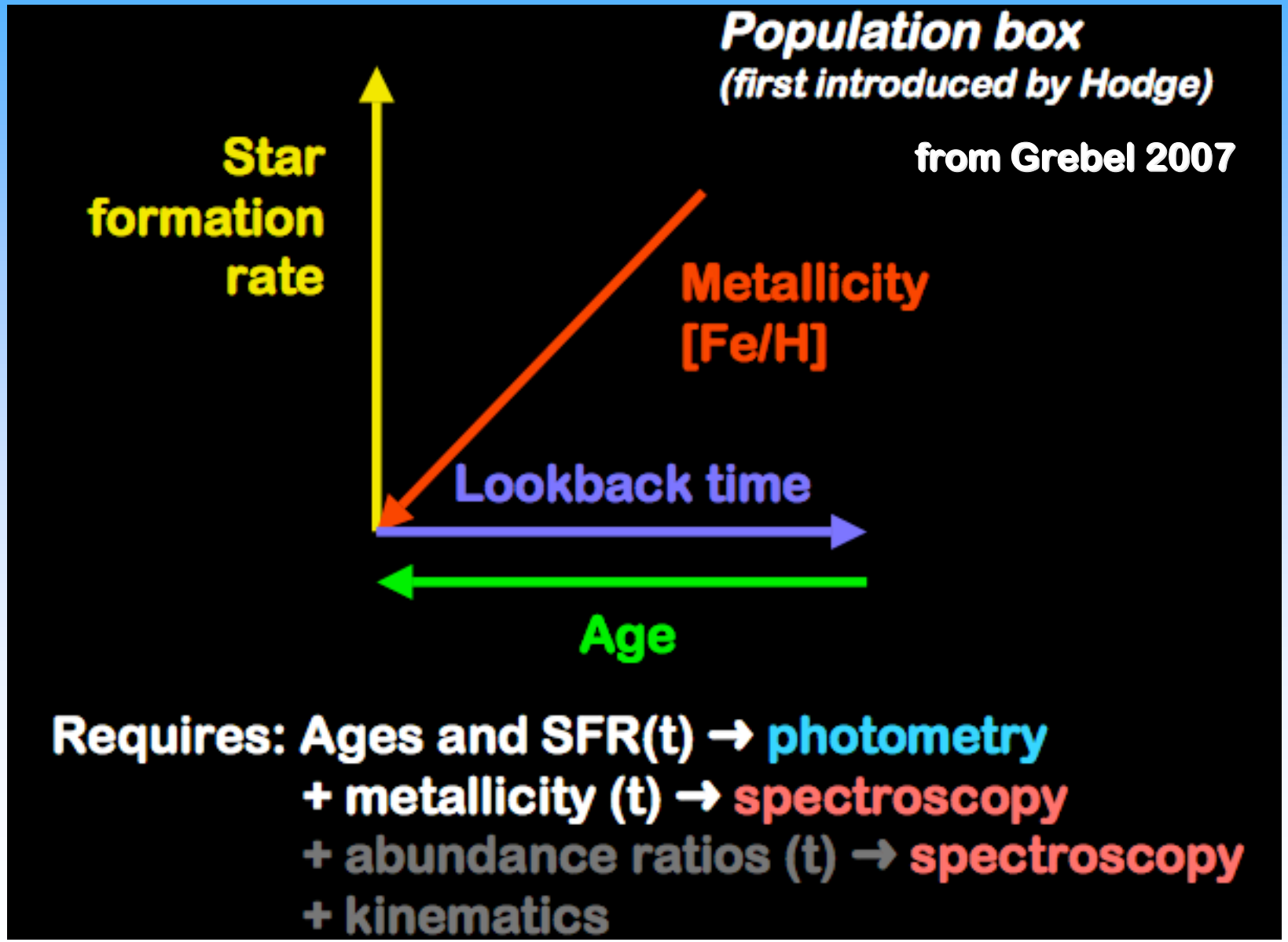






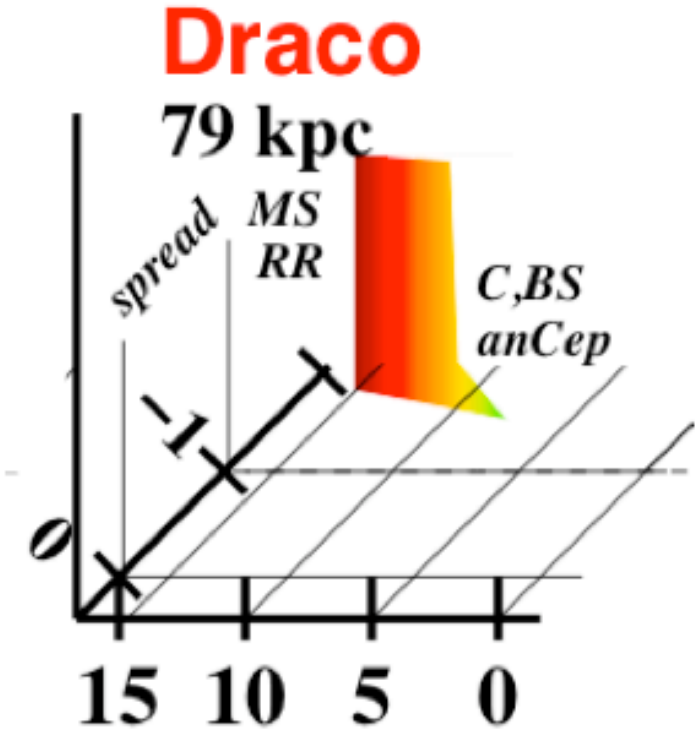
SF history for lookback time ~2 Gyr

The SFHs of Dwarf Galaxies

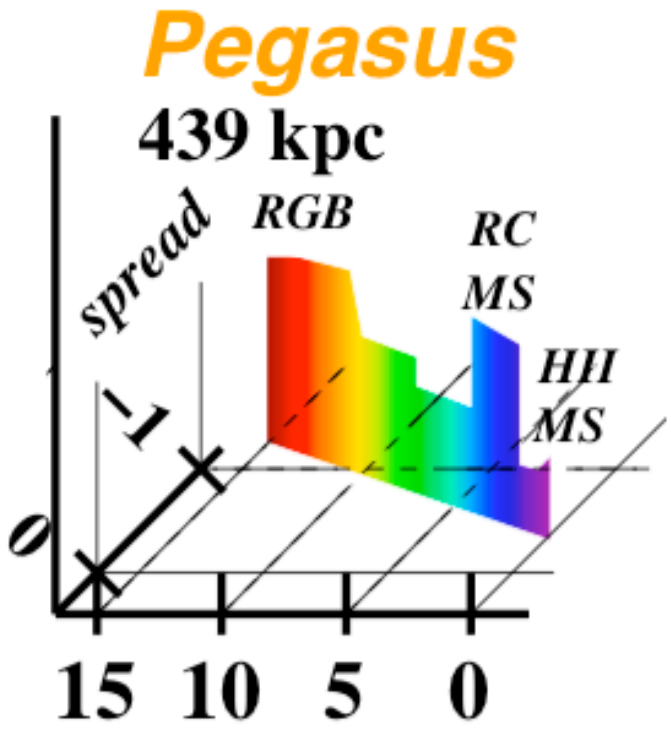


The SFHs of Dwarf Galaxies

from Grebel 2007



of a dSph

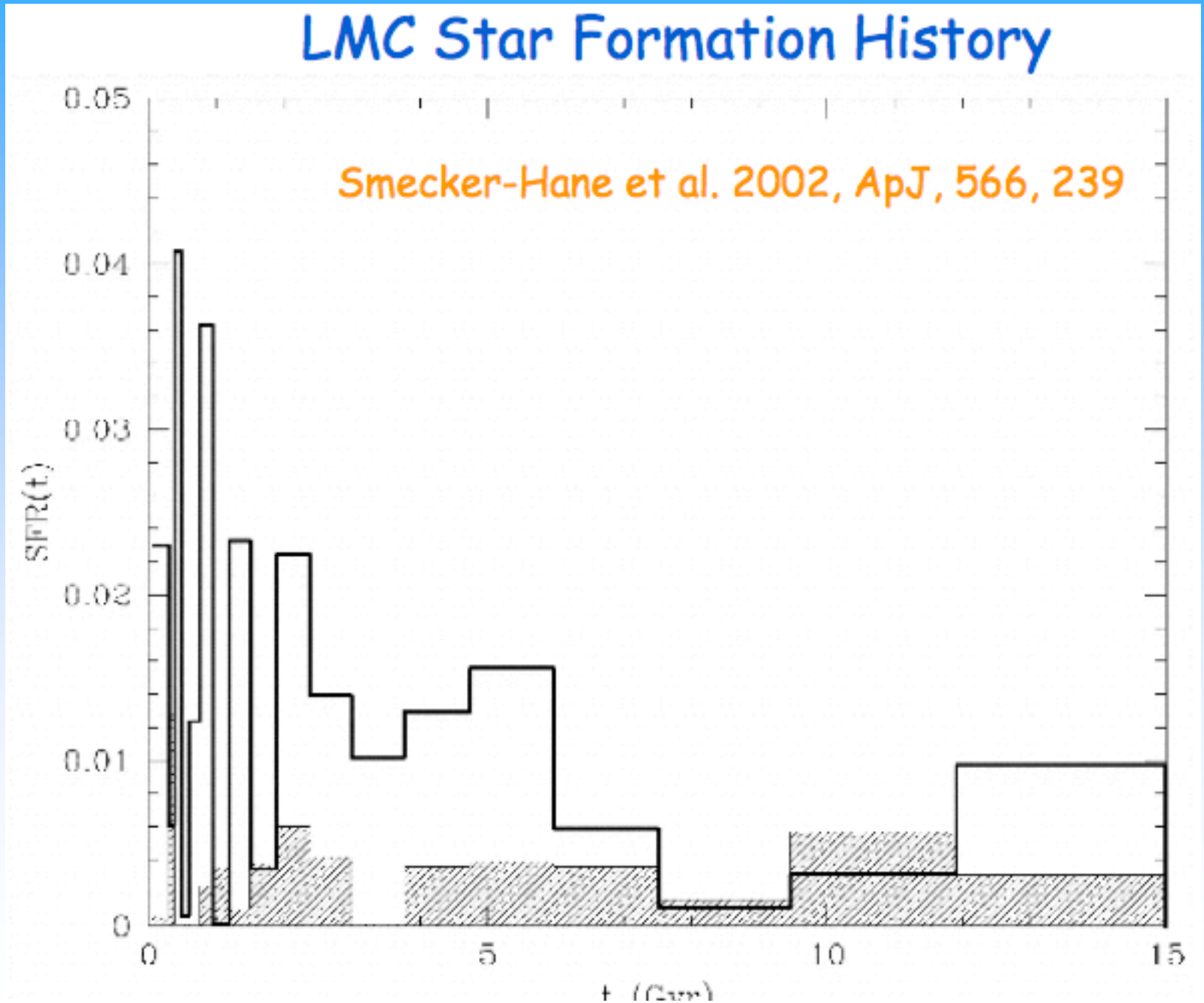


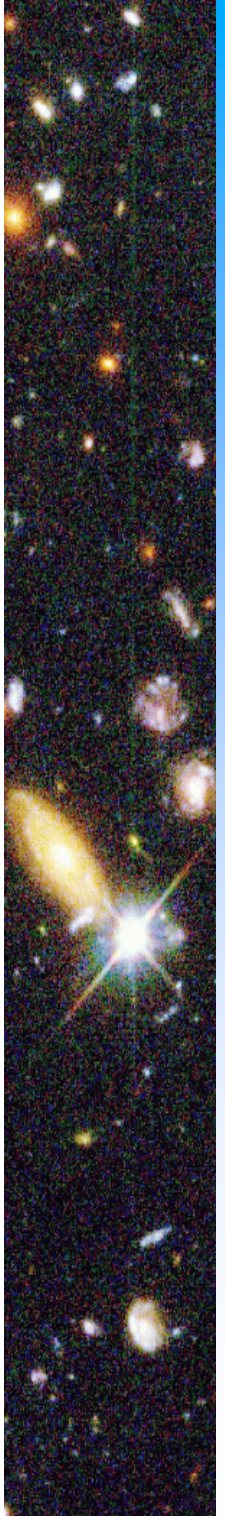
of a dIrr

(Note: even within the same type, each dwarf has its own, unique star formation history; no two dwarfs are alike.) Grebel 1997

Dwarf Irregular Galaxies dIs

Dwarf Irregular Galaxies : LMC





Dwarf Irregular Galaxies : LMC

- **Field stars**
  - LMC contains outer halo of old field stars and globular clusters
  - evidence for large star formation events 3-10 Gyr ago
  - peak in star formation occurred in last 3 Gyr
- **Clusters and asssociations**
  - age distribution is bimodal, with gap between 3-10 Gyr (field stars show different behavior)
  - LMC contains population of massive young "blue globular clusters", and supergiant HII regions

