Spectral Evolution of a Galaxy

Integrated light, no spatial resolution, no dynamics

Galaxy spectrum (t) = $\sum_{(1-200)*10^9}$ Stellar spectra + gas (em./abs.)

+ dust (abs./ em.)

Stellar spectrum = black body

+ 50 million atomic & molecular lines

high mass stars :	hot,	bright + blue :	UV - opt.	short - lived
low mass stars :	cool,	faint + red :	opt. - NIR	long - lived

Stellar population :

→ Stellar Initial Mass Function

→ Stellar lifetimes & evolutionary tracks (mass, composition)

→ Star Formation History of the galaxy

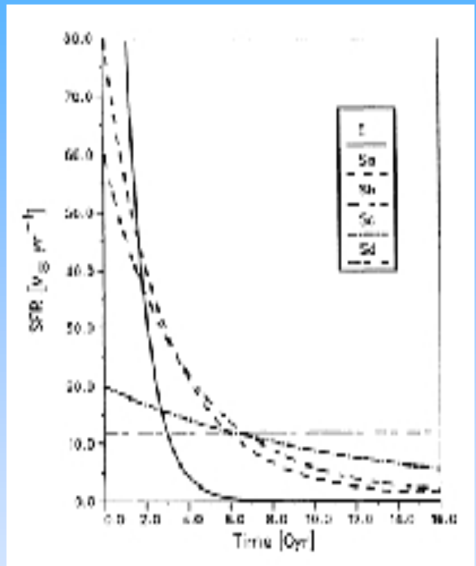
Z : Metallicity := Mass fractions of heavy elements (>H, He)

Sun : Z=0.02

Spectral Evolution of a Galaxy

Star Formation History $\Psi(t)$ -- single burst --> **star cluster**

-- extended --> **galaxies**



Initial Mass Function : Salpeter, Kroupa, ...

\+ Stellar evolutionary tracks / isochrones

--> **HRD / CMD (t)** (star cluster / galaxy)

\+ Spectra

--> **integrated spectrum (t)** (star cluster / galaxy)

\+ Filter characteristics/zeropoints

--> **integrated luminosities, magnitudes, colors**

Spectral Evolution of a Galaxy : GALEV

Input :

Stellar evolutionary tracks / isochrones :

Padova / Geneva

Spectra : Lejeune et al. 1997, 1998

Gaseous emission : Continuum & lines

N_{Lyc} : Schaerer & de Koter 1997, Smith et al. 2003

Line Ratios : Izotov et al. 1994, 1997, 1998

Stellar absorption features : Lick index calibrations

Gorgas et al. 1993, Worthey et al. 1994

Spectral Evolution of a Galaxy : GALEV

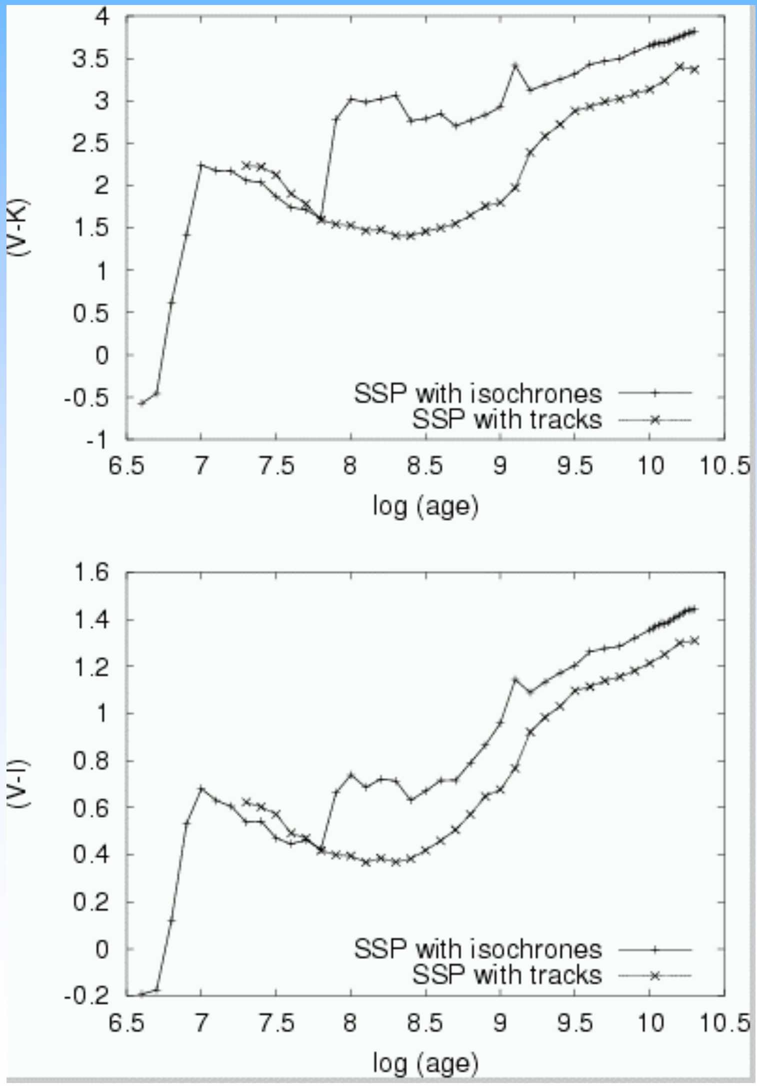
Output :

Time evolution of

- **Stellar mass**
- **Gas content and gas abundances**
- **CMDs**
- **Spectra** 90 A ..... 160 μm
- **Emission line strengths & equivalent widths**
- **Luminosities U ..... K** Johnson, HST, Washington, Stroemgren, ...
- **Colors**
- **Absorption features** Lick $H\beta$,Mg2, Mgb, Fe5270, Fe5335, TiO1, TiO2, ...

Simple Stellar Populations

Completeness of stellar tracks / isochrones :



with TP- AGB
without TP- AGB

Age dating from V-I without TP- AGB :
ages wrong by ≥ 50 %

e.g. V- I ~ 0.6 :

Age| $_{w/o\ TP\text{-}AGB}$ ~ 6.3 10^8 yr

Age| $_{TP\text{-}AGB}$ ~ 6.6 10^7 yr

(Schulz, FvA, Fricke 2002)

Gaseous Emission

Gaseous emission important at young ages

N_{Lyc} [1/s] (T_{eff}, $R_{☆}$) ionising flux

summed over all O-, B-stars

(Stroemgren spheres, case B recomb. Osterbrock)

Lines and continuous emission

$F(H_{\beta}) \sim N_{Lyc}$

hydrogen line ratios : atomic physics

(Lyman, Balmer, Paschen, Brackett series)

heavy element line ratios : depend on metallicity

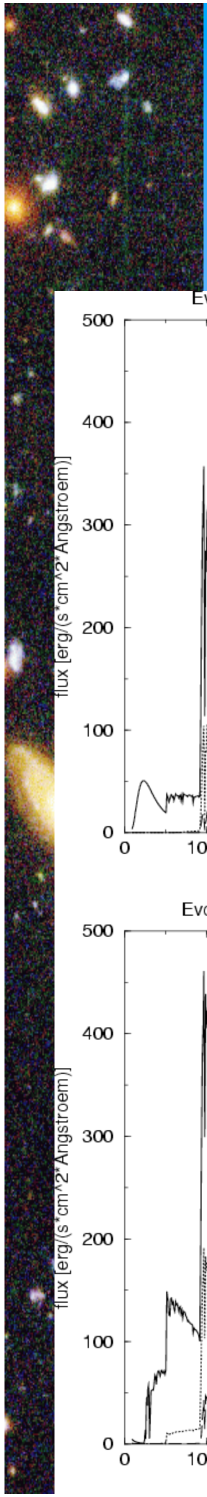
- from photoionisation models
- from observations

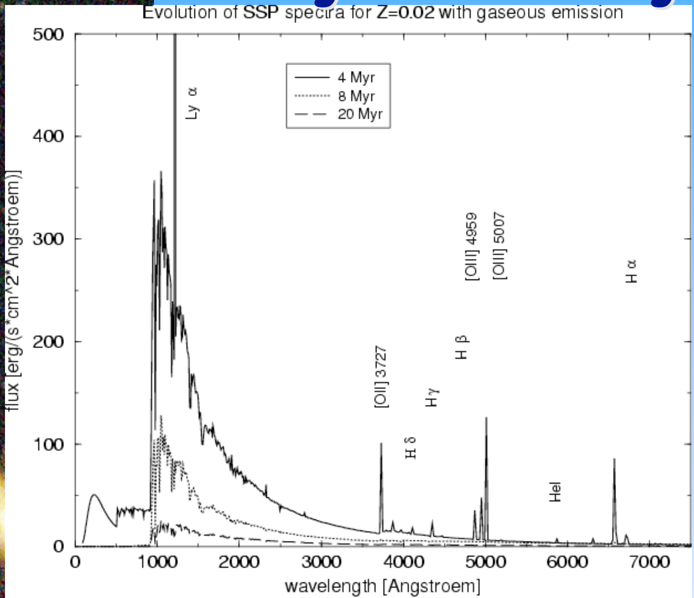
Continuous emission ~ N_{Lyc}

Evolution of 1 Generation of Stars

Simple Stellar Population (= SSP = star cluster)

