Comparing the Local and Cosmic Star Formation Histories:

Local Cosmology from Isolated Dwarf Galaxies

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and the LCID collaboration (http://www.iac.es/project/LCID)

❑ *Goals:*

- **Calculate the integral Star Formation History of the Local Group and other nearby galaxies via analysis of their resolved stellar populations ("fossil records" study).**
- **Compare the recent star formation density of the Local Group with the larger nearby volume via the emission line and UV-Blue luminosities. This will allow us to evaluate if the Local Group is representative of the local universe mean.**
- **Match the Local and Cosmic (measured through surveys of distant galaxies) SFHs. The quantity being compared is the comoving space density of the star formation rate as a function of look-back time. The early epoch (look-back time > 10 Gyr) of the star formation is of particular interest.**

❑ *High-redshift surveys*

- **We are living in an exciting era of observational cosmology in which a huge effort is devoted to studies of galaxy formation and evolution using observations of distant, or high-redshift, galaxies. These surveys are looking for signs of recent star formation in the galaxies at different cosmic epochs. One drawback of this approach is that it is not directly possible to connect different galaxies, measured at different redshifts, into a coherent evolutionary sequence, to provide a consistent picture of *observed* galaxy evolution. The detail in which these galaxies can be studied is moreover limited since they are mostly unresolved, and their faintness limits the wavelength resolution of spectroscopic measurements.**

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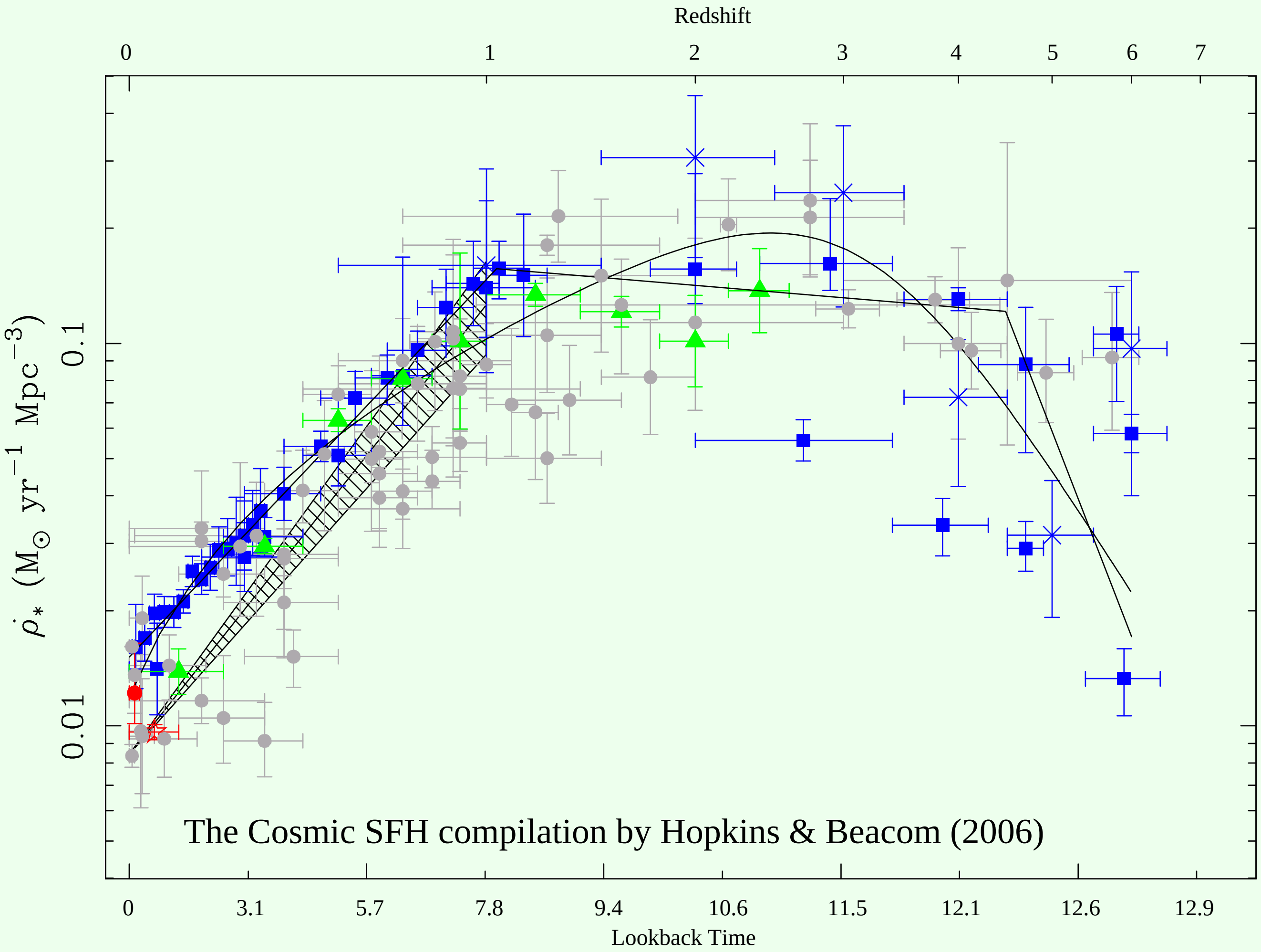
- **Uncertainties in star formation rate (SFR) calibrations and in normalization.**
- **Extinction corrections at optical and near-infrared wavelengths.**
- **The different selection criteria of various contributing surveys.**

❑ *The Cosmic Star Formation Rate Evolution*

In the last decade measurement of the Cosmic SFH has tremendously progressed:

- a consistent picture of the SFH out to z~6, with especially tight constraints for z<1.
- growing evidence that the evolution is essentially flat beyond z=1
- for z>3 it is still unclear whether the evolution flattens, declines, or continues to increase.



An alternative, and complimentary, approach focuses on galaxies nearby enough to be resolved into their component stars.

- **Stars retain memory of initial/early conditions from the time of their birth — age, chemical abundances, and orbital angular momentum (modulo resonances, torques).**
- **The stellar evolution theory of majority of evolved stars is well established.**
- **The faint ($M_V \sim +4.5$, $M_K \sim +3$) low-mass stars (like the Sun), with a main sequence lifetime that is of order the age of the Universe, is a key component to derive the early, initial SFH of a galaxy — studying evolved stars allows us to do Cosmology locally.**

❏ *Tools:*

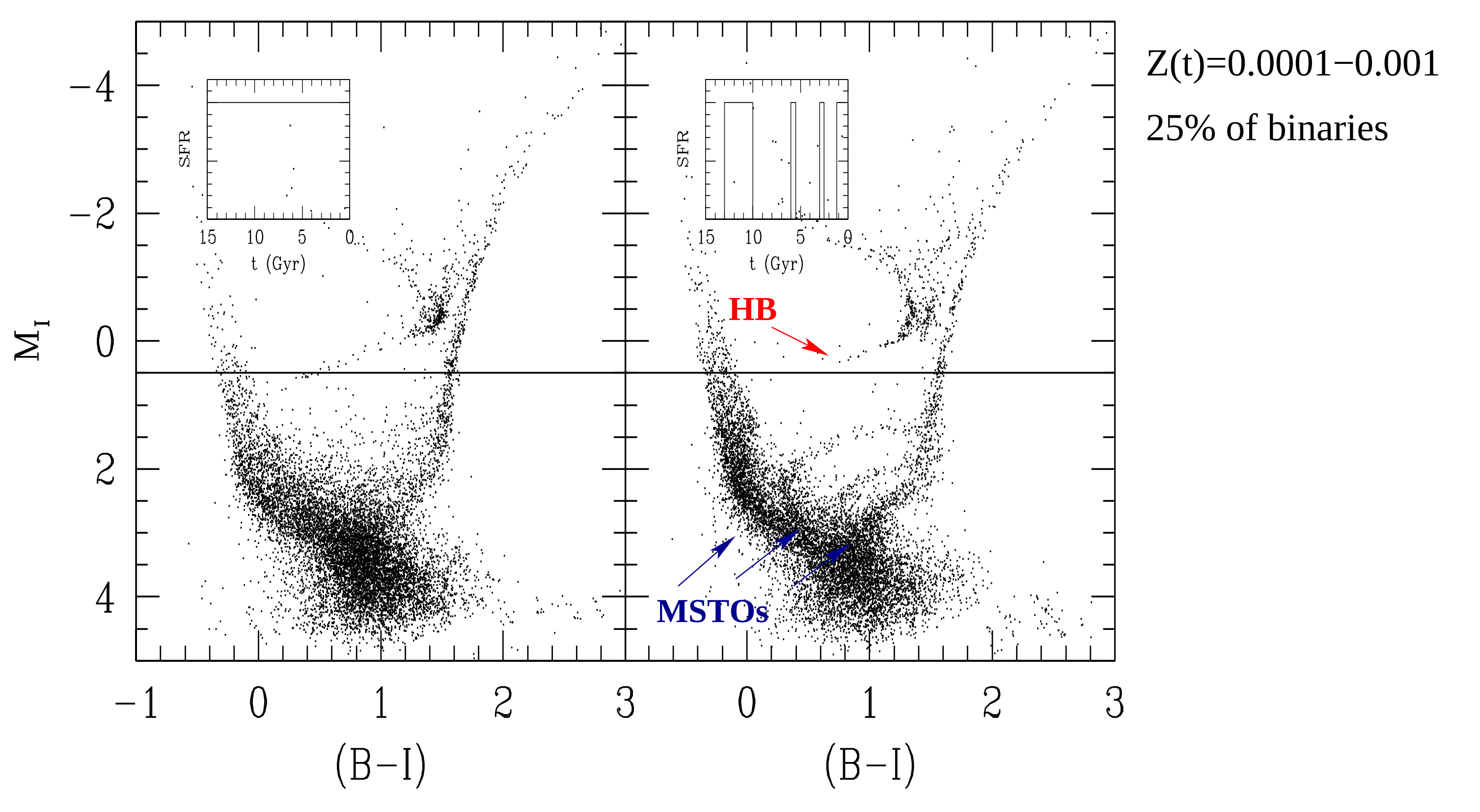
$$\text{Star Formation History} = \begin{cases} \bullet \text{ Color} - \text{Magnitude Diagram} \\ \bullet \text{ Variable stars} \\ \bullet \text{ Spectroscopic abundances} \end{cases}$$

Method:

- **generate synthetic observations from model of stellar evolution, given a set of parameters (*e.g.*, age, metallicity, distance, reddening, binary properties, and IMF slope) describing the model stellar population.**
- **model the photometric errors and completeness, these are influenced by a combination of crowding and instrumental noise and are best estimated through artificial star tests.**
- **derive the star formation history by computing the likelihood that the observations are a representation of a given model.**

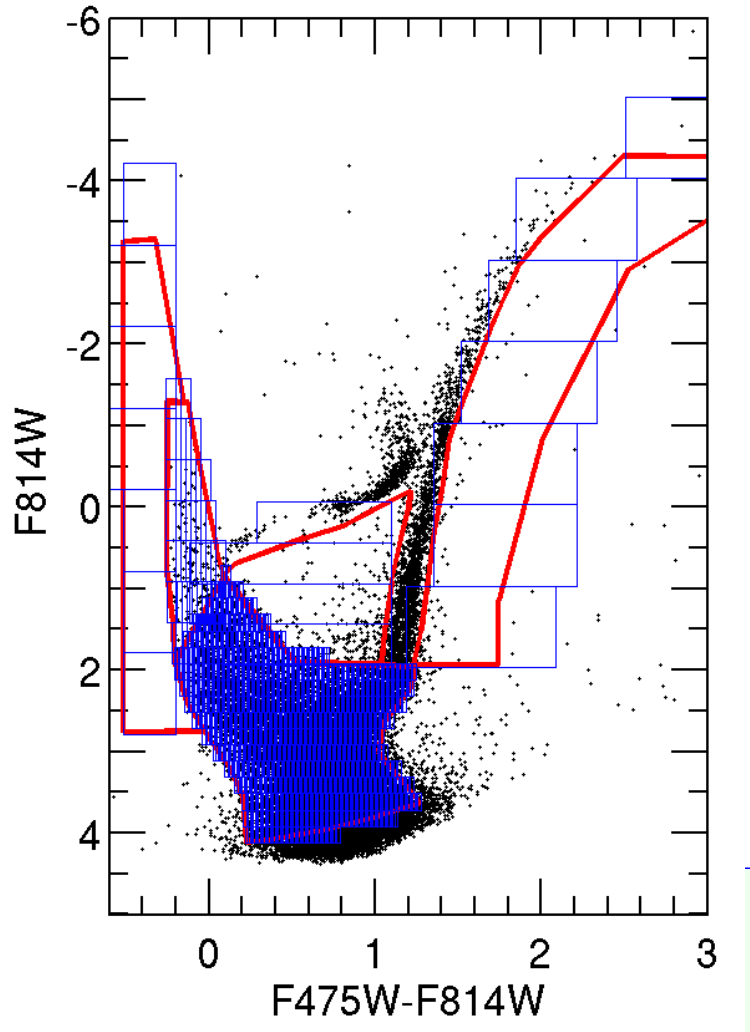
$$\text{Mass assembly} = \begin{cases} \bullet \text{ Stellar Population gradients} \\ \bullet \text{ Radial velocities} \end{cases}$$

The Importance of Deep Stellar Photometry



CMDs reaching the oldest MSTOs for two hypothetical galaxies with different SFHs shown schematically in the insets. Note that both stellar populations would be indistinguishable from a CMD reaching only the level of the HB.