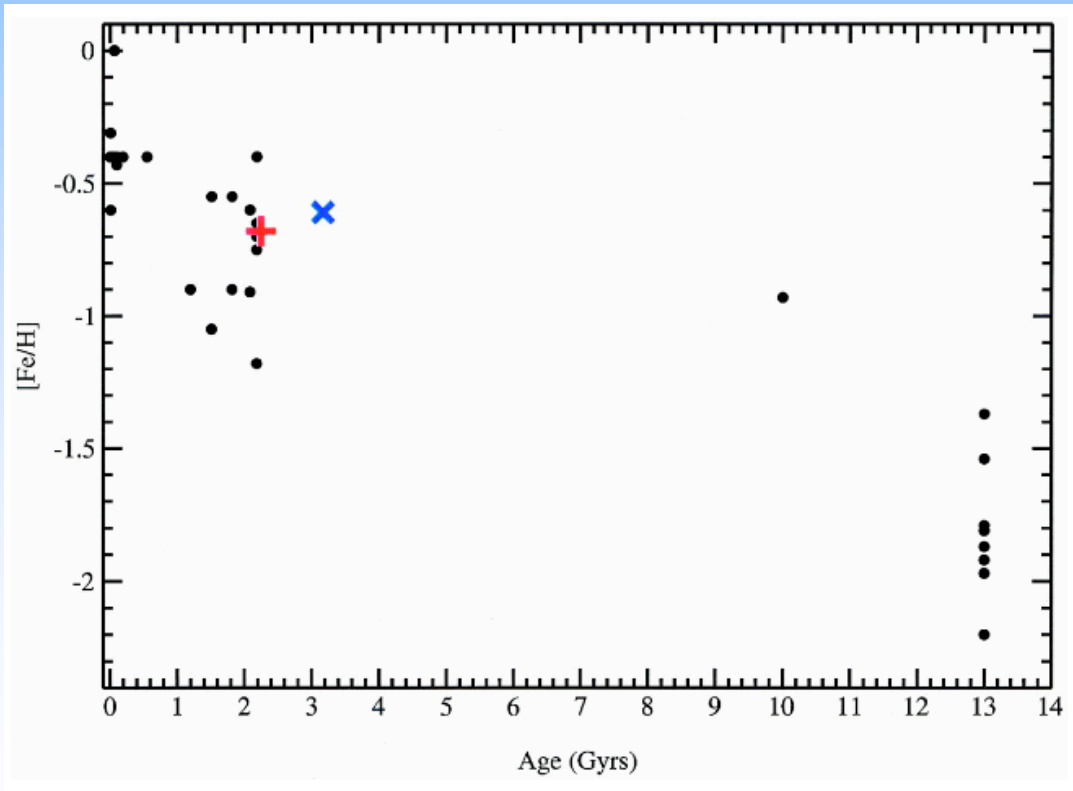
Dwarf Irregular Galaxies : LMC

Star clusters in the LMC show age gap : 10 - 3 Gyr ago