4 Myr . . . 16 Gyr effects of the chemical composition



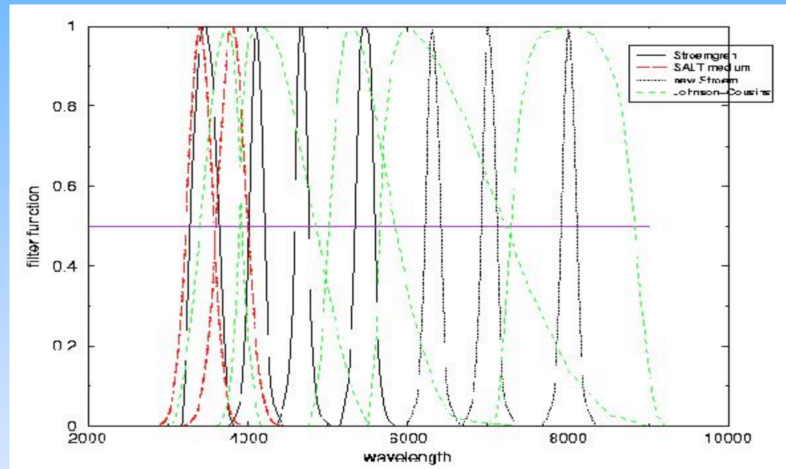


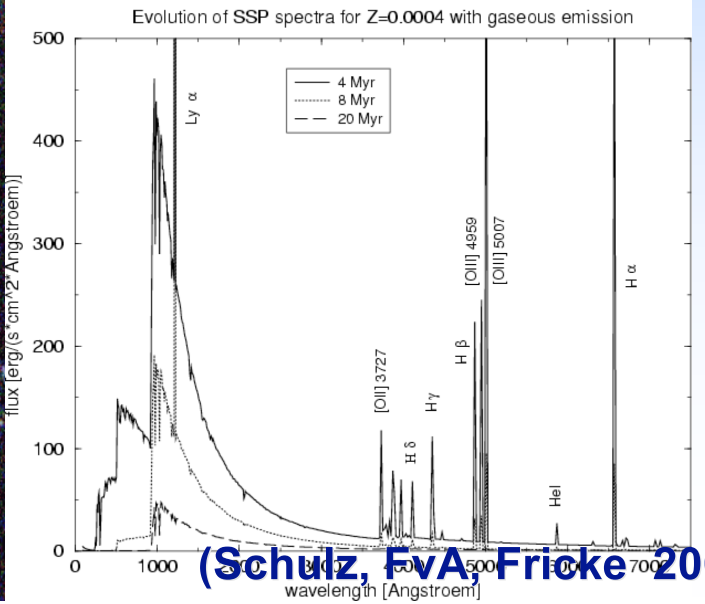
4 Myr

8 Myr

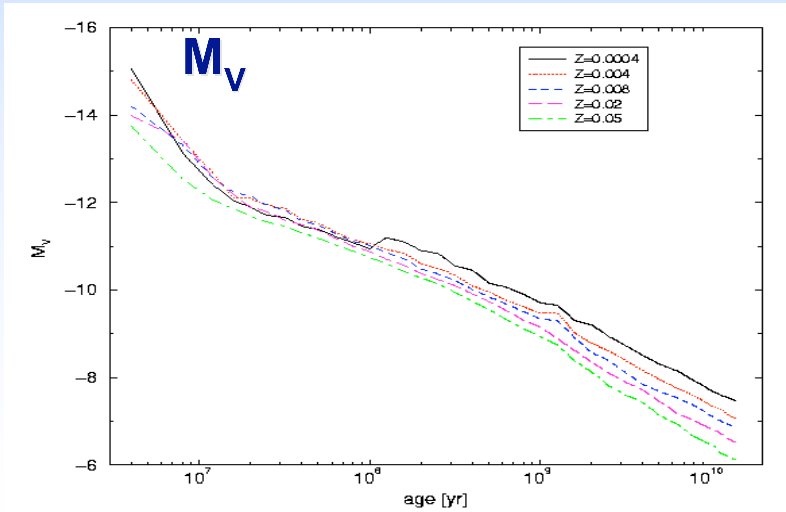
20 Myr

Solar metallicity





[Fe/H]= - 1.7



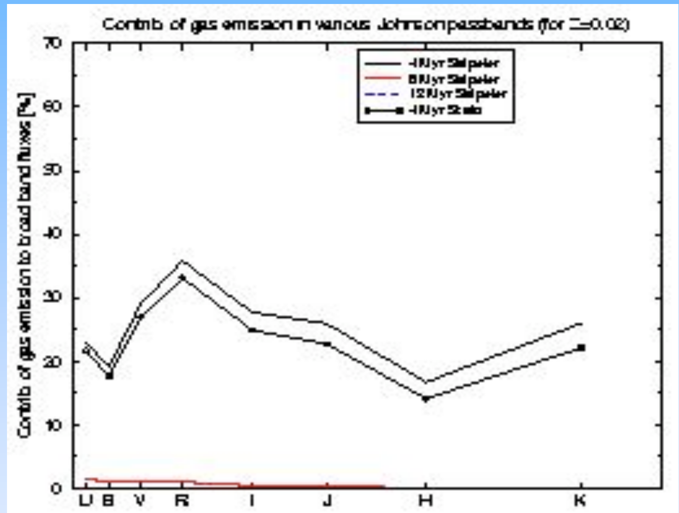
(Schulz, FvA, Fricke 2002, Anders & FvA 2003)