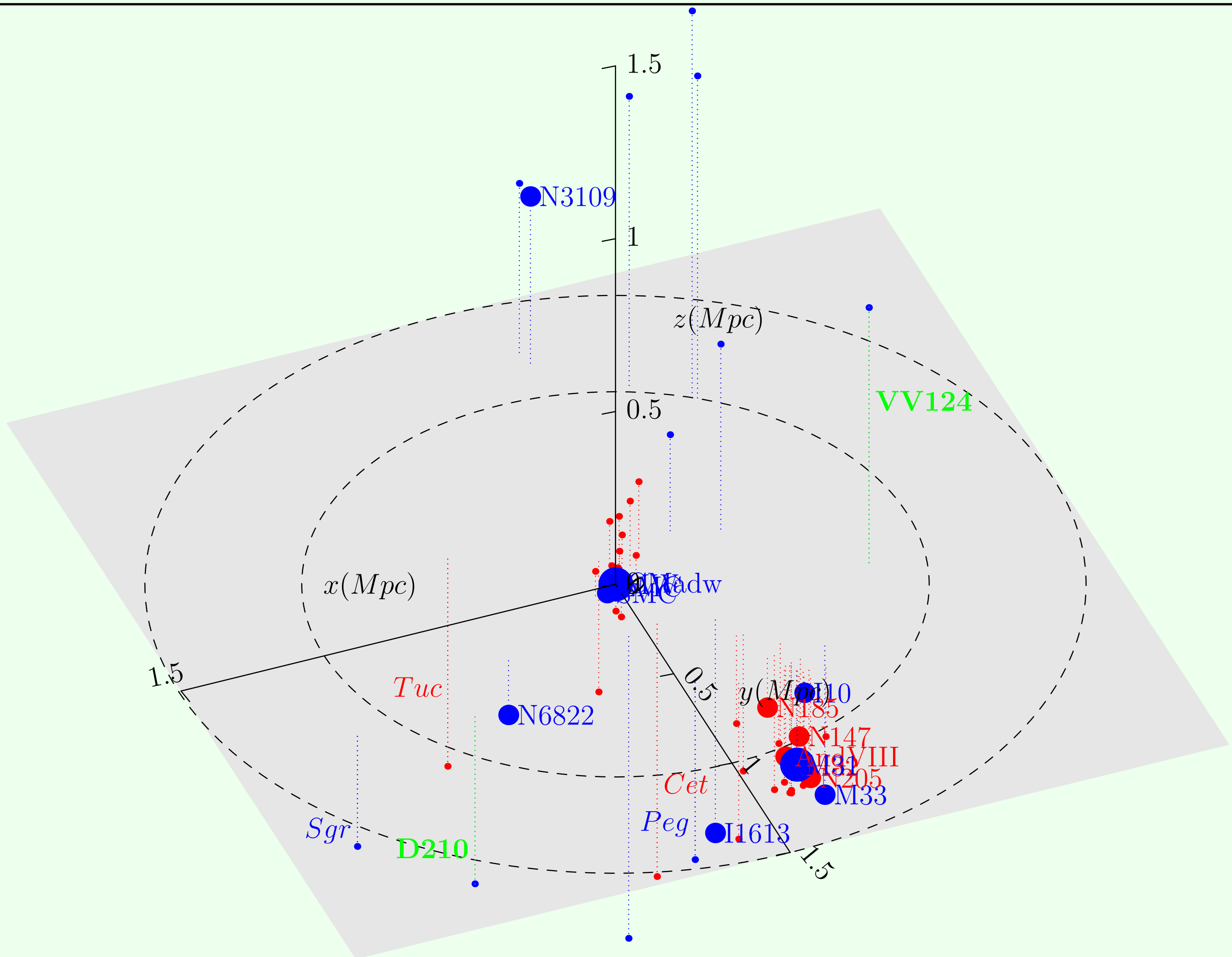
The Importance of Deep Stellar Photometry



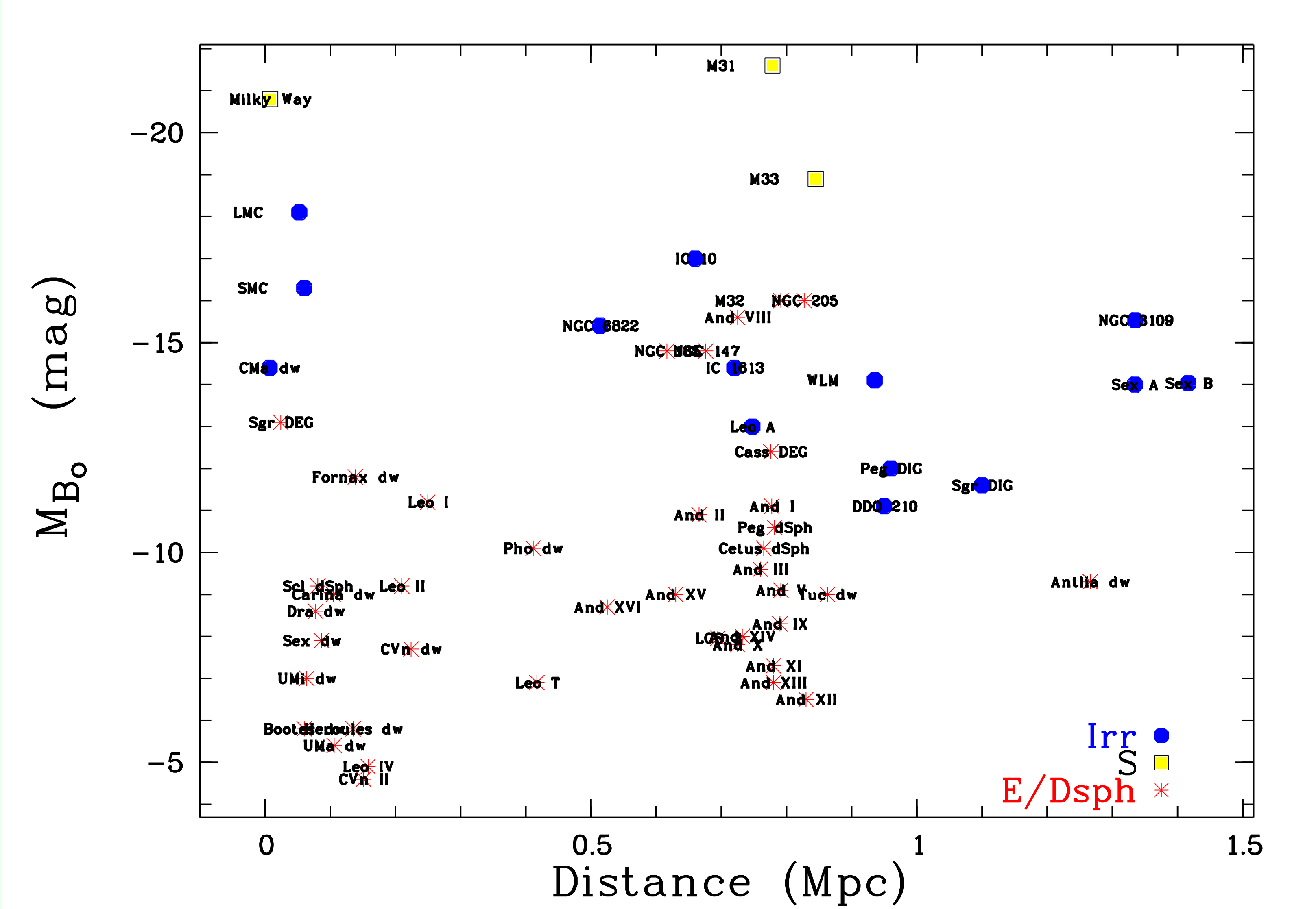
Meet the neighbors: the Local Group

The Local Group: **three spiral galaxies M31, M33 and the Milky Way, and numerous dwarf companions, both gas−rich and gas−poor. By resolving individual stars and measuring their age, kinematic and chemical properties one can study them in a detail and with a mass and spatial resolution that can only be dreamed of elsewhere.**

Meet the neighbors: the Local Group



Meet the neighbors: the Local Group



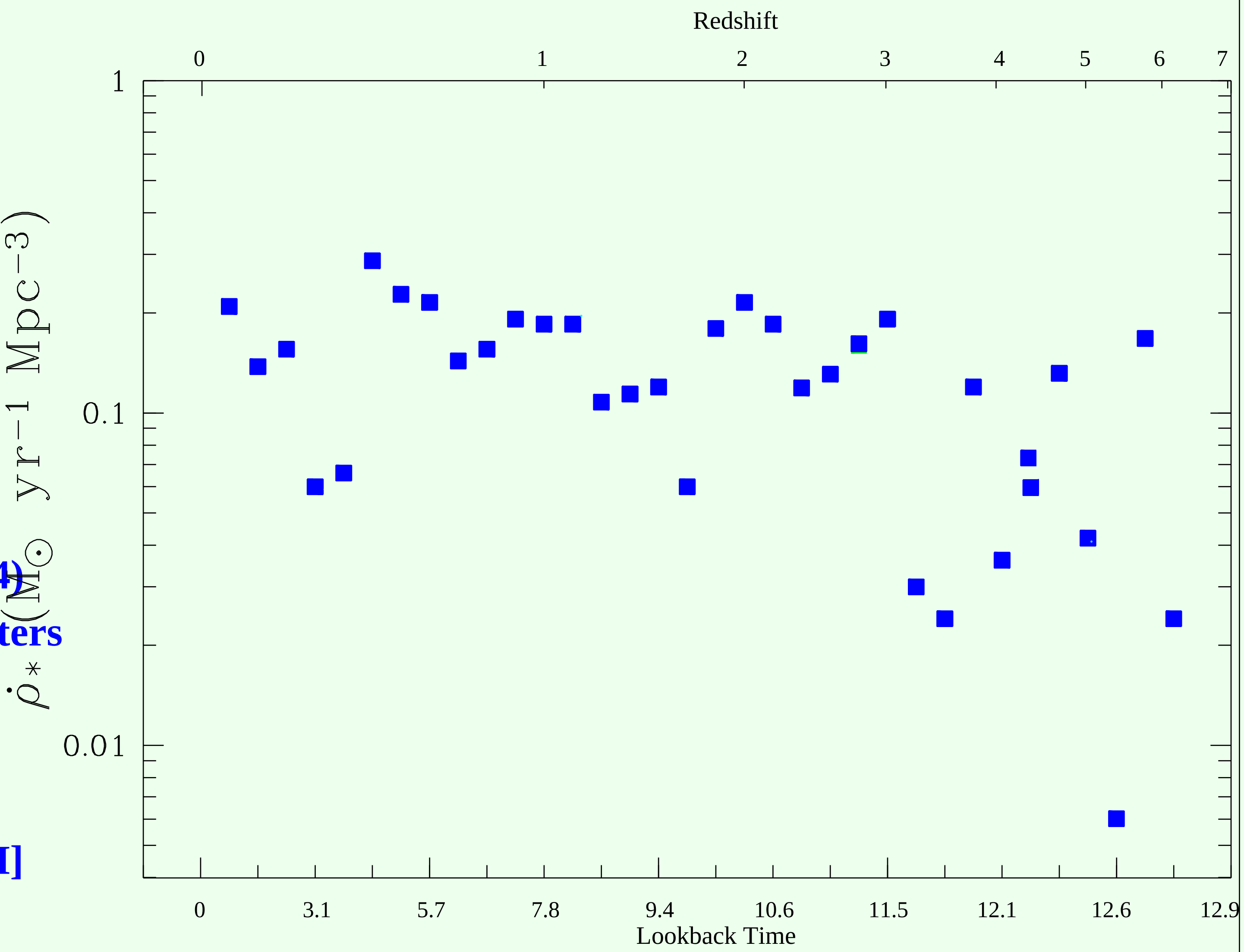
❑ *the Galaxy versus M31:*

Stellar Component	MW	Ref.	M31	Ref.
Disk mass ($10^{10}\mathcal{M}_\odot$)	3.6-5.4; (4.5)	1,2	7.8-10; (8)	1,3
Bulge mass ($10^{10}\mathcal{M}_\odot$)	1.0-1.3; (1.1)	1,2	$\sim$3	3
Halo mass ($10^{9}\mathcal{M}_\odot$)	$\sim$1	1	$\sim$1	1
Thin d. scale length (kpc)	2.5-3.5; (3)	1,4,5	5.5-6.1; (5.6)	1,5,6
Thick d. scale length (kpc)	$\sim$4	5	$\sim$5.9	5
Thin d. scale height (kpc)	0.3-0.4	1,5	0.3	1,5
Thick d. scale height (kpc)	$\sim$1	5	$\sim$1	5
Bulge r$^{1/4}$ length (kpc)	0.8	1	1.8	1
Total current SFR	1-5; (3)	4,7,8	0.4-1.0; (1)	6,9,10,11,12