-- not seen in field stars

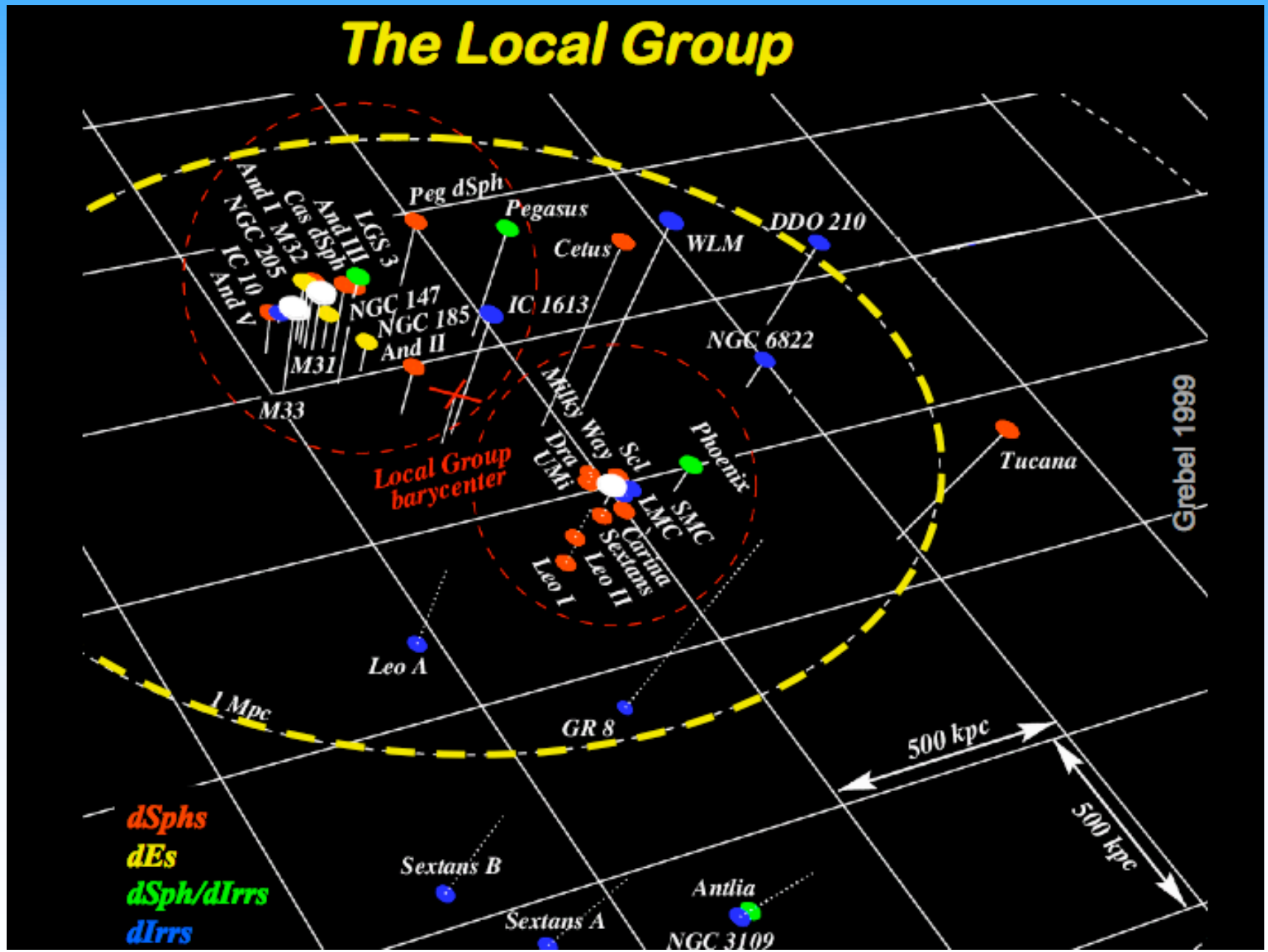
-- chemical enrichment continued

➜ Formation of long-lived star clusters only during peak SF phases

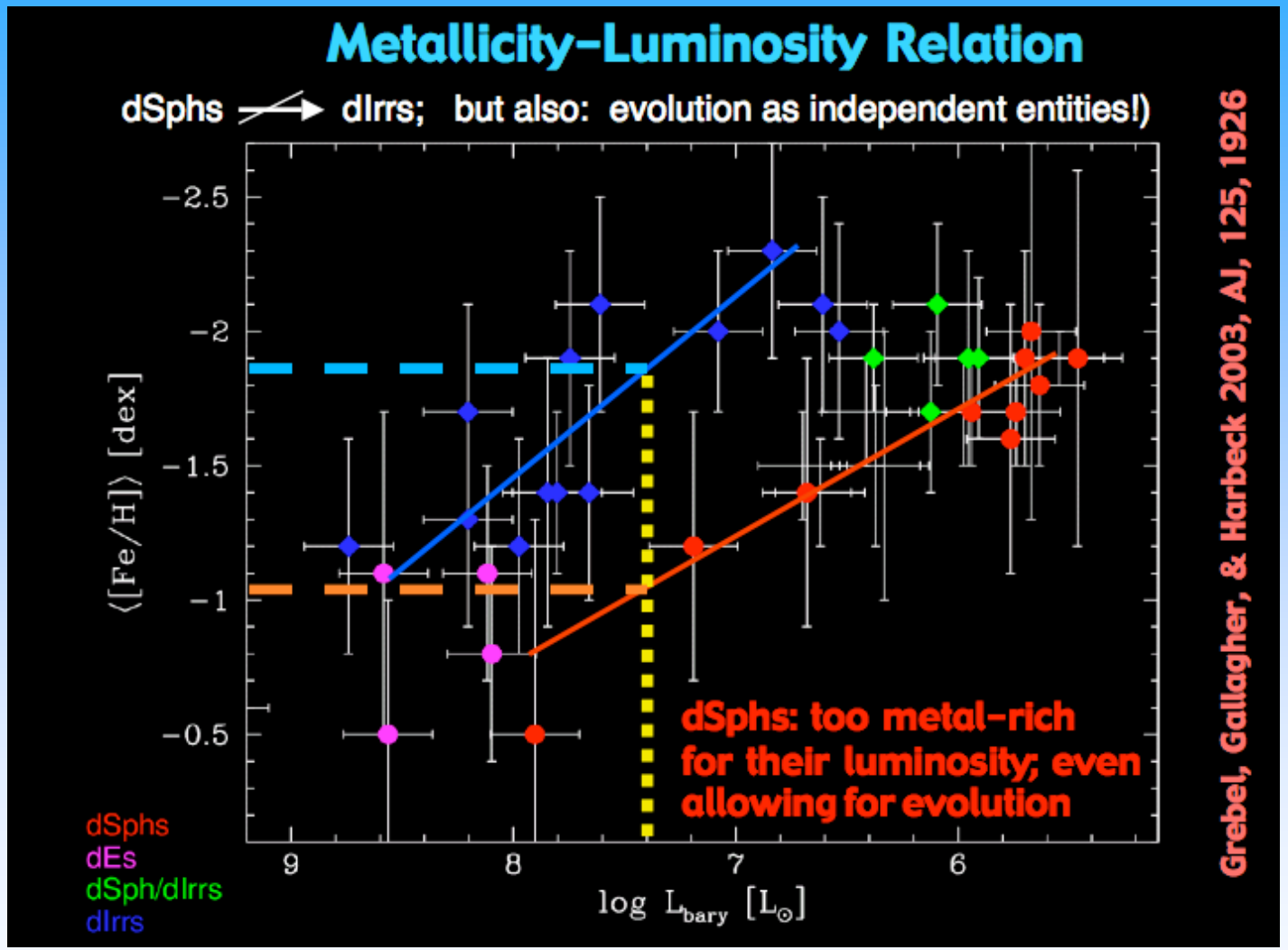


-- related to close passages of SMC and Milky Way ! ?

The Local Group

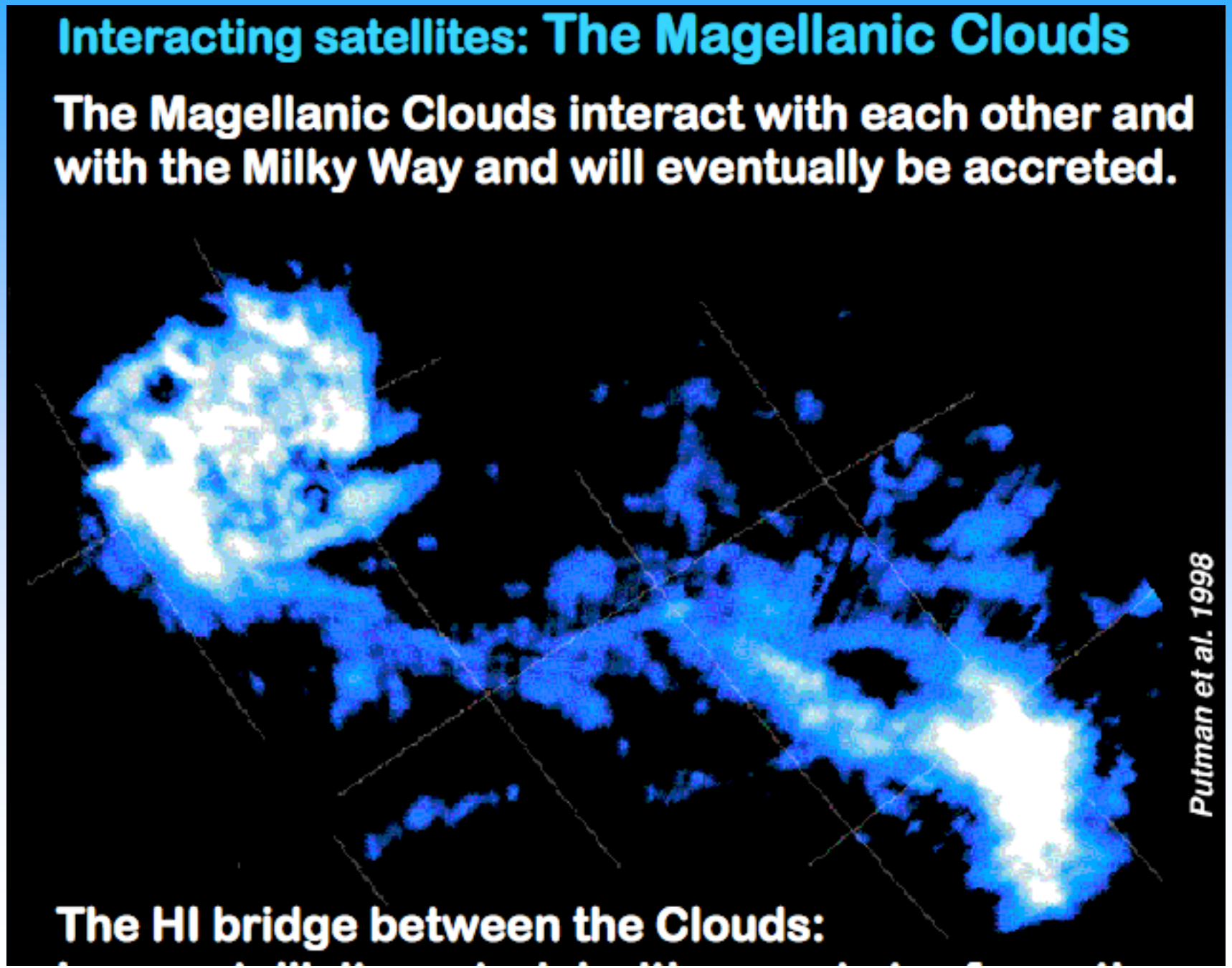


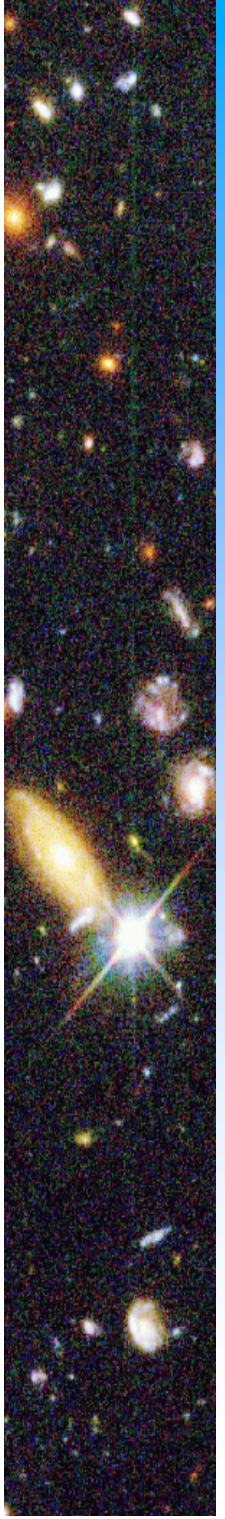
Dwarf Galaxies in the Local Group



dSphs more massive before ? got shred down by tidal forces & past close passages to the MW ?

The LMC -- SMC -- Milky Way System





The Fate of the Local Group (Forbes+00)

The elliptical galaxy formerly known as the Local Group

MW and M31 will probably merge in ~ 4 Gyr

by that time they will have swallowed all their smaller comp.

➜ normal field elliptical

When young stellar pops will have faded: $M_V \leq -21$.

The Globular Clusters will survive.

[Gas-rich mergers may produce new GCs]

Collect all 700 Local Group GCs with their luminosities (+fading) and metallicities [Fe/H]

➜ ~ universal GC Luminosity Function

➜ ~ normal bimodal GC [Fe/H] distribution with peaks at [Fe/H] = -1.55 & -0.64

MP / MR = 2.5 / 1 MP metal-poor, MR metal-rich

➜ ~ normal GC specific frequency $S_N = N_{GC} \cdot 10^{0.4(MV+15)} \sim 3$

The Fate of the Local Group (Forbes+00)

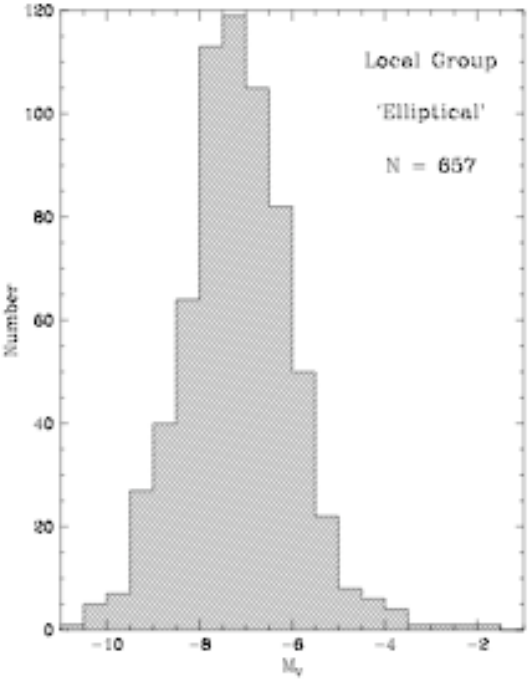


Fig. 1. Absolute magnitude distribution for the Local Group 'Elliptical'. The distribution resembles the 'universal' globular cluster luminosity function.

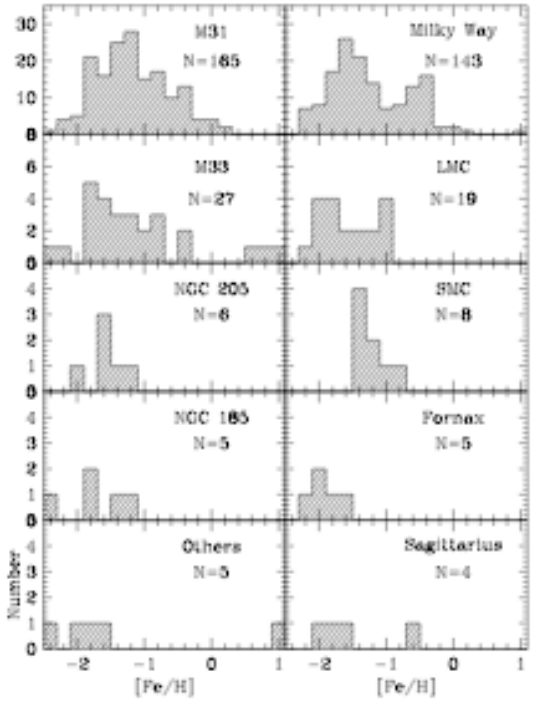


Fig. 2. Metallicities of Local Group globular clusters. The number of available globular clusters with individual measurements is indicated in each panel.

Local Group merger

➜ normal field elliptical

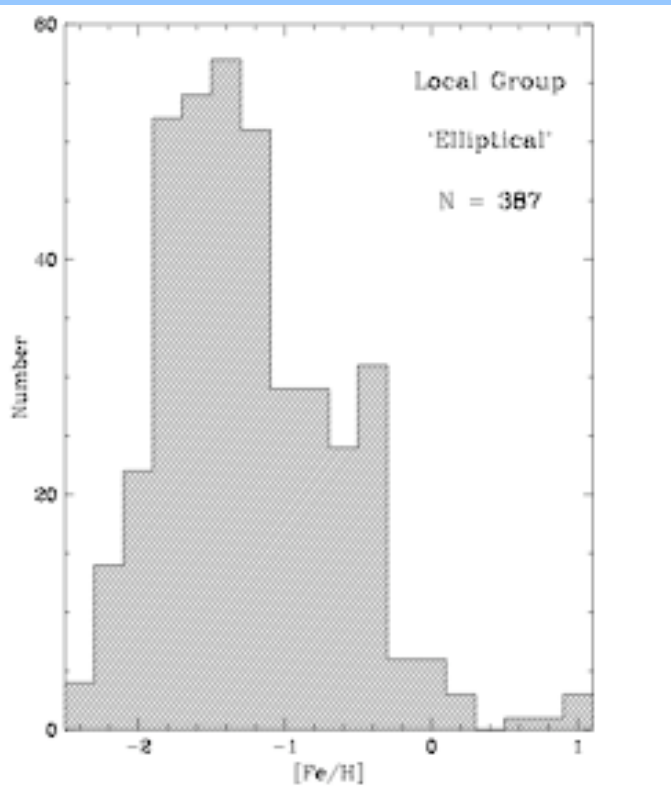


Fig. 3. Metallicity distribution for the Local Group 'elliptical'. The distribution reveals two peaks at [Fe/H] = –1.55 and –0.64.