Simple Stellar Populations

Gaseous emission : at young ages 6 . . . 15 Myr

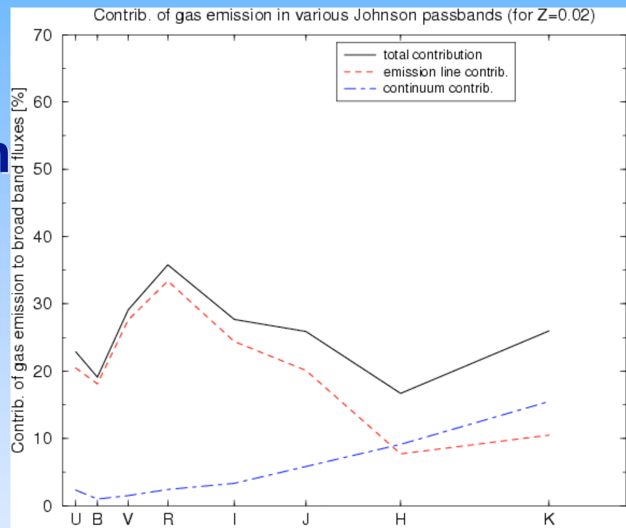
effects of metallicity

$Z_\odot$

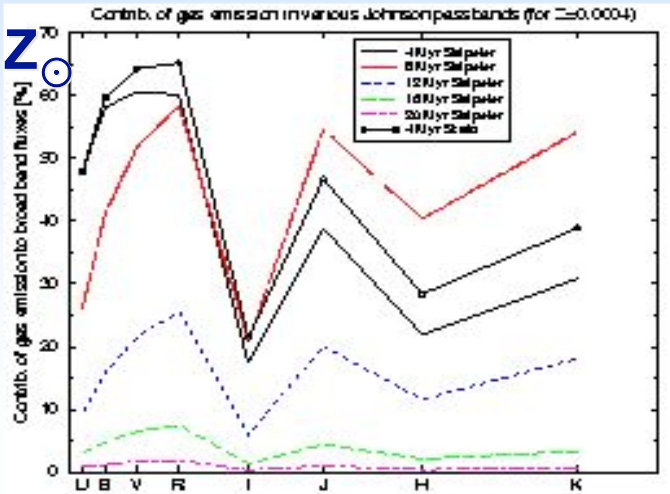


lines

continuum



1/50 $Z_\odot$



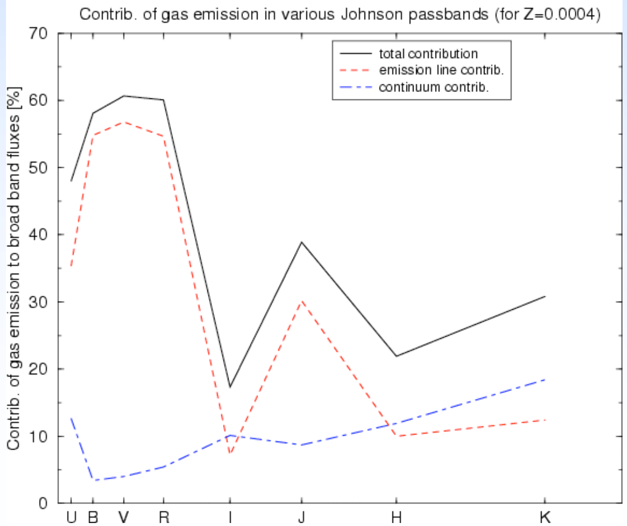
4 Myr

8 Myr

12 Myr

16 Myr

20 Myr

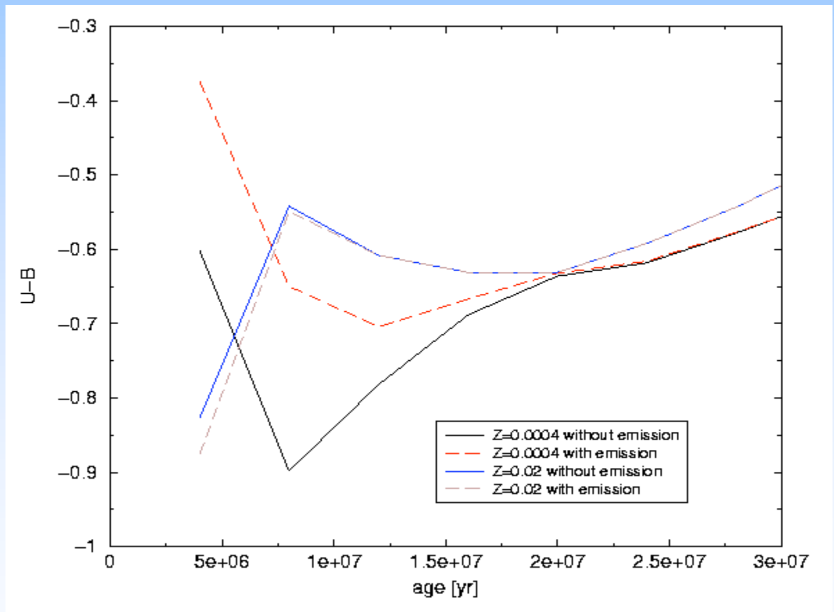


Simple Stellar Populations

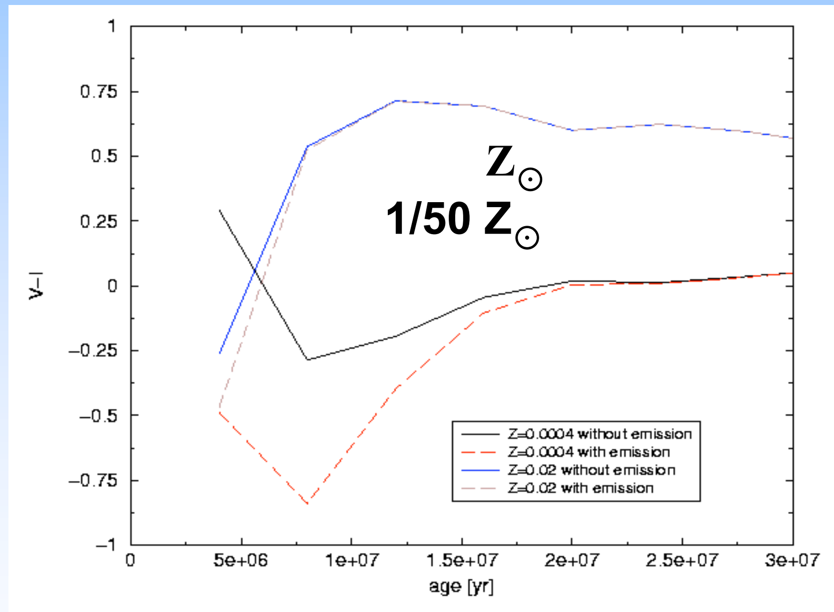
Gaseous emission : at young ages 6 . . . 15 Myr

important contributions to broad band fluxes & colors

U-B



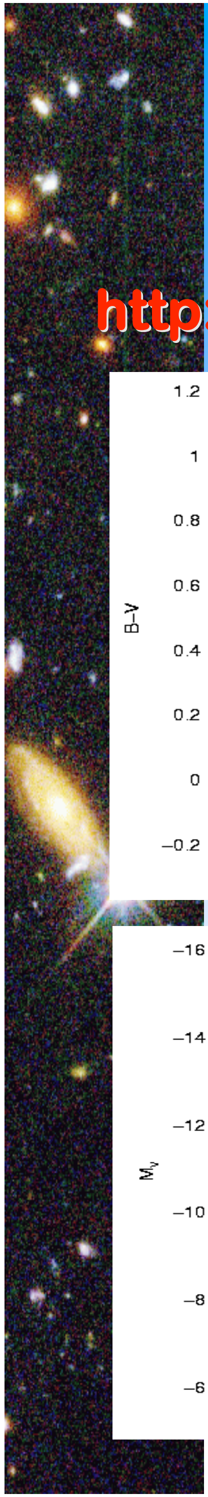
V-I

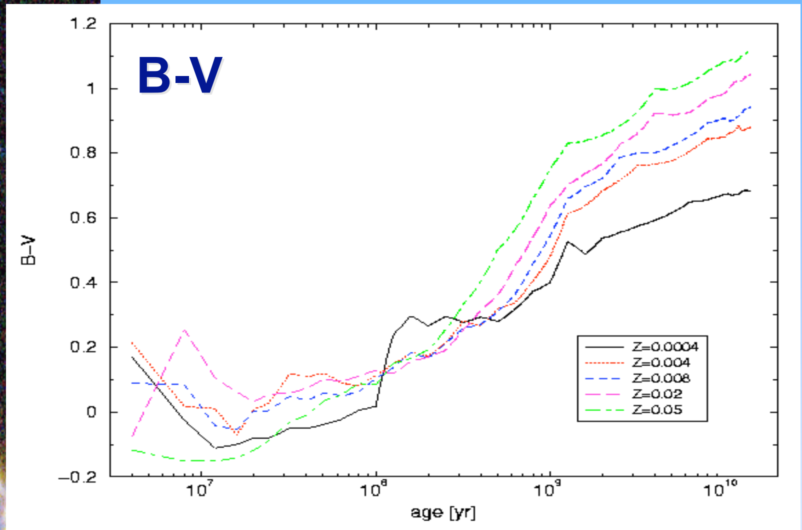


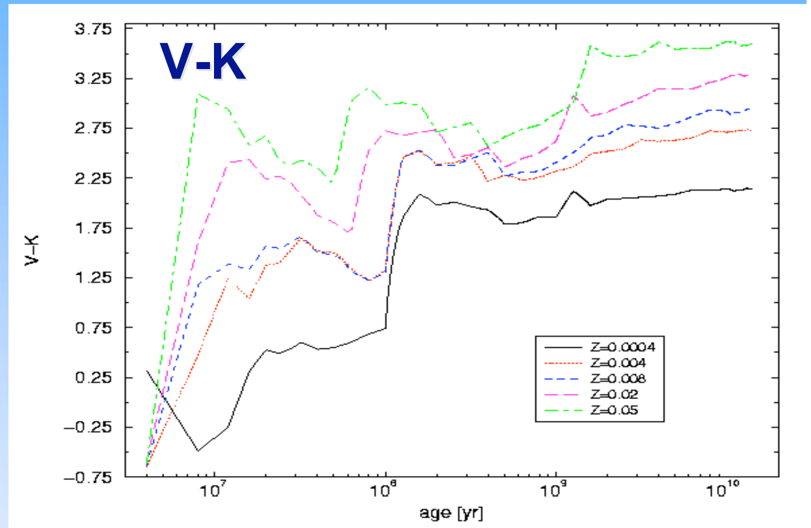
Evolution of a Simple Stellar Population

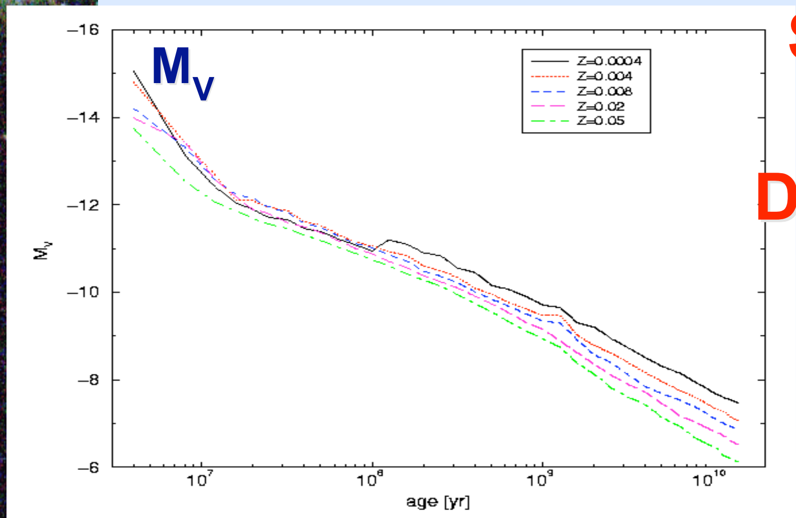
(Schulz, FvA, Fricke 2002, Anders & FvA 2003) **(= star cluster)**