(1) Widrow & Dubinski (2005); (2) Flynn et al. (2006); (3) Trentham (2005); (4) Naab & Ostriker (2006); (5) Hurley-Keller et al. (2004); (6) Barmby et al. (2006); (7) Avila-Reese et al. (2001); (9) Walterbros & Braun (1994); (10) Devereux et al. (1994); (11) Williams et al. (2003); (12) Gordon et al. (2006)

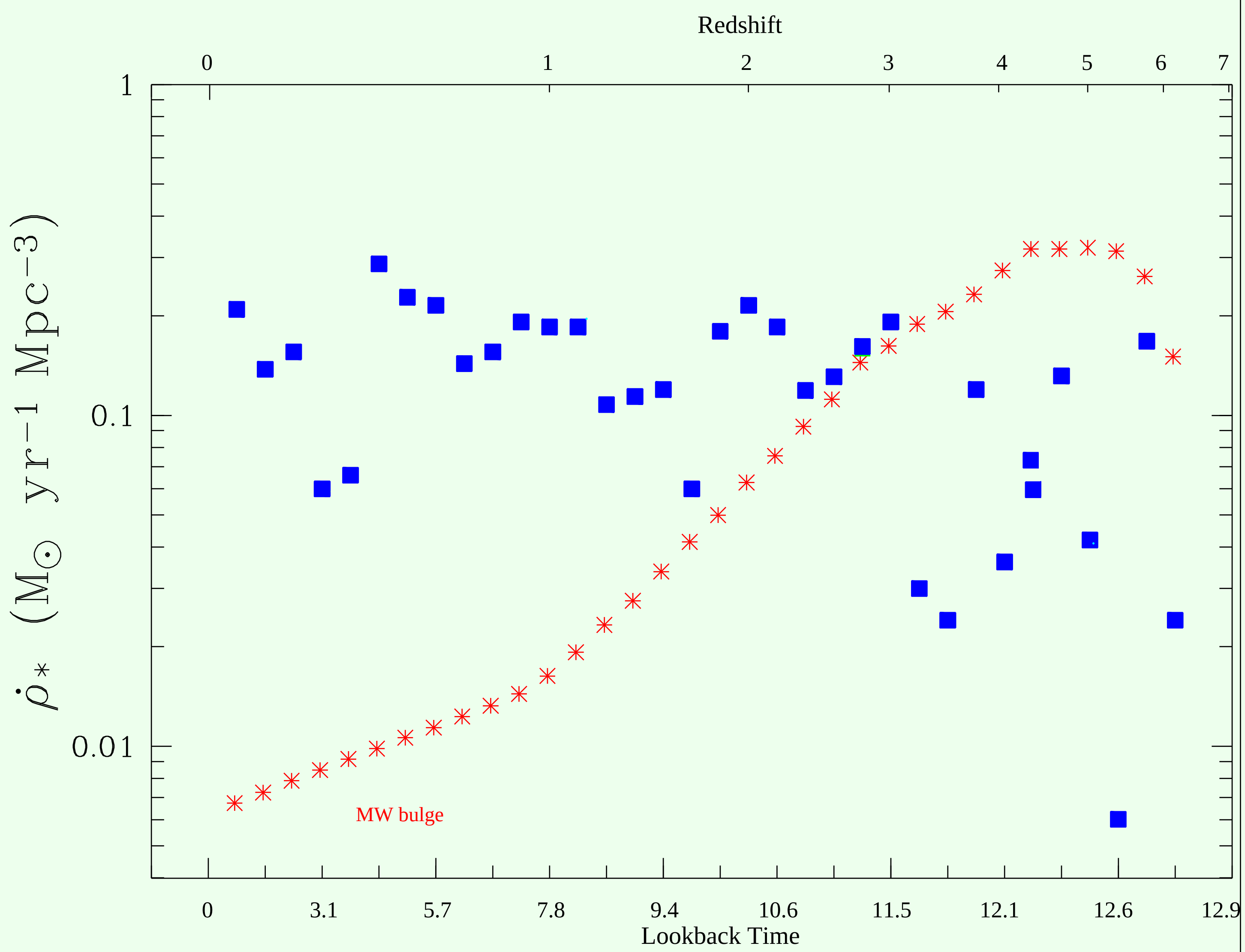
Comparing the Local and Cosmic SFHs

SFH of the MW disk:
compilation from
− Hernandez et al. (2000)
CMD modelling of the
SFH of the solar neighborhood
−Rocha−Pinto et al. (2000)
CaT abundances−vs−age
of 552 stars with Hipparcos
parallaxes
−de la Fuente Marcos et al. (2004)
age distribution of 580 open clusters
−Noh & Scalo (1990)
white dwarf luminosity function
−Kurbatov et al. (2007)
[Fe/O],[Eu/Ba],[Mg/Fe] vs. [Fe/H]



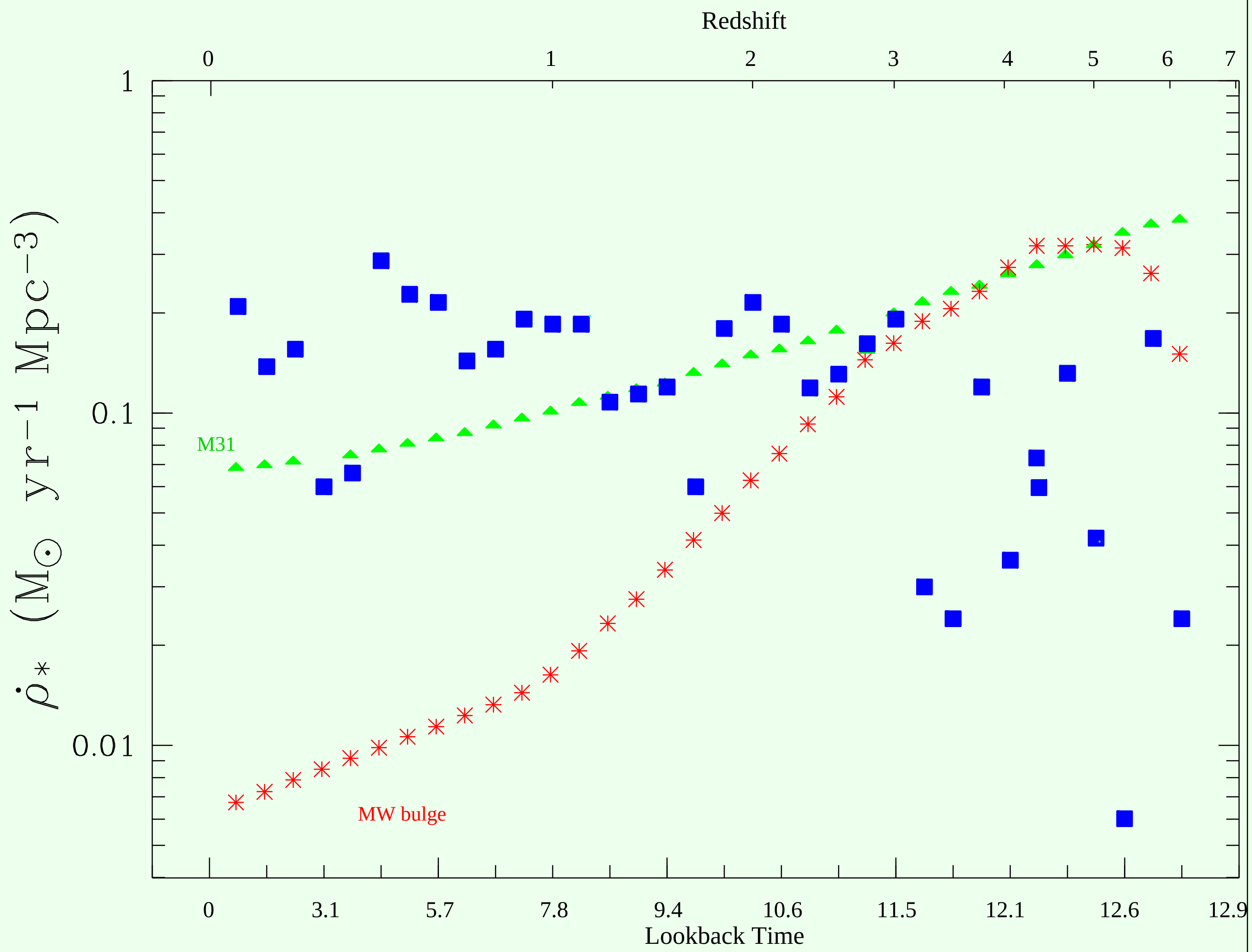
Comparing the Local and Cosmic SFHs

SFH of the MW bulge:
Prantzos & Silk (1998)
Feltzing & Gilmore (2000)
Blum et al. (2003)
Zoccali et al. (2003)
van Loon et al. (2005)



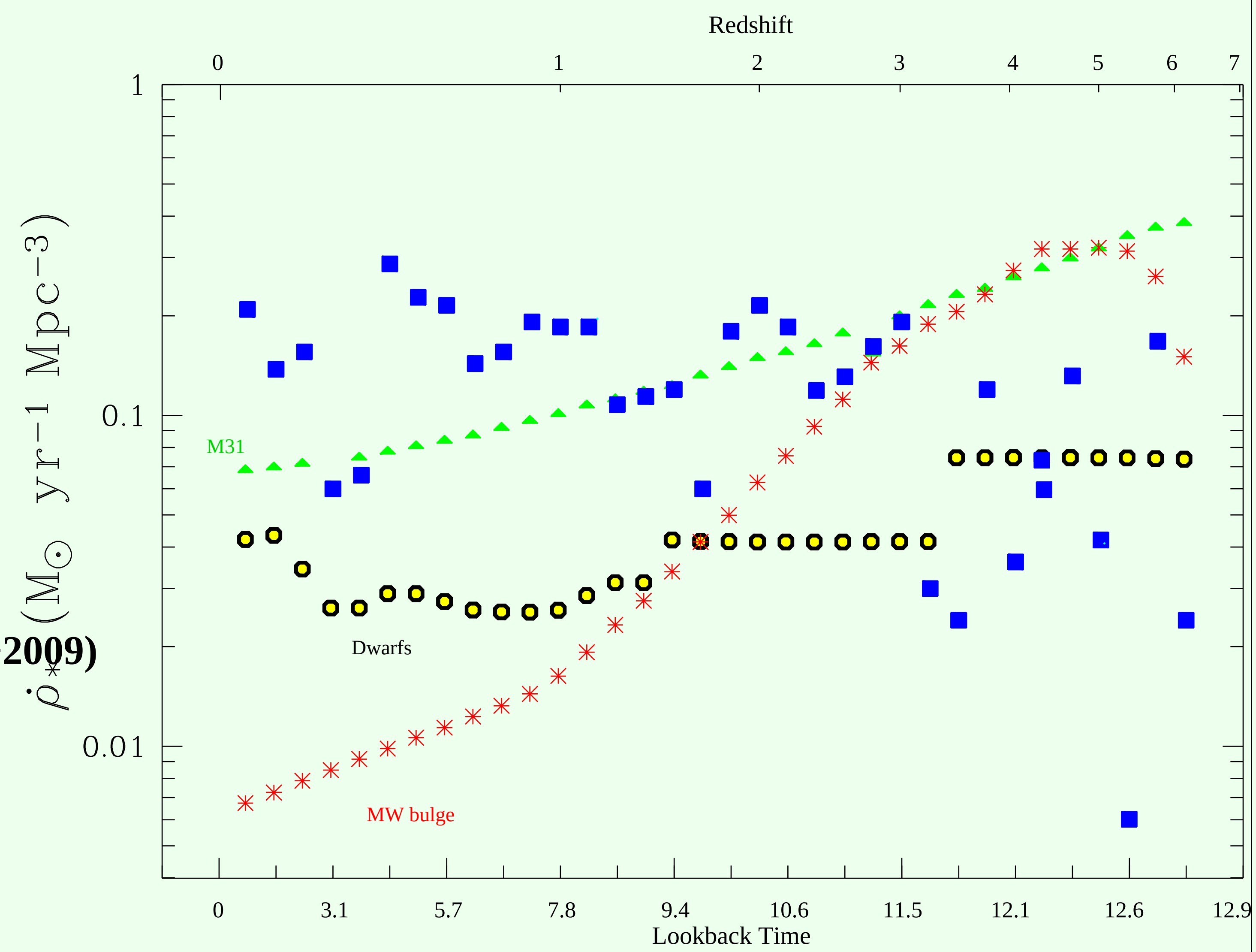
Comparing the Local and Cosmic SFHs

SFH of the M31:
compilation from
−Brown et al. 2003,2006,2007
−Sarajedini & Jablonka(2005)
−Olsen et al. (2006)



Comparing the Local and Cosmic SFHs

SFH of the LG dwarfs :
Matteo (1998)
Dolphin (2005)
Barker et al. (2007)
Tolstoy et al. (2009)
The LCID team results (2007−2009)



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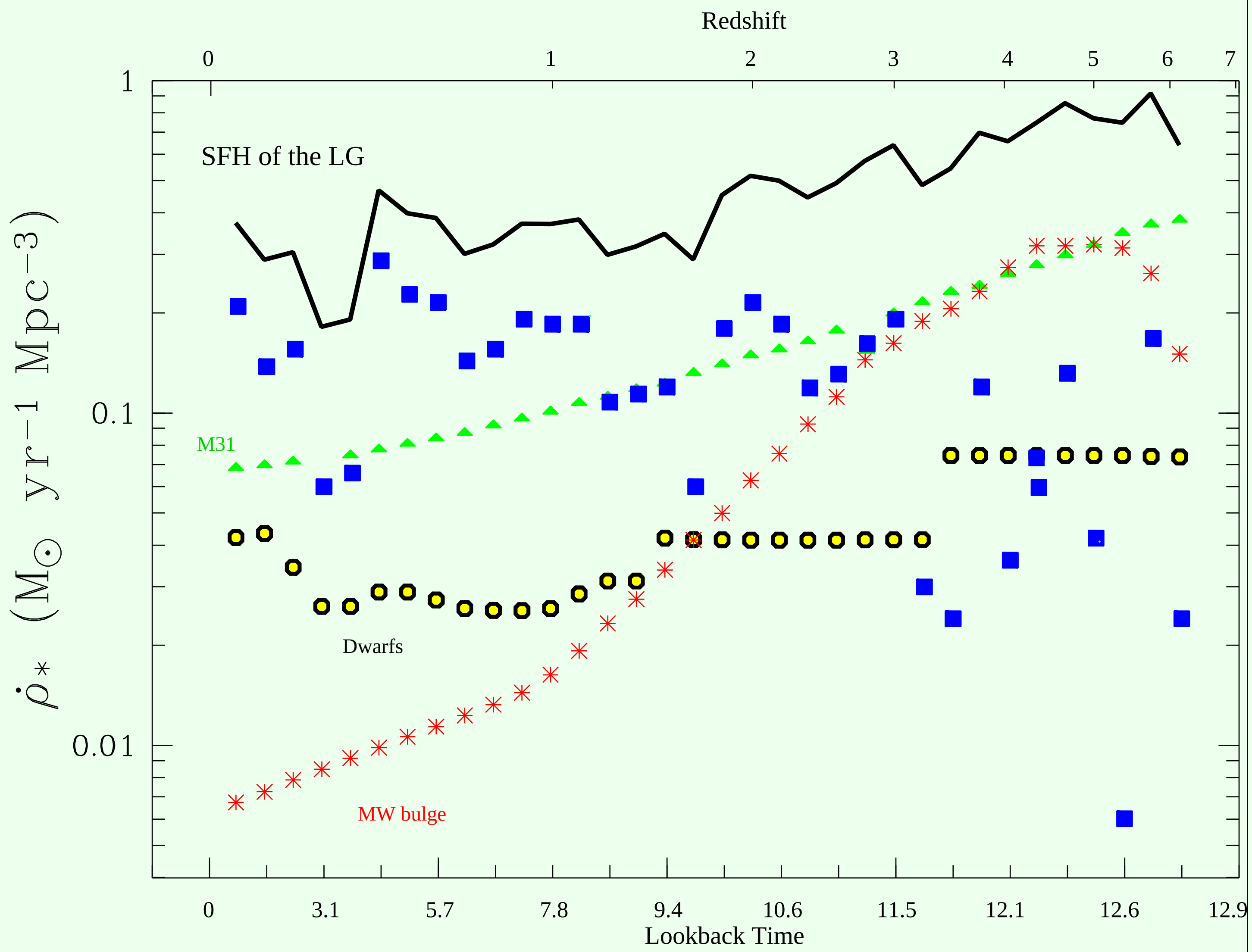

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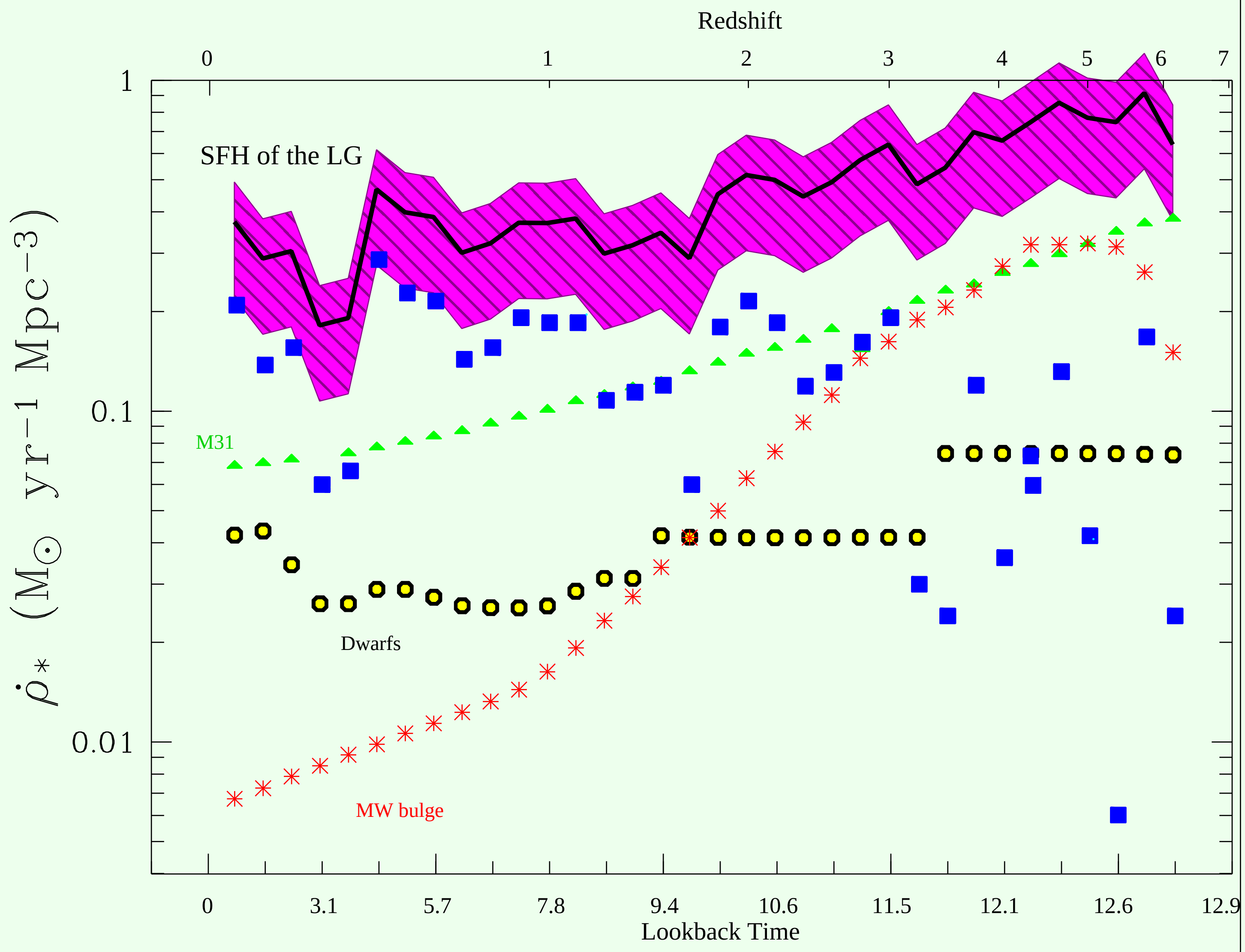
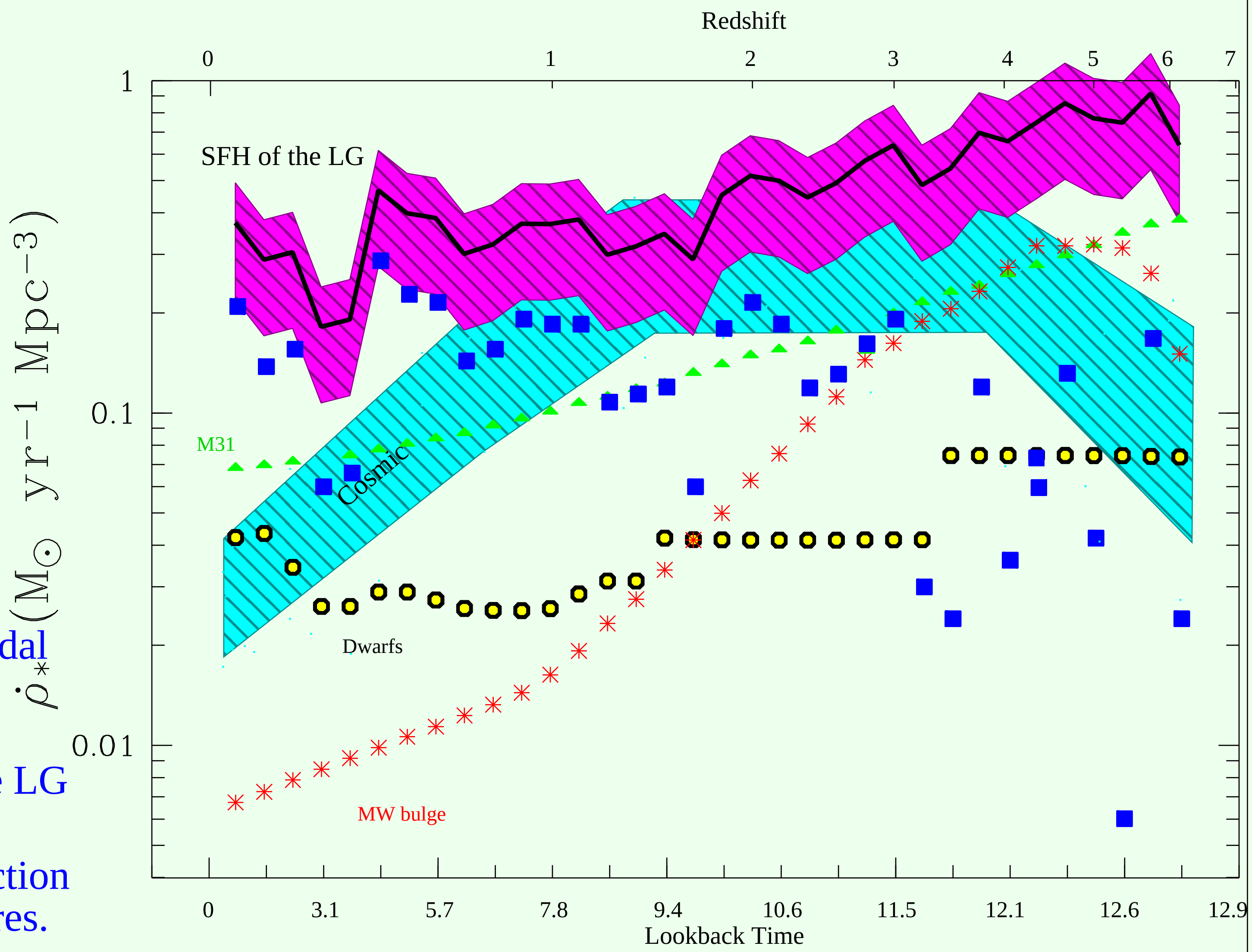


Comparing the Local and Cosmic SFHs

- An excess of the local star formation density in the recent ~5 Gyr mainly due to the fluctuations of star formation of the MW disk.
- Between ~8 and ~12 Gyr, the SFH of the LG is rather consistent with the Cosmic one.
- The early/initial evolution of the LG was dominated by spheroidal component of the MW and M31.
- The overall trend of ρ_* from the LG supports a fairly flat evolution.

=>factors of ~10 extinction correction to high−Z UV−based SFR measures.



A. Aparicio, I. Drozdovsky, C. Gallart, S. Hidalgo, M. Monelli (IAC), E. Bernard (U. Edinburgh), G. Bertelli (U. Padova), S. Cassisi (INAF-Teramo), P. Demarque, (U. Yale), H.C. Ferguson (STScI), L. Mayer (U. Zurich), M. Mateo (U. Michigan), J. Navarro (U. Victoria), A. Cole (U. Tasmania), E. Skillman (U. Minnesota), P.B. Stetson (DAO), E.Tolstoy (Kapteyn), A. Dolphin (Ratheon)

http://www.iac.es/project/LCID

Accurate SFH over the whole life-time of isolated LG galaxies, to answer fundamental questions:

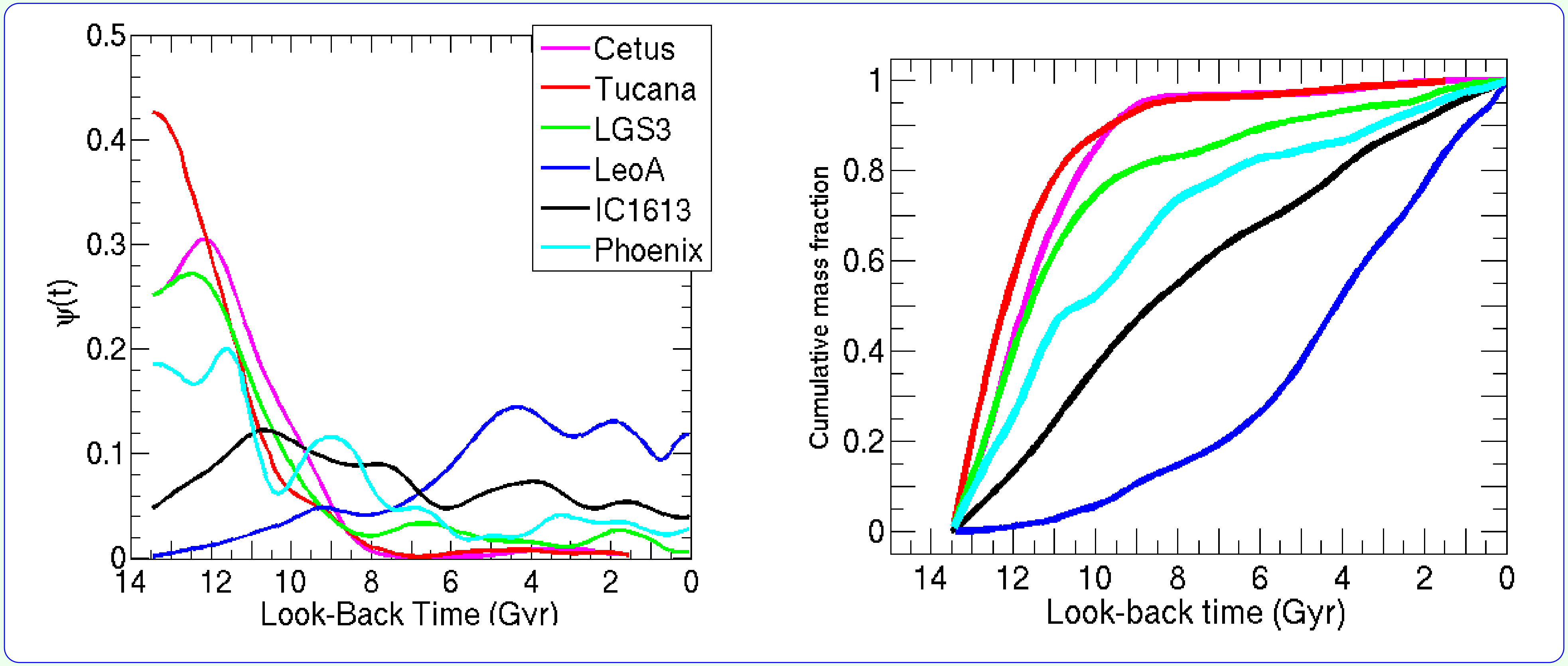
- **Was there any delay/suppression of the first event of star formation?**
  - **can we infer the role of the *reionization* ?**
- **Are there big differences with nearby MW satellites due to environmental effects**
- **How well did these small galaxies could retain the gas?**
  - **How important was the SNe feedback?**

❏ *The LCID project HST data:*

Galaxy	Type	M_B	σ_r	D(kpc) MW/M31	# Orbits
IC1613	dIrr	-14.5	25	770/520	24
Leo A	dIrr	-11.6	26	790/1180	16
LGS3	dIrr/dSph	-9.9	18	630/270	12
Phoenix	dIrr/dSph	-10.0	21	460/610	22_{wfpc2}
Cetus	dSph	-10.2	17	760/680	25
Tucana	dSph	-9.1	18	900/1340	32

- **Homogenous set of HST/ACS data reaching the oldest (> 13) Gyr MSTOs**
- **Homogenous photometric reducion (DAOPHOT IV, cross-check with DolPhot)**
- **Homogenous SFH analysis ('IACpop' + Basti & Padova stellar evolution libraries; comparison with the 'Match' and 'Cole')**
- **Extreme care in the control of systematic effects**
- **The age of the peak at ages $>$10 Gyr is known with 0.5 Gyr precision**

The SFHs of Isolated Dwarf Galaxies



Old Cetus and Tucana had similar SFH to each−other and the MW satellite dSphs

Transitional type galaxies, LGS3 & Phoenix, are closer to dSph than to dIrr

No single template of SFH for Irrs, continuous SF until the recent times (LeoA!)

Histories of dwarfs

- ***Irregulars:***
  - **Recent SFR is at least 50% of the lifetime average.**
  - **Continous star formation to the limits of the photometry.**
  - **No single template SFH.**
- ***Transitional dSph/dIrr:***
  - **Recent SFR is less than 50% of the lifetime average.**
  - **All formed half of their stars by 10 Gyr ago.**
- ***dEs/Sphs:*** **Two types divided at M$_B \sim -11.5$:**
  - **The most massive had prolonged star formation, often with a later peak.**
  - **Many fainter ones have a dominant, ancient episode.**

- ***“…galaxies are clearly diverse in their properties, for example in bulge-to-disk ratio, but theories should be able to produce the galaxy population in the Local Group rather naturally, without appeal to special conditions. Thus the Local Group members are ‘typical’ galaxies in their properties and for theory, but they are atypical for observation.”***

(Rosemary Wyse)

- ***“…about 85% of galaxies are situated outside the rich clusters. Roughly a half of them belong to groups of different size and population, while the remaining half are scattered in diffuse (unvirialized) ‘clouds’ and ‘filaments’ usually called the ‘field’.***

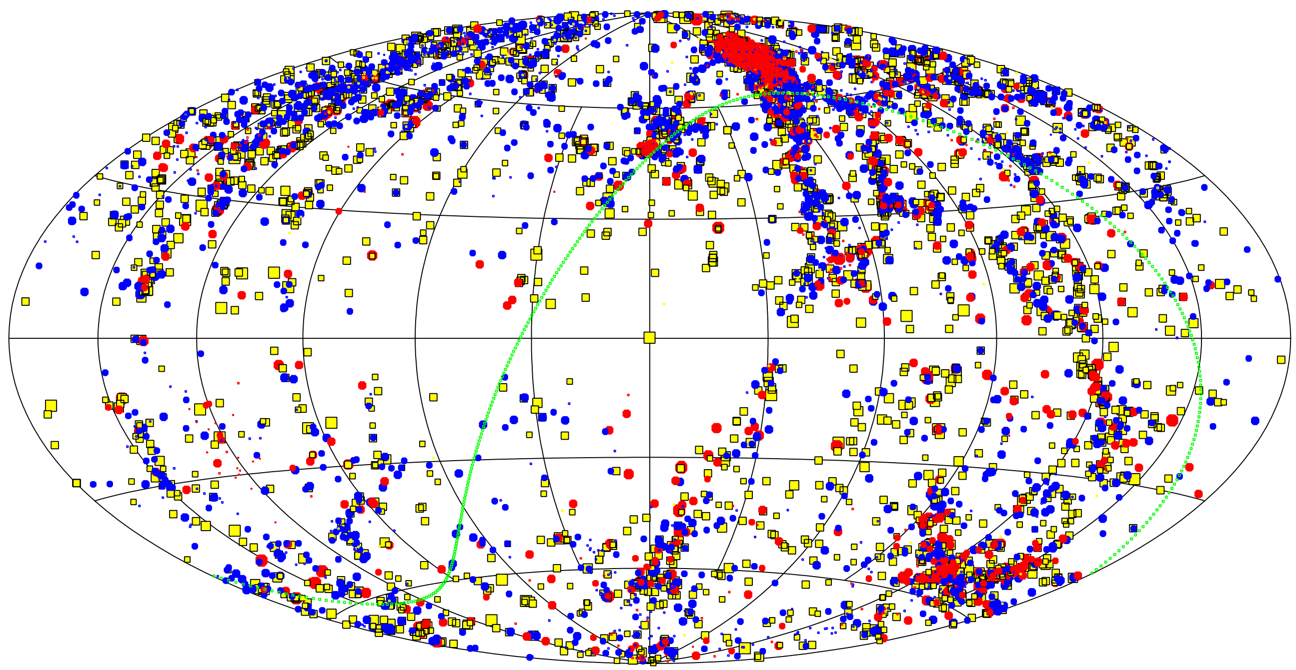
(Igor Karachentsev)

The Local Supercluster within 30 Mpc Volume

The Local Supercluster: **We have compiled the catalog of 8600 galaxies with distances up to 30 Mpc. The catalog contains the data on basic optical, IR, and HI properties of the galaxies.**

The major focus of this study is to compare the true "redshift−zero" and the mean characteristics of the nearby Universe as a function of the volume size. This allow us to track variations of the local baryonic content and shed light on the process of galaxy formation and evolution.

The Local Supercluster within 30 Mpc Volume



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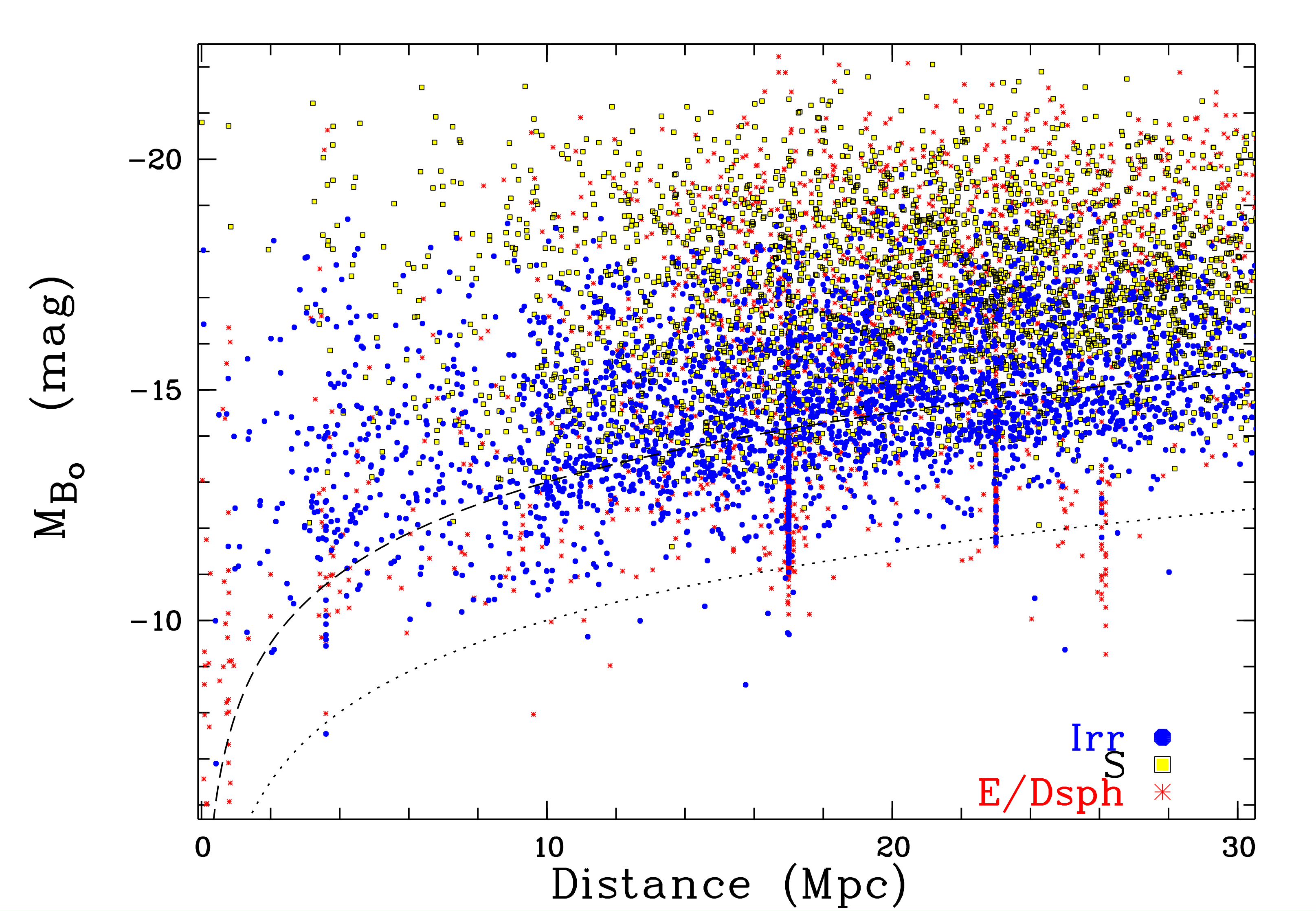

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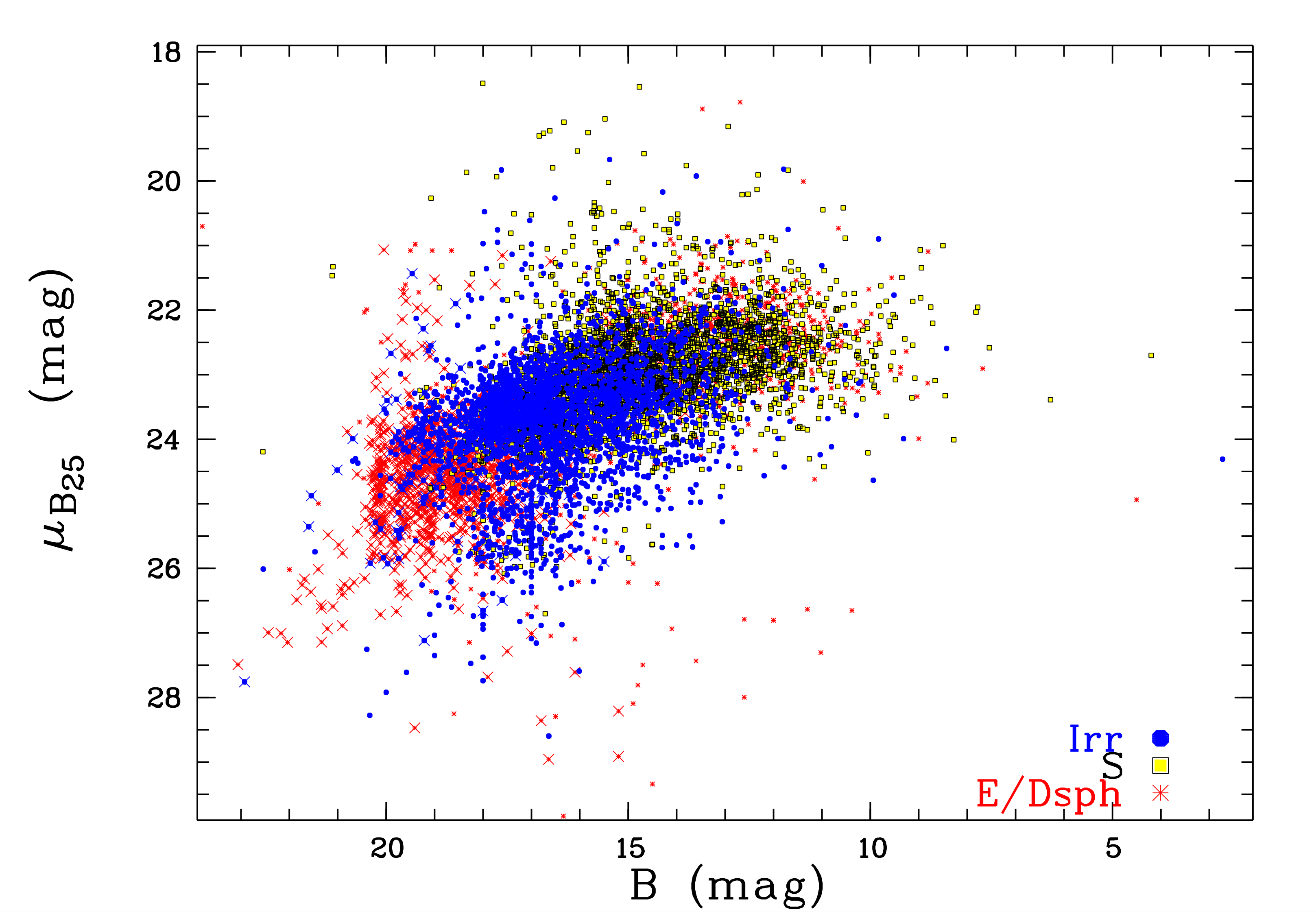

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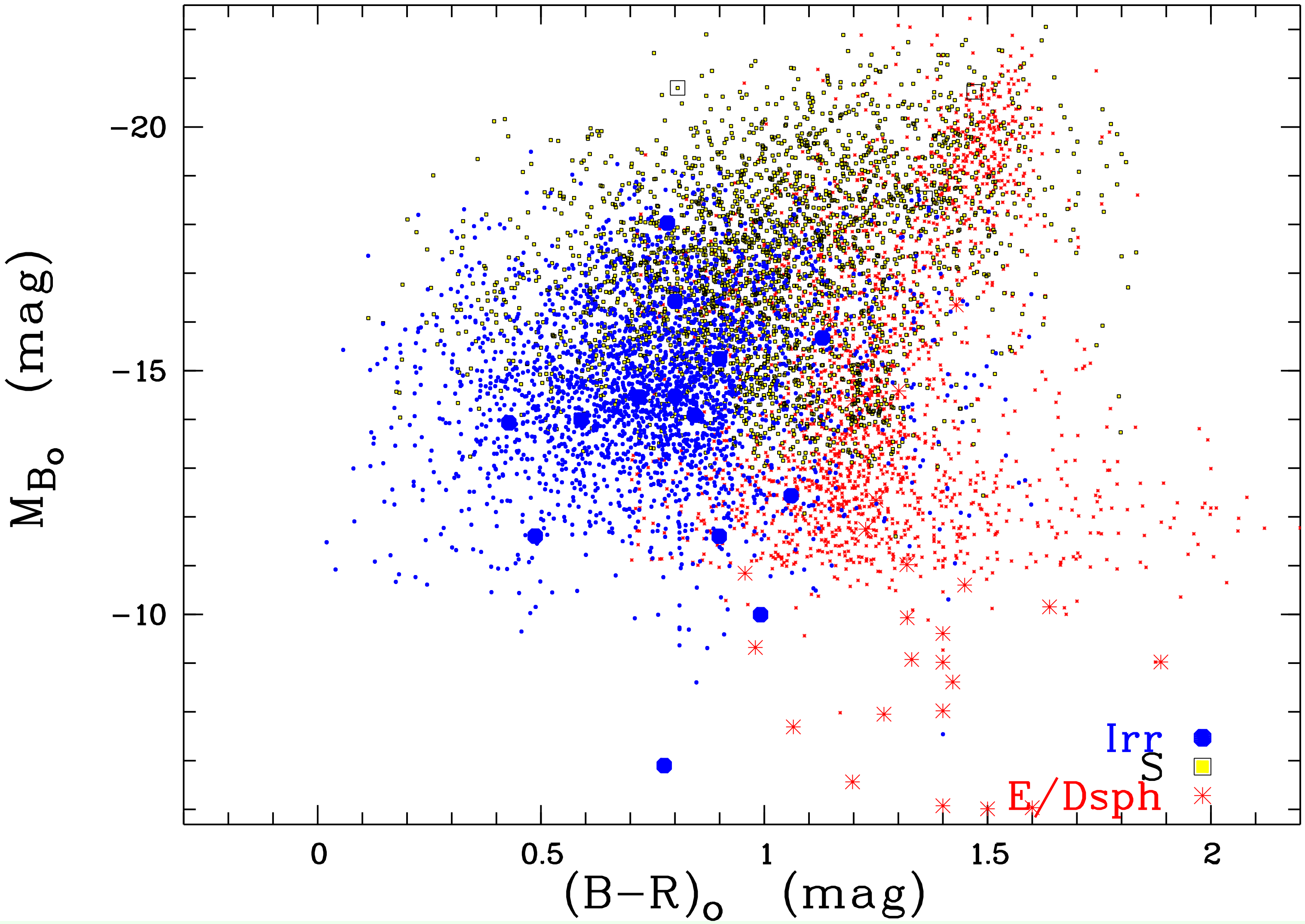

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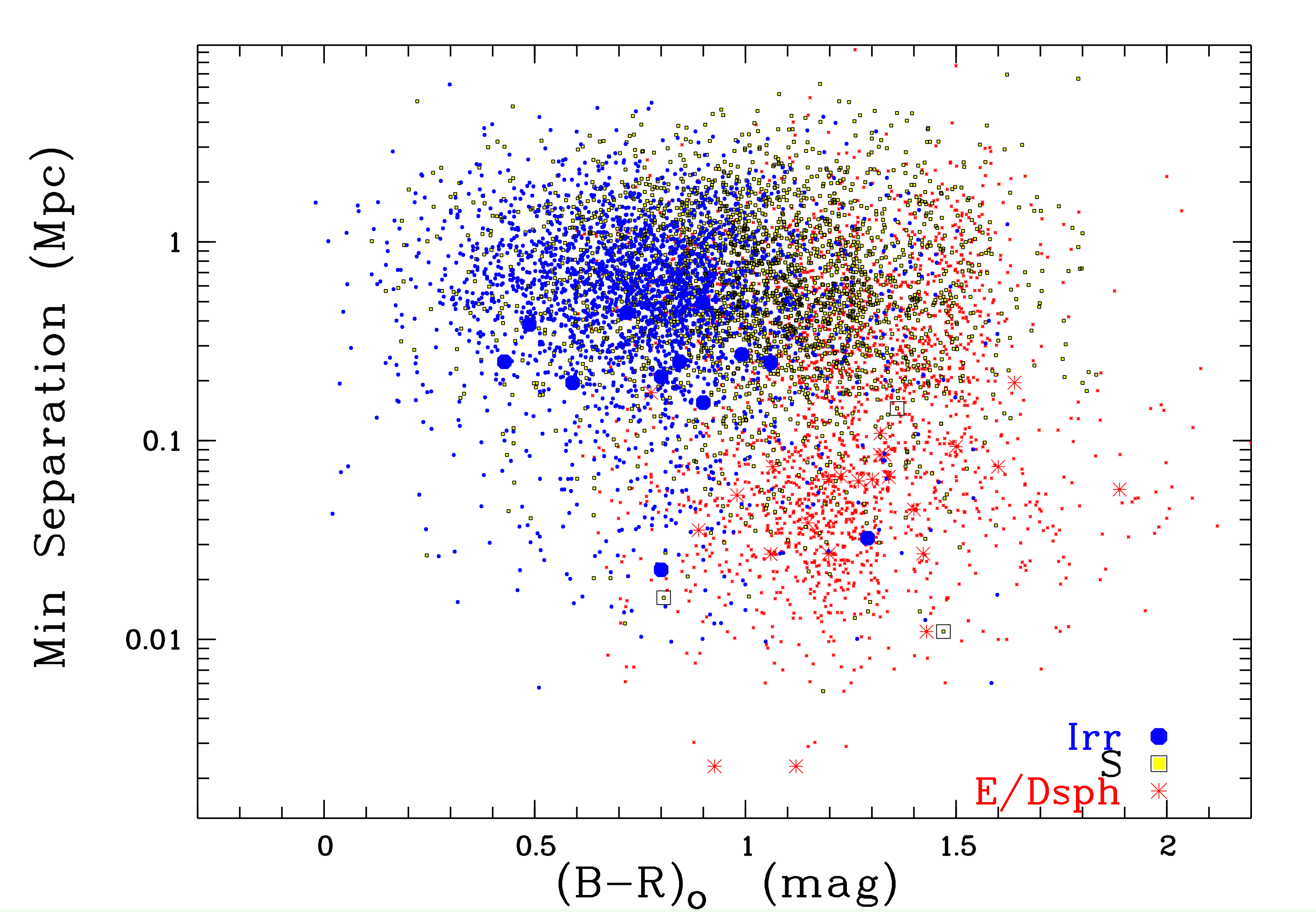
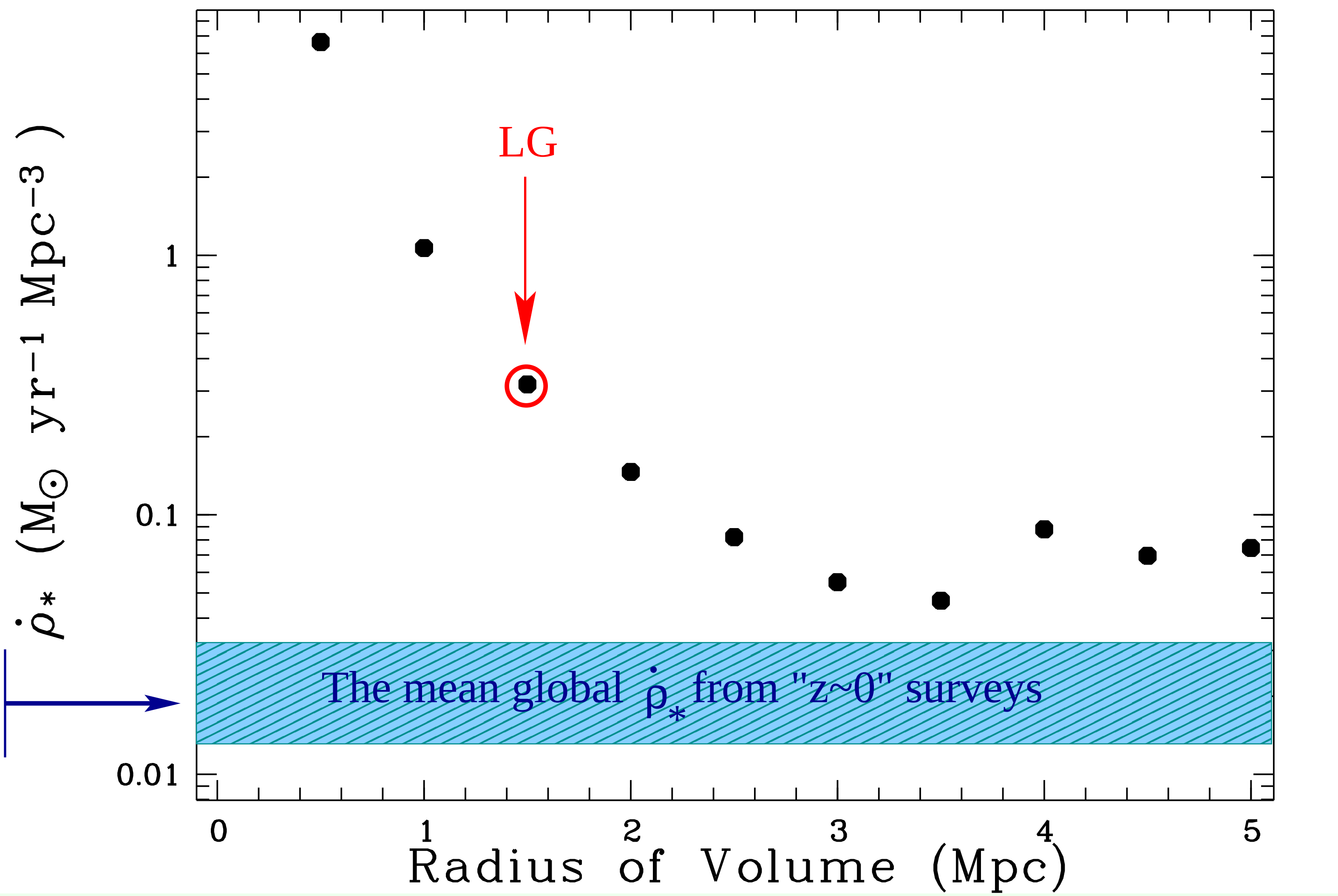


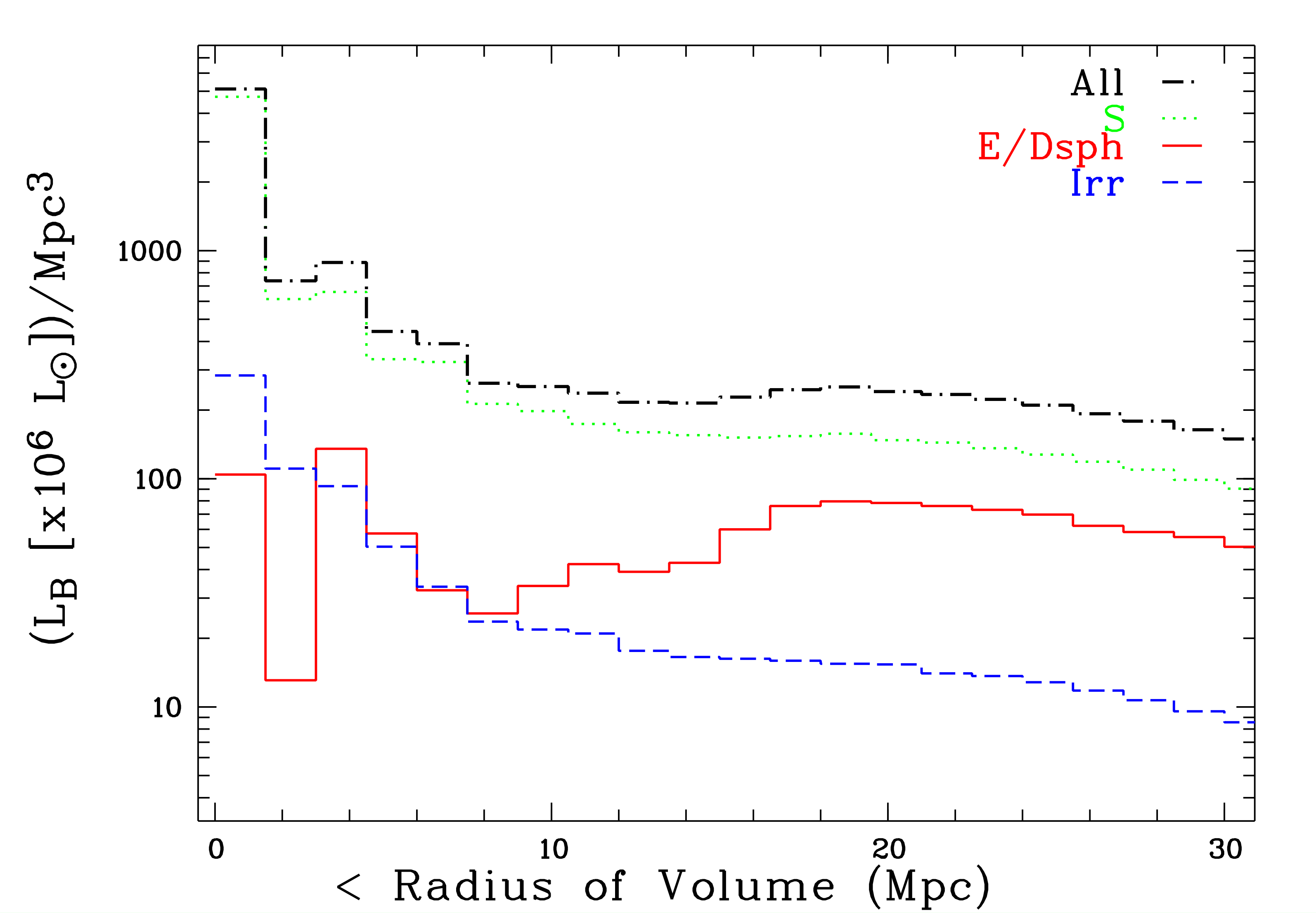
The Current Star Formation Density of the Local Universe

The Local Volume demonstrates the current star formation activity 5−8 times high than the average global rate in the typical neighboring volume at "z=0"

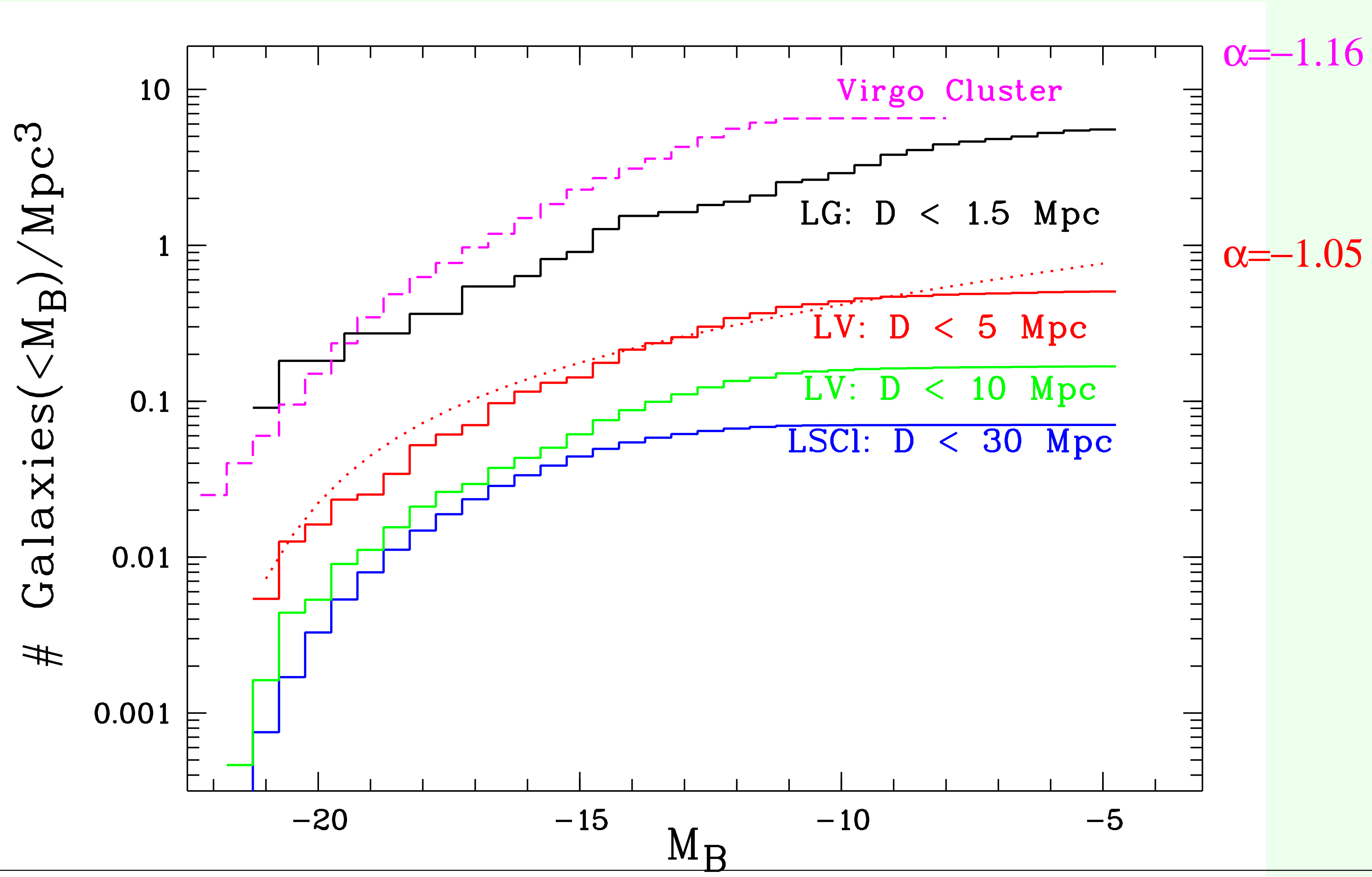
Nakamura et al. 2004
Martin et al. 2005
Hanish et al. 2006



Volume−Averaged Luminosity of the Local Supercluster



Integral Blue Luminosity Function of Galaxies



❑ *Results:*

- **An excess of the local star formation density in the recent ~ 5 Gyr is mainly due to the fluctuations of star formation of the MW disk.**
- **Between ~ 8 and ~ 12 Gyr, the SFH of the LG is broadly consistent with the Cosmic one.**
- **The early/initial evolution of the LG was dominated by spheroidal component of the MW and M31.**
- **Reionization had no obvious effect on the SFH of our sample of six isolated dwarf galaxies in the outskirts of the Local Group. Leo A is the only galaxy presenting a delay of few Gyr in the age of the peak of star formation.**
- **Despite of some peculiarities of the LG environment, such as dominance by two large spirals and an excess of the local current SFR density, the LG is a fairly representative galaxy sample of the Local Universe, although an extension to at least of 5 Mpc radius volume would provide a more robust comparison of the Local and Cosmic evolution.**

❑ *Results:*

- **The Virgo Cluster contribute 10% to the total blue luminosity of the 30 Mpc-radius Volume. About 5% of all currently known galaxies within LSCl are extremely isolated (nearest neighbor farther than 2 Mpc). The blue luminosity density varies from** $\sim 3 \times 10^7\ L_\odot/Mpc^3$ **in the Local Void to** $\sim 2\times 10^{10} L_\odot/Mpc^3$ **in the central 5 degrees of the Virgo Cluster (the mean luminosity density of the Local Supercluster is** $\sim 1.6 \times 10^8 L_\odot/Mpc^3$**).**
- **The overall trend of star formation density from the LG supports a fairly flat evolution of the SFR, without showing the turnover implied by the Lyman dropout measurements of (e.g.) Bouwens et al. and Banker et al. This suggests factors** ~ 10 **extinction correction to high-redshift UV-based SFR measures.**

❑ *Understanding of the Decline of the Cosmic SFH*

- **Declining rate of major galaxy mergers (+ dry mergers and morphologies evolving towards Es).**
- **Drop in the rate of minor tidal interactions**
- **Progressive consumption of cold gas (fuel exhaustion)**

Open Questions

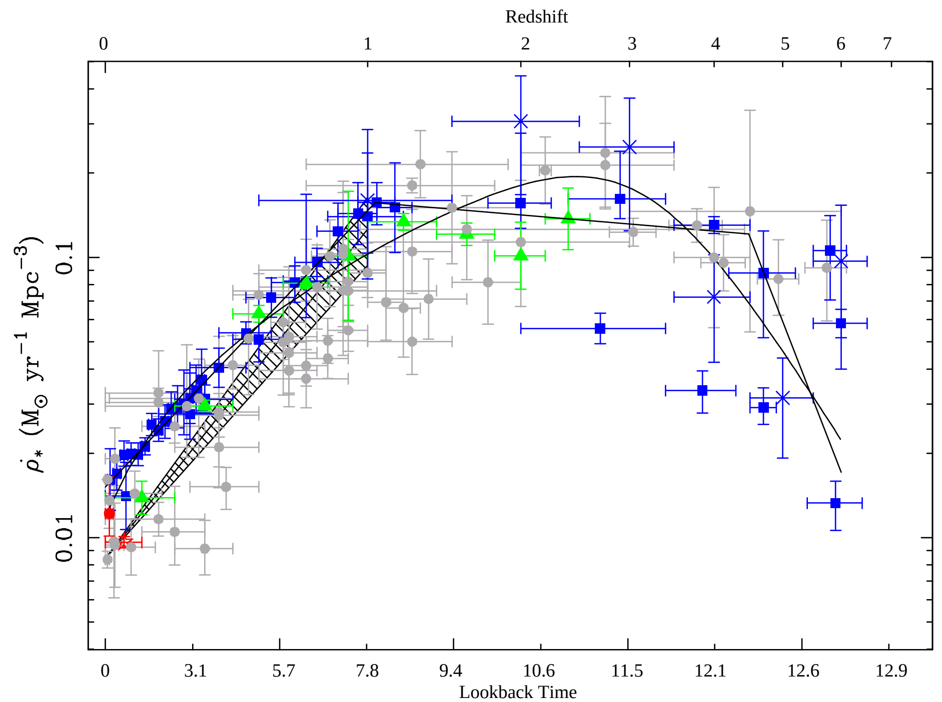
- **Does the star formation in disks evolve slowly, while merger-induced starbursts evolve rapidly?**
- **Does the decreasing number density of galaxies with high SFR reflect a decline in star formation in L_*-galaxies or reflect a disappearance of a population of bursting dwarf galaxies?**

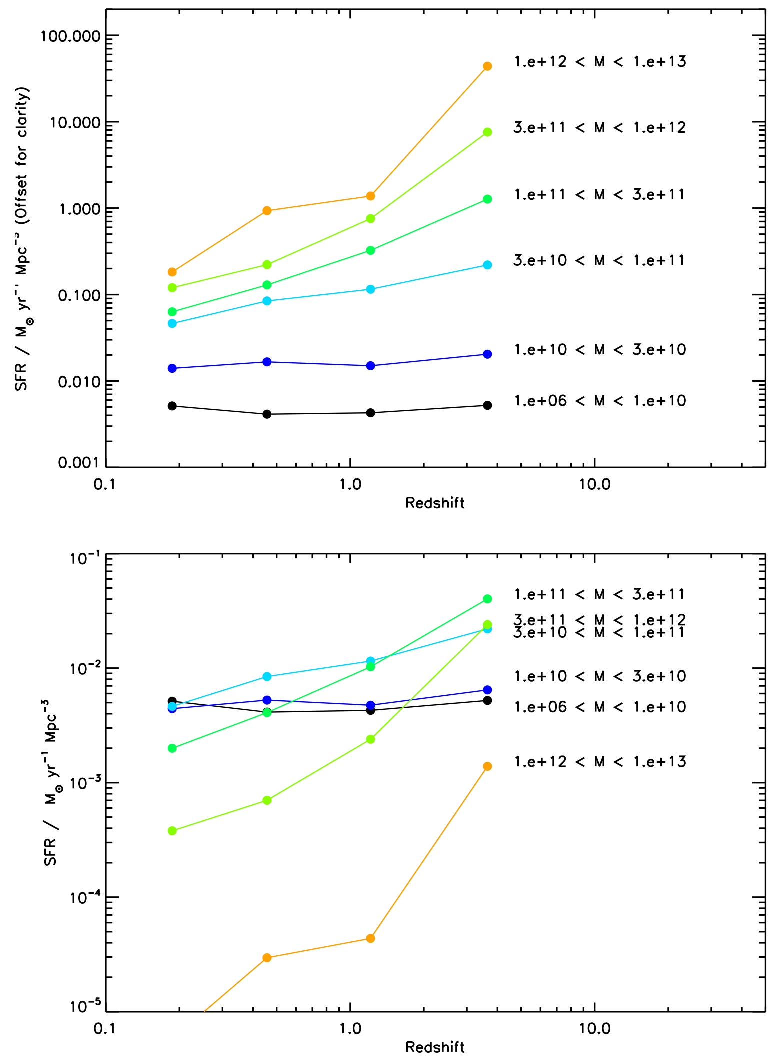
❑ *Specific Star Formation Rates & Downsizing*

- **Downsizing: more massive galaxies undergo a larger fraction of their star formation at earlier times than less massive ones (e.g., Cowie+96, Giavalisco+96, Cimatti+04, Glazebrook+04, Kodama+04).**
- **Bauer+05: the Specific Star Formation Rate (SSFR: SFR per unit galaxy mass) decreases as galaxy stellar mass increases, suggesting that star formation contributes more to the growth of low-mass than high-mass galaxies at redshifts $z < 1.5$.**

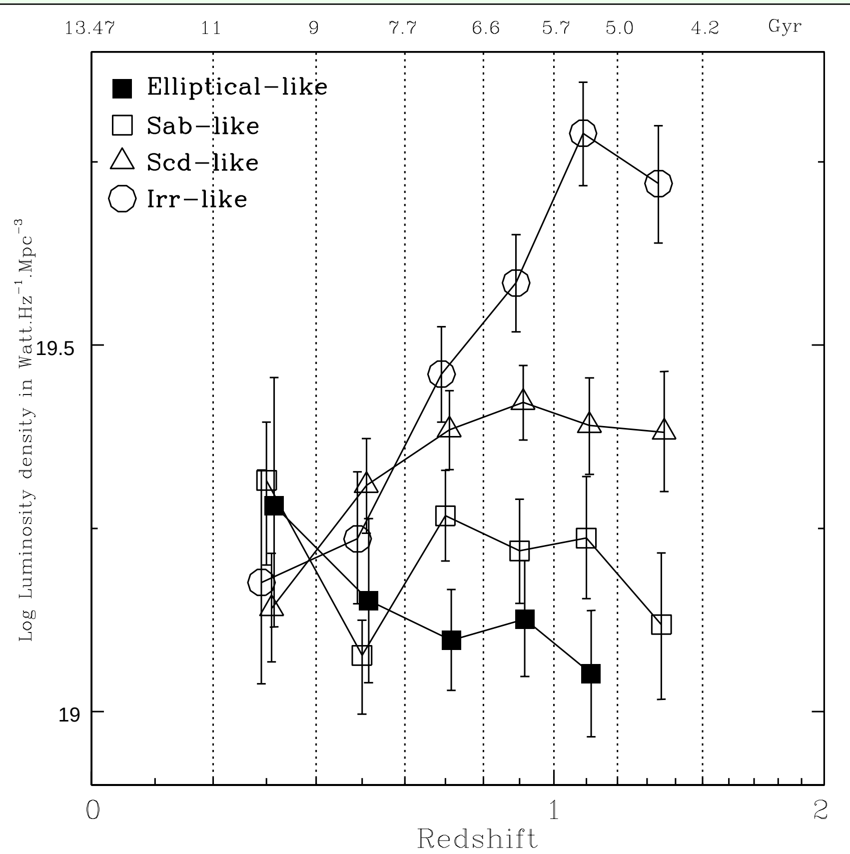
Cosmic SFH from Population Synthesis

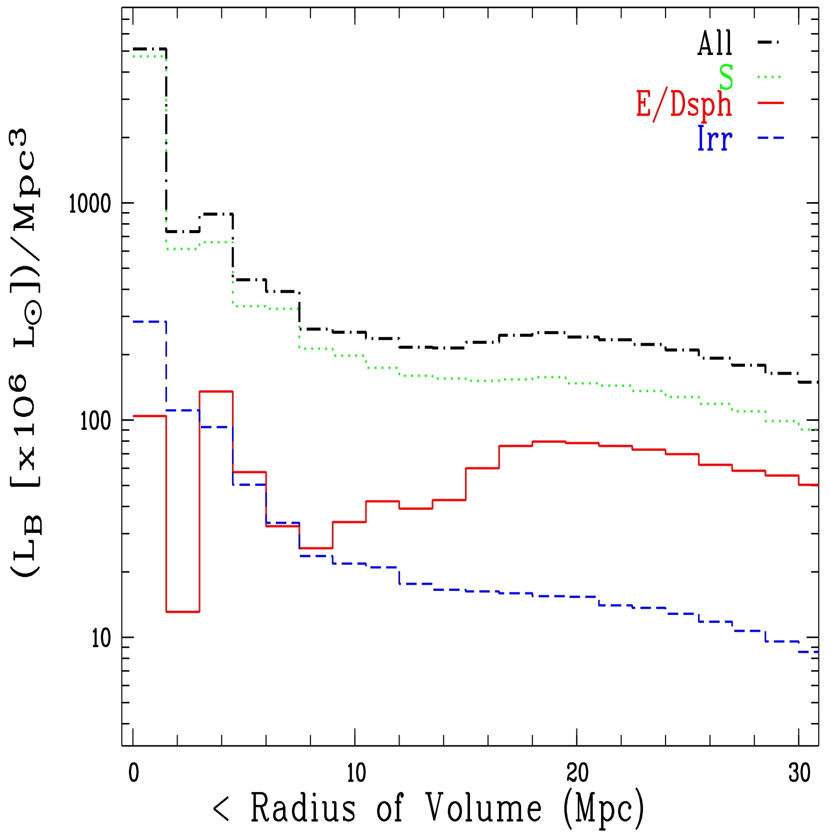
(Panter+06) MOPED analysis of ~300000 spectra
No conclusive peak in the SFR out to z<2,
but continue to show evidense for ’downsizing’
Main factors affecting results:
the IMF and theoretical models





Details of the Cosmic SFH





(Tresse+08) Evolution of Blue luminosity per type.

The Irr−like type emissivity decreases markedly by a factor of 4, while the E−like increases by a factor 1.7 (at z>0.4 Es are dominanting ???)

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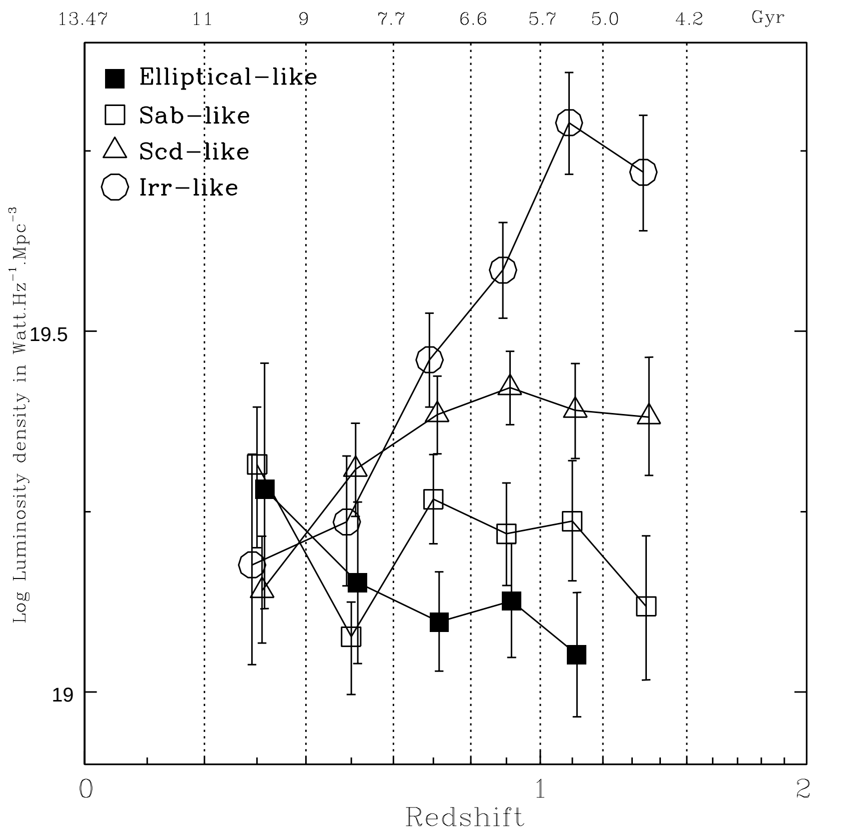

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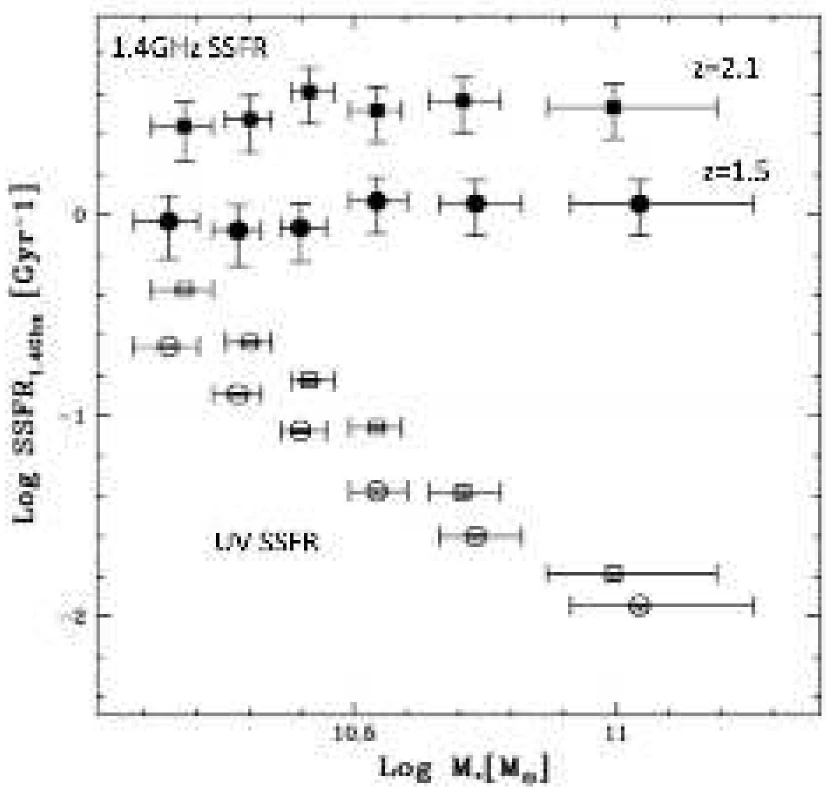

(Pannella+09) The SSFR(HI) at z=1.5 and z=2.1 are roughly constant with the host stellar mass M*, unlike the UV−derived SSFR that shows a strong differential extinction effect as a function of M*.