http://www.astro.physik.uni-goettingen.de/~galev/panders/SSPModels

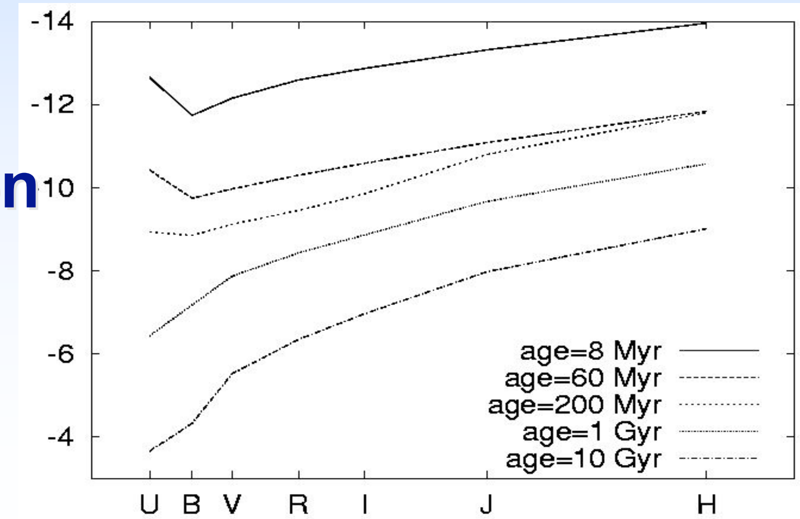








Spectral Energy Distribution SED



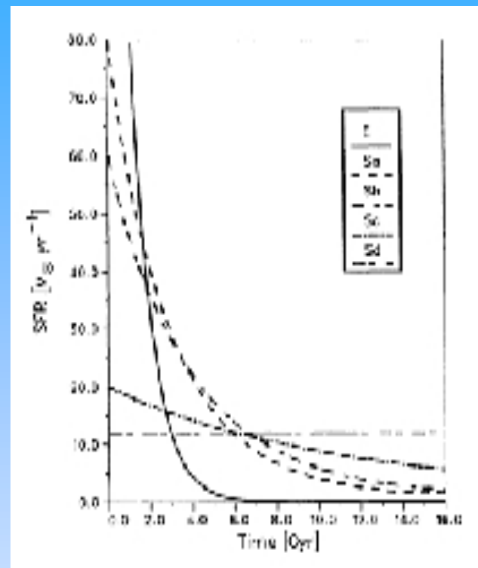
Spectral Evolution of a Galaxy

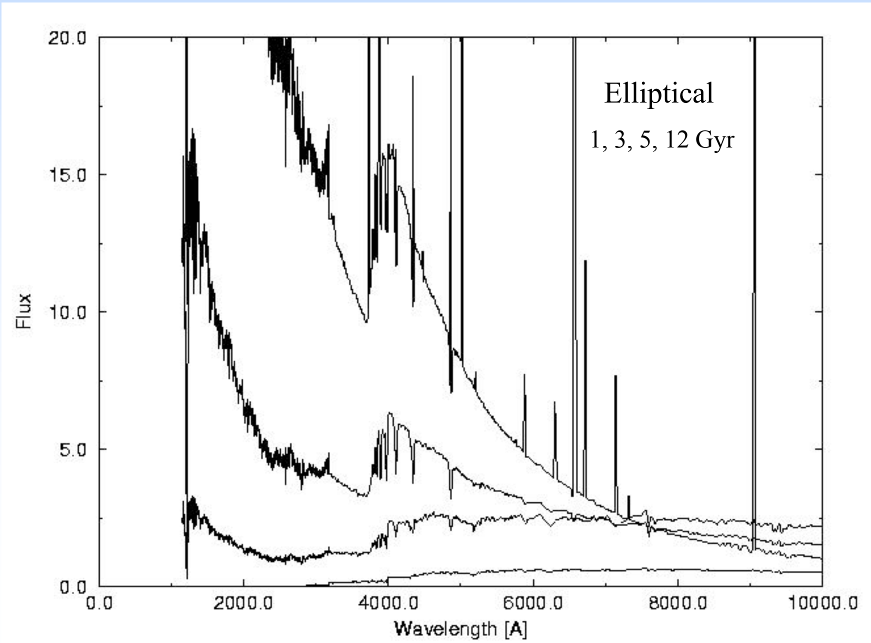
Stellar population :

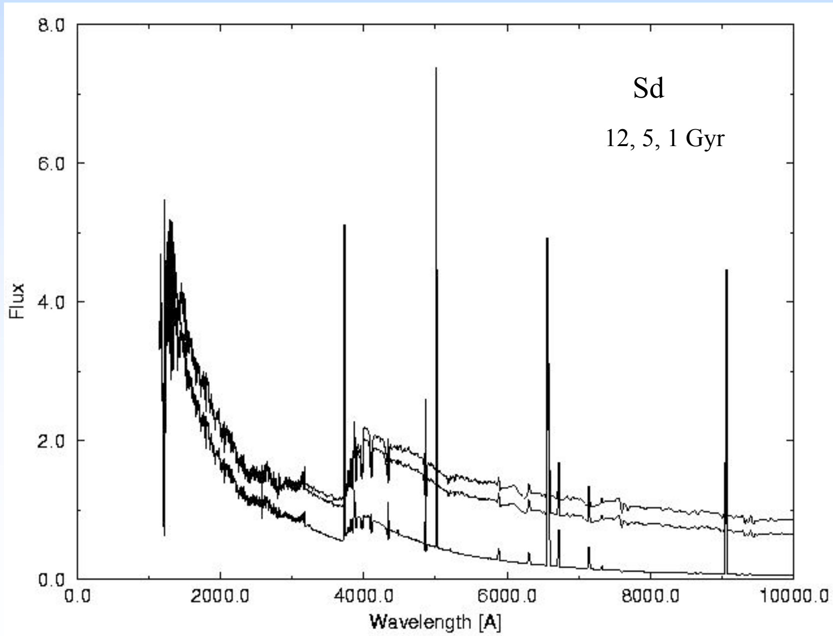
→ **Stellar Initial Mass Function**

→ **Stellar evolutionary tracks (m, Z)**

→ **Star Formation Histories of various galaxy types**





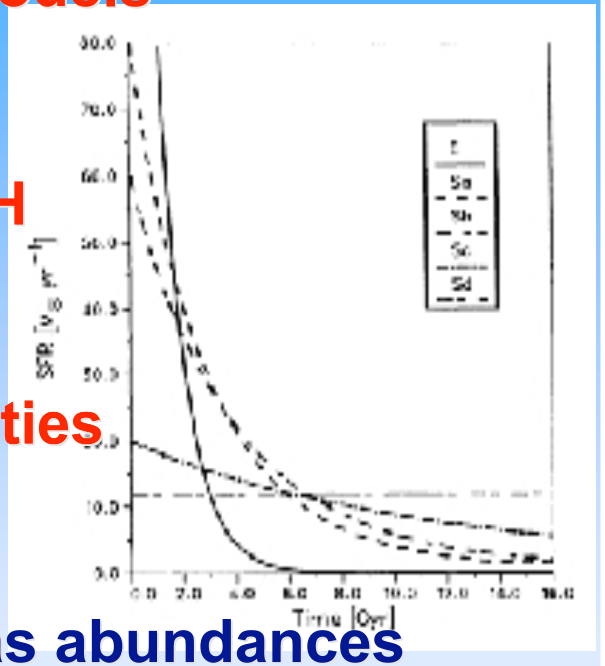


Philosophy of GALEV Models for Galaxies

Ockham's Razor: Simplest possible models

closed-box (→ inflow , outflow)

Small # of free parameters : (IMF), SFH



Calculate :

large number of observational quantities

CMDs, spectra, luminosities, colors,

emission & absorption lines, chem. gas abundances

Comparison with

☆ multi-band observation

☆ spectral & chemical properties

➜ severe constraints on free parameters

Galaxy Models

Models for E, S0, Sa, Sb, Sc, Sd (spectral types!) at ages 13 Gyr have to agree with

- ☆ average colours U – B, B – V, V – I, V – K of the respective types from RC3, Virgo, Coma samples, . . .
- ☆ average absorption/emission line strengths
- ☆ stellar metallicities (E, S0), gas metallicities (spirals)
- ☆ template spectra
- ☆ gas-to-total mass ratios
- ☆ average luminosities in B

➜ tight constraints on SFHs of different spectral galaxy types

Galaxy Models

Models for E, S0, Sa, Sb, Sc, Sd (spectral types!) at ages 13 Gyr have to agree with

- ☆ average absorption/emission line strengths
- ☆ stellar metallicities (E, S0), gas metallicities (spirals)

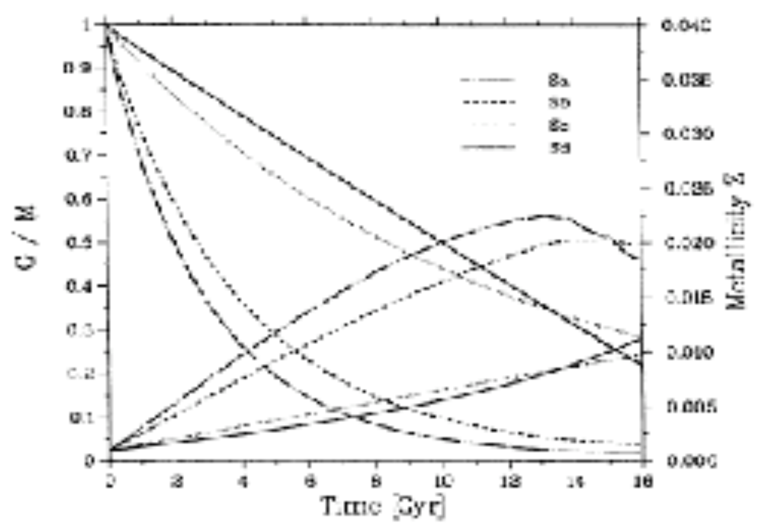
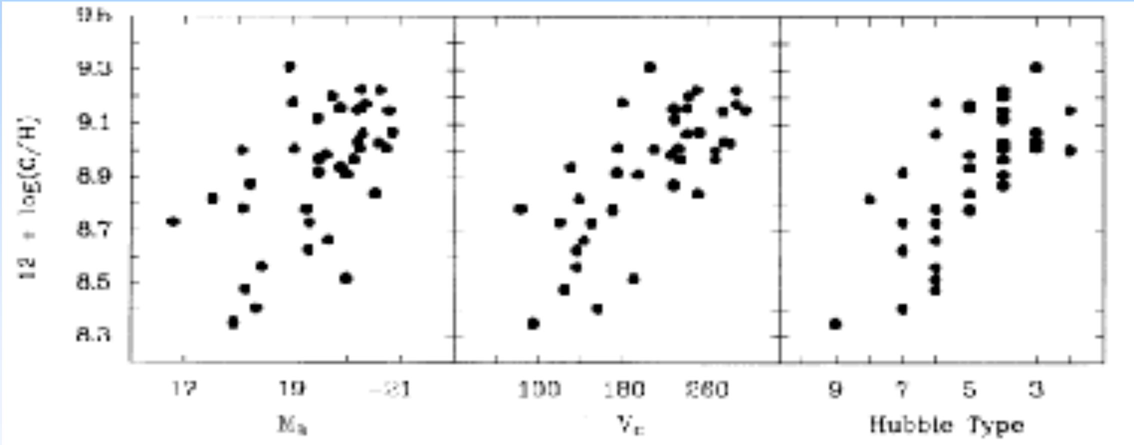


Fig. 3. Evolution of the gas fraction G/M and the global metallicity Z in different merger progenitor models



(FvA & Gerhard 1994a)

(Zaritsky et al. 1994)

Galaxy Models

Models for E, S0, Sa, Sb, Sc, Sd (spectral types!) at ages 13 Gyr have to agree with

☆ emission line strengths : SFR_o

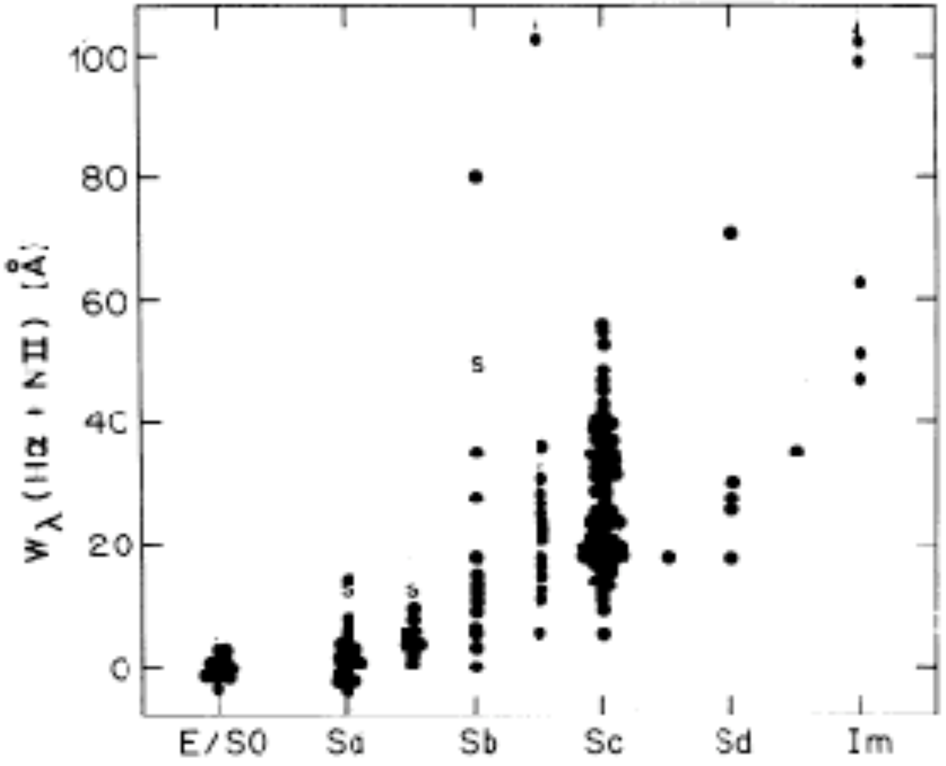


FIG. 5. Distribution of Hα + [N II] emission equivalent width, binned by RSA Hubble type. The symbol *S* denotes a Seyfert galaxy.

(Kennicutt & Kent 1983)

Galaxy Models

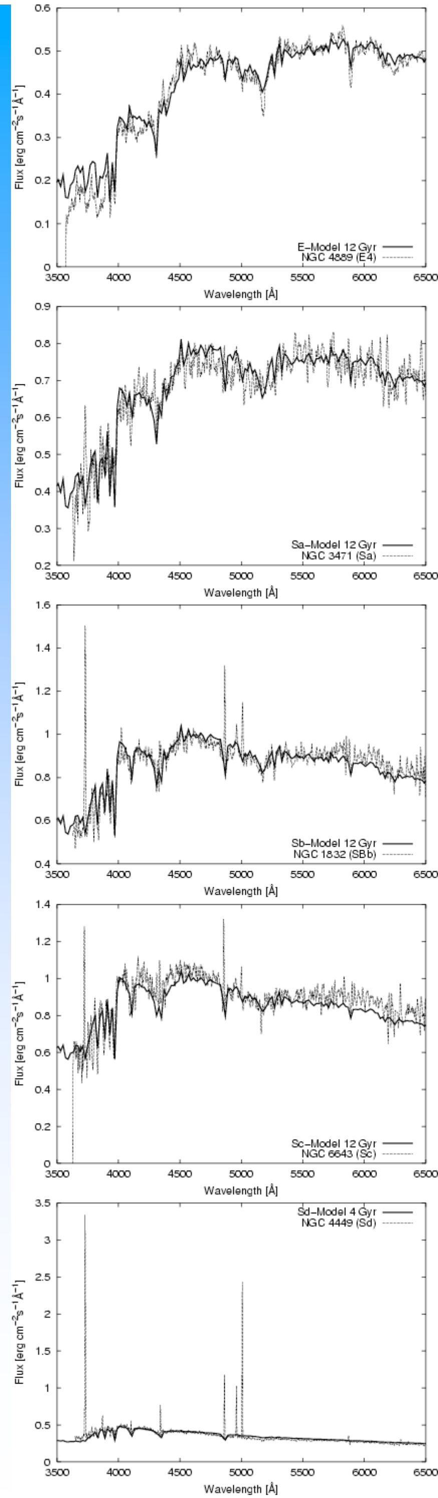
Models for E, S0, Sa, Sb, Sc, Sd
(spectral types!) at ages
13 Gyr have to agree with

☆ template spectra

(Kennicutt 1992, Kinney et al. (UV))

(Sd template can only be fit at age ~4 Gyr)

(Bicker et al. 2004)



Galaxy Models

Models for E, S0, Sa, Sb, Sc, Sd (spectral types!) at ages 13 Gyr have to agree with

- ☆ **gas-to-total mass ratios**

(Zaritsky et al. 1994)

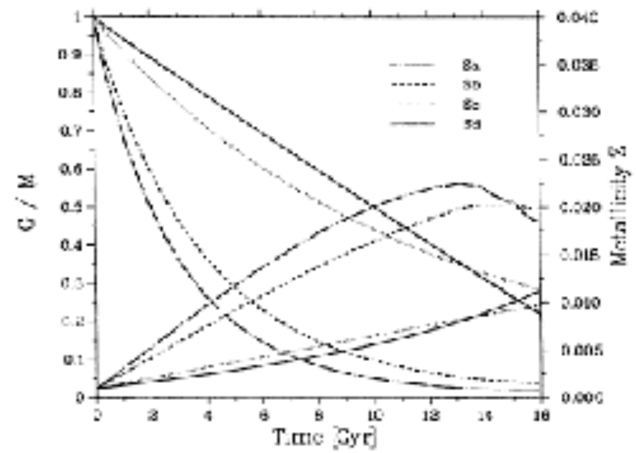


Fig. 3. Evolution of the gas fraction G/M and the global metallicity Z in different merger progenitor models

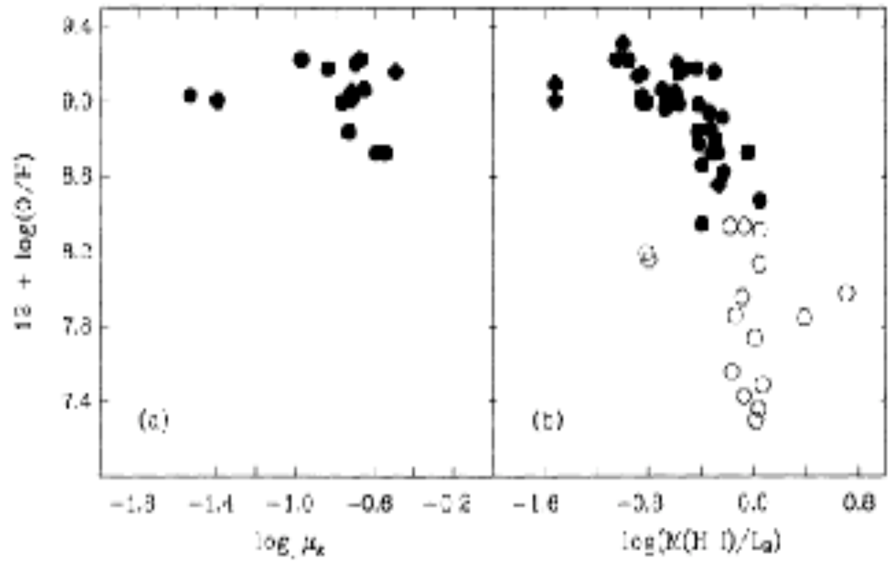


FIG. 14.—O/H plotted vs. gas fraction in the left panel (a) and vs. the galaxy's mass in H I divided by its blue luminosity (in solar units) in the right panel (b). Filled circles indicate our abundance data for galaxies for which the gas data was available in the literature. Open circles represent data from Skillman et al. (1989).

Chemically Consistent Evolutionary Synthesis
GALEV

simultaneous modelling of the

★ chemical evolution of the gas/ISM and the

★ spectral evolution of the stellar component (incl. gaseous emission : HII regions)

➜ chemically consistent approach

: = account for increasing initial abundances of successive stellar generations

by using input physics of appropriate metallicity for each stellar generation

Why Chemically Consistent Modelling ?

★ **Bulk of local galaxy population have subsolar abundances**

late – type & dwarf galaxies

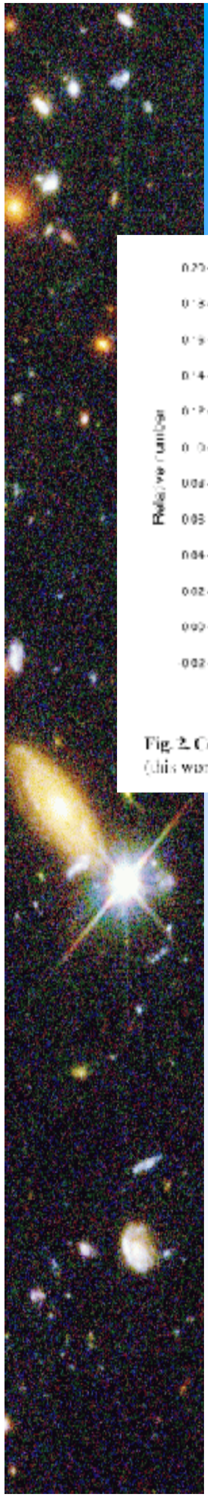
★ **Normal local galaxies feature broad stellar metallicity distributions**

solar neighbourhood, MW & M31 bulges, ellipticals

★ **Distant galaxies are less evolved / enriched**

in particular the faint ones in Deep Fields

Observed Stellar Metallicity Distributions



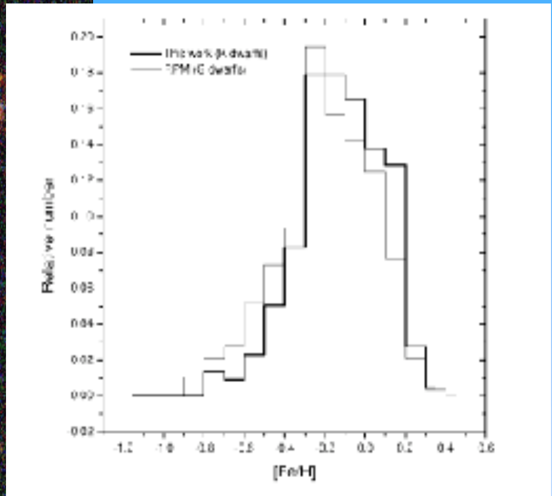
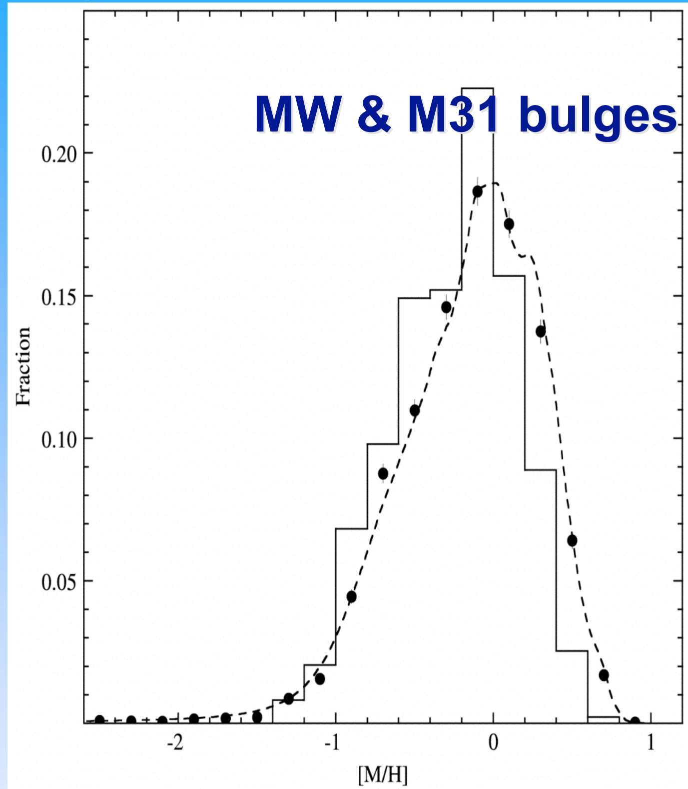


Fig. 2. Comparison between the metallicity distributions for K dwarfs (this work) and G dwarfs (RPM).

Solar neigh-
bourhood
G-, K-, M- stars

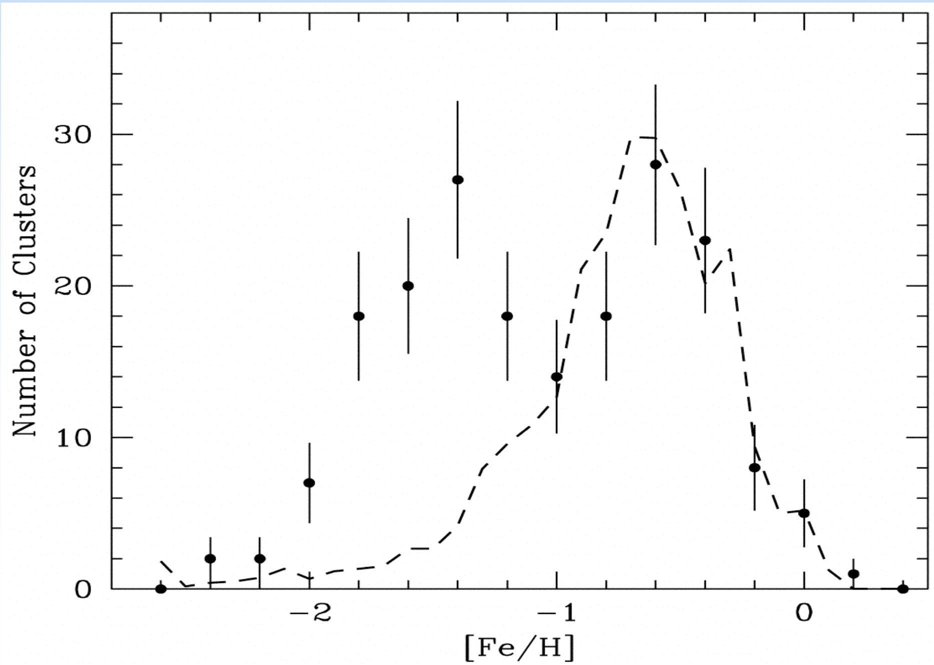
(Rocha-Pinto & Maciel 1998)

Δ[Fe/H] ~ 2 dex



MW & M31 bulges

(Sarajedini & Jablonka 05)



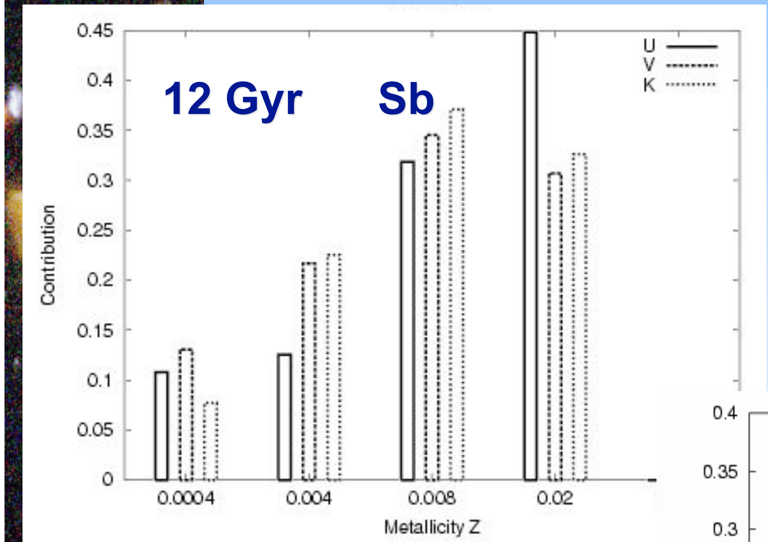
E : NGC 5128 halo

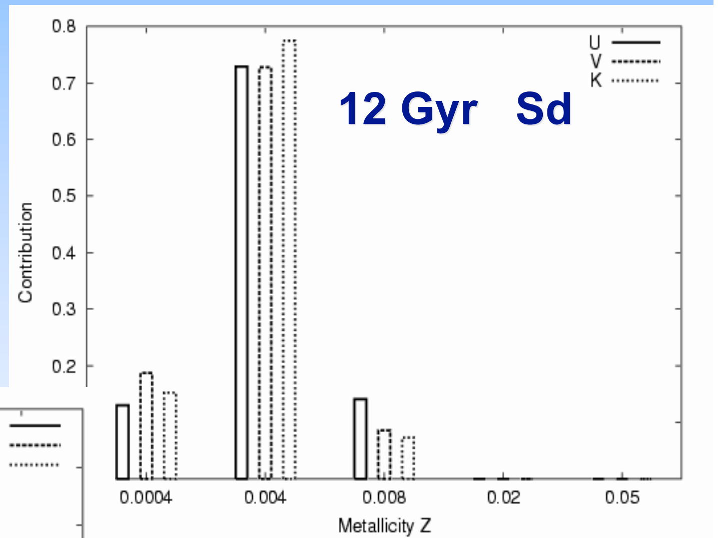
(Harris & Harris 2000)

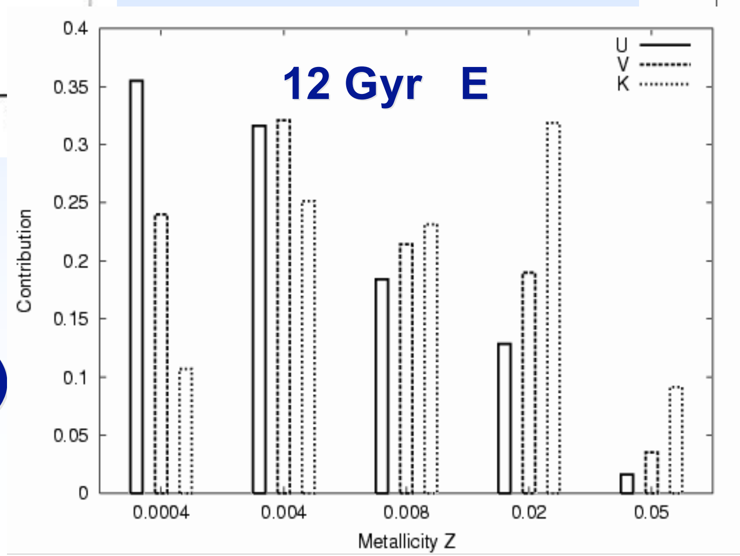
Chemically Consistent Evolutionary Synthesis

Stellar metallicity distributions in model galaxies

➜ light contributions from different metallicity & age subpopulations dominate at different wavelengths





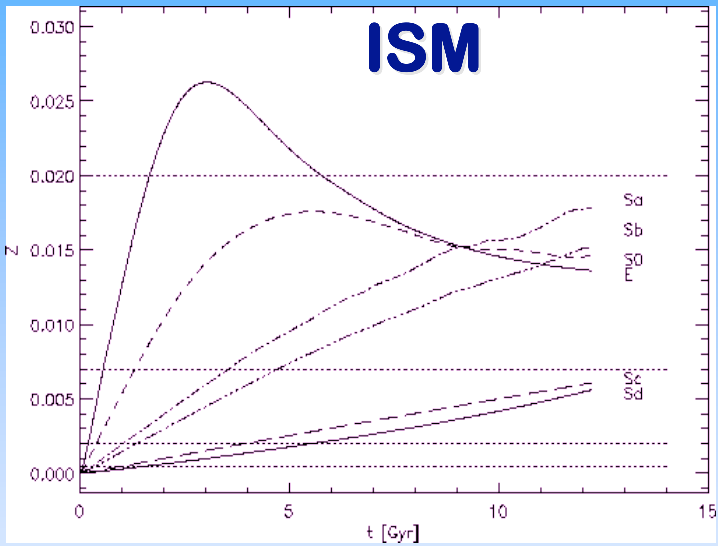


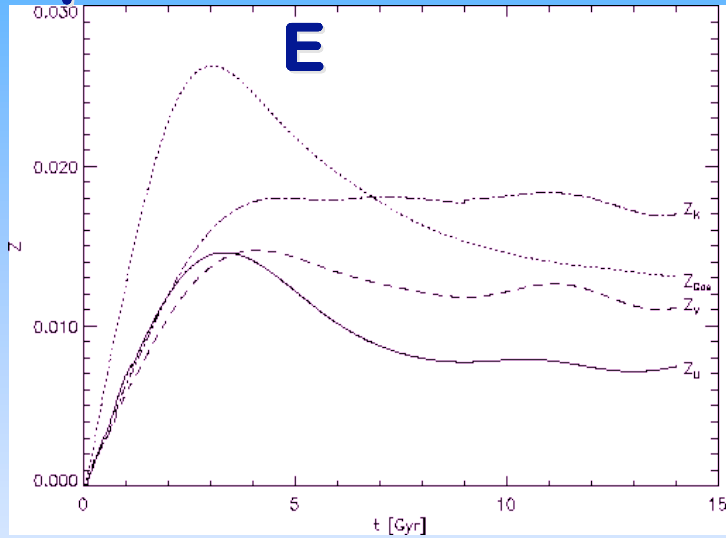
(Bicker et al. 2004)

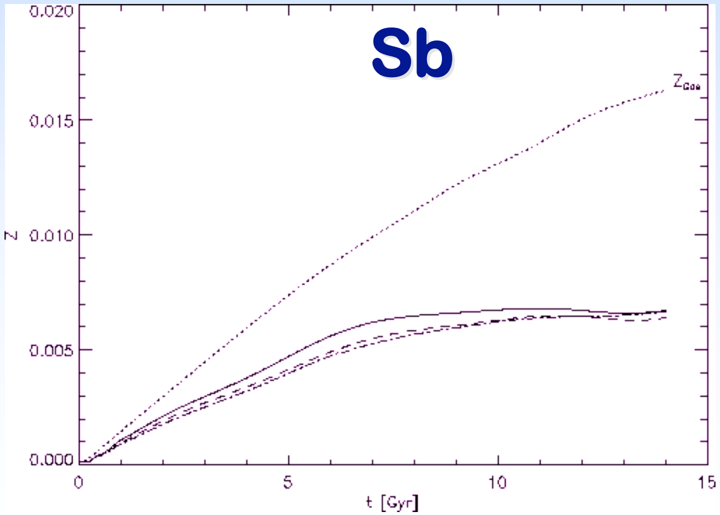
Elliptical ≠ SSP

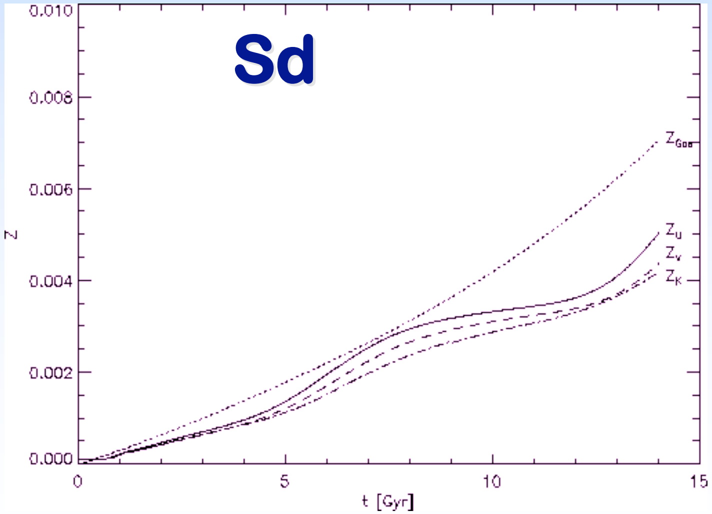
Chemically Consistent Evolutionary Synthesis

ISM abundances and luminosity weighted stellar metallicities in various passbands



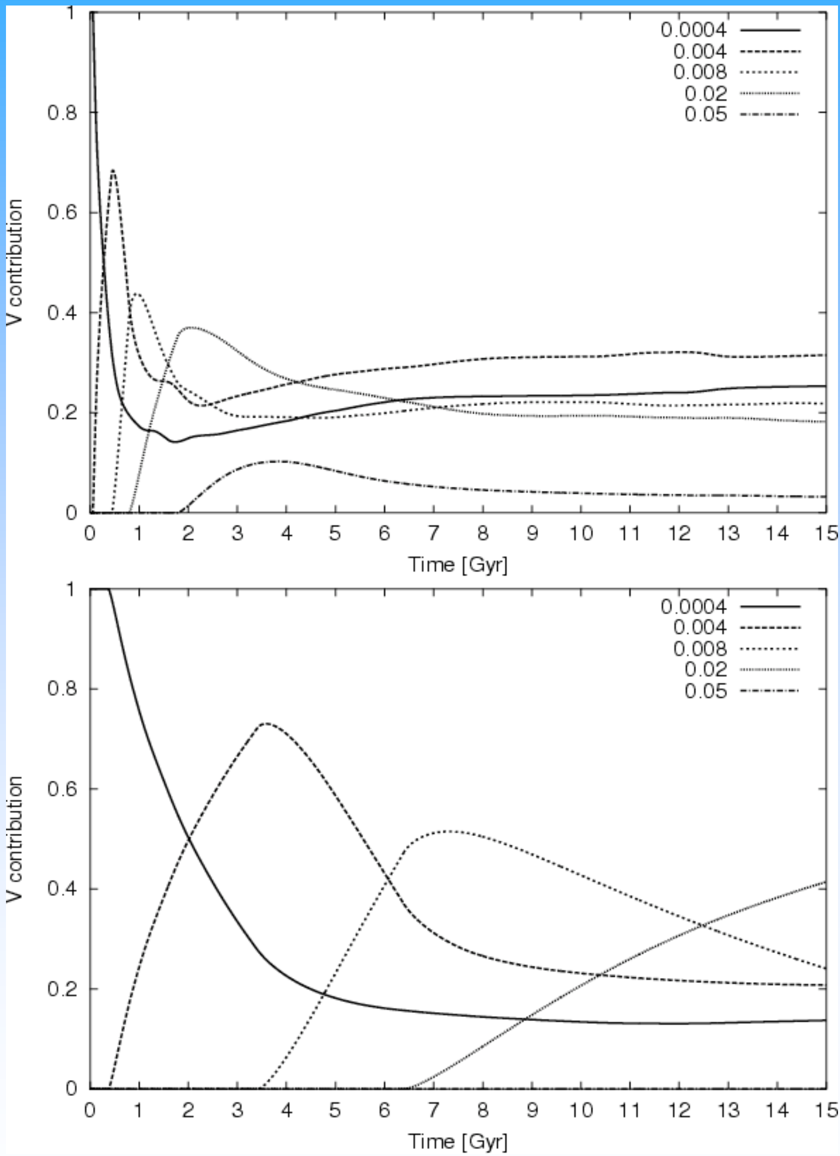






Möller, FvA, Fricke 1997

Chemically Consistent Evolutionary Synthesis



V – band luminosity contributions of different metallicity subpopulations

E

Sb

Bicker, FvA, Möller 2004

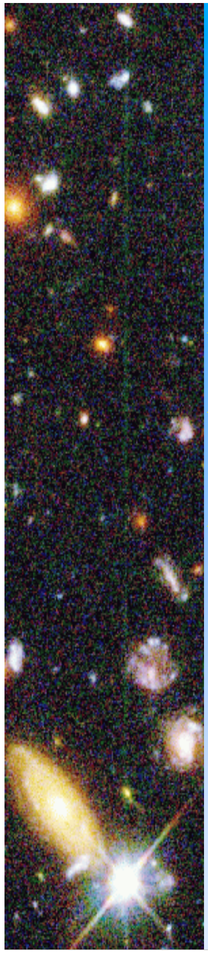
Implications for Local Galaxies

SFRs from H_α , O[II], UV severely overestimated for low metallicity galaxies

	Z=0.0004 I ZW 18, SBS 0335	$Z_\odot$	Z=0.05
H_α	2	1	0.85
O[II]	3	1	0.87
UV(1500)	1.3	1	0.89
UV(2800)	1.4	1	0.89

when using standard calibrations (Kennicutt 98, Gallagher et al. 89) **valid for $Z \sim Z_\odot$**

(Bicker & FvA 2005)

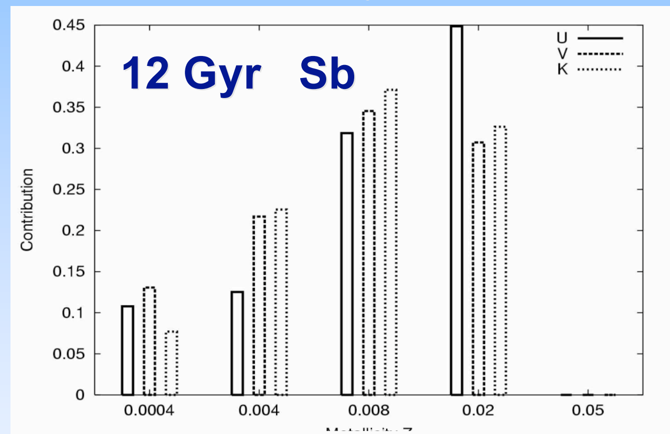


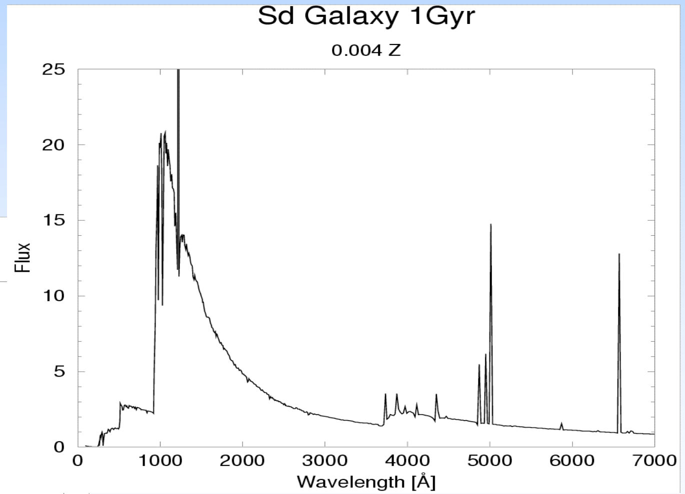
Chemically Consistent Evolutionary Synthesis

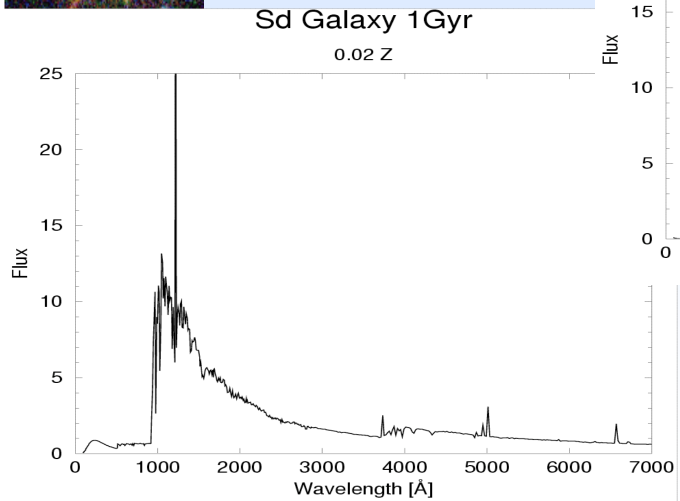
important in the Local Universe for :

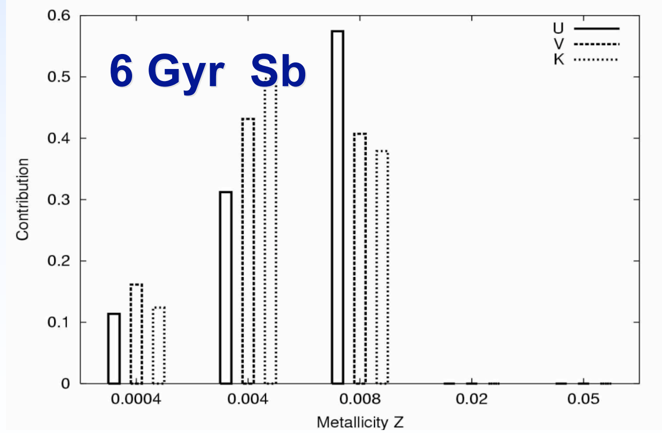
- ★ **low metallicity galaxies (late type spirals & dwarfs)**
- ★ **composite metallicity stellar pop's in normal galaxies**
- ★ **age determinations, M/L, SFRs, metallicities, etc.**

➜ **galaxies in the early Universe**









GALEV Evolutionary Synthesis Models

+ Cosmological model $(H_o, \Omega_o) = (70, 1)$

$(\Omega_m, \Omega_\Lambda) = (0.3, 0.7)$

Big Bang → Universe expanding

Hubble's law : distant galaxies recede : $v = H_o \cdot r$

recession velocity v → redshift z (relativistic Doppler effect)

redshift z = measure of distance r

c finite → distant galaxies seen in earlier evolutionary stages

Lookback time t_1 to redshift z_1

$$t_0 - t_1 = H_0^{-1} \int_0^{z_1} (1+z)^{-1} [(1+z)^2 (1+\Omega_M z) - z(2+z)\Omega_\Lambda]^{-1/2} \, dz.$$

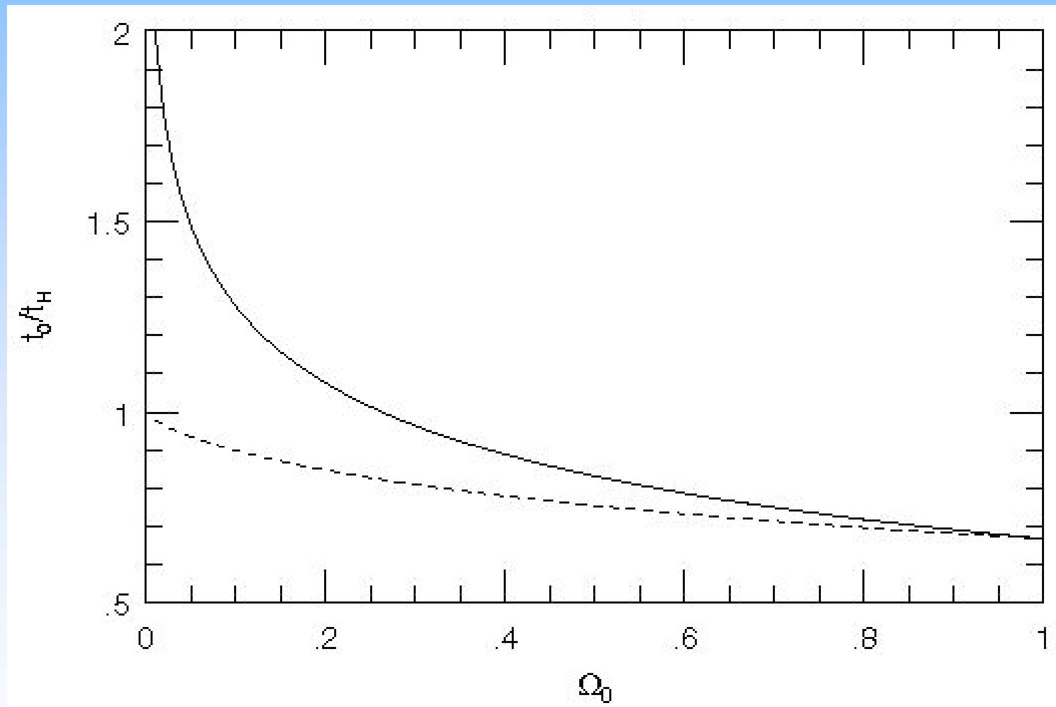
z =	0	1	2	4	6	
age =	14	5	3	1	0.5	Gyr

Cosmological Effects

Time $t(z=0) = 1/H_o = t_H$ **only for** $\Lambda_o = 0$,

for $\Lambda_o \neq 0$: $t(z=0) > 1/H_o$ **. With scale parameter a**

$$t(a)=1/H_o \int_0^a da\,[a^{-1}\,\Omega_m + (1-\Omega_m - \Omega_\Lambda) + a^2\,\Omega_\Lambda]^{-1/2}$$



$H_o=70$

$\Omega_m=0.3$

$\Omega_\Lambda=0.7$

Redshift of galaxy formation : $z_f = 6 - 10$, $t_{gal} = t_H - t\,(z_f)$

Cosmological Effects

Light dimming : luminosity distance D_L

$$D_L := (L_{abs} / 4\pi\, L_{app})^{1/2}$$

= analogue to Euklidian distance in curved spacetime

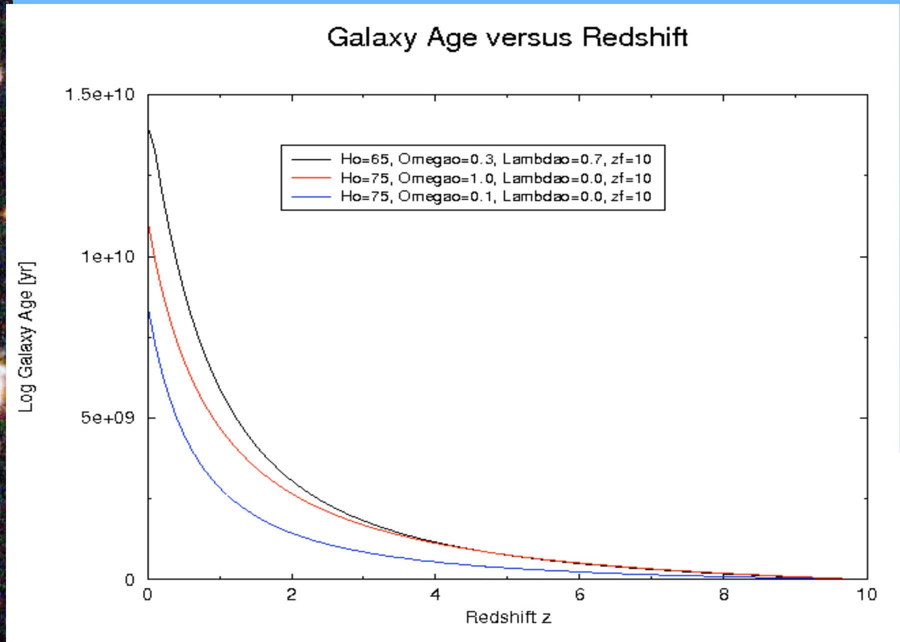
$$H_0\, D_L = \frac{1}{|\Omega_k|^{1/2}} \,\mathrm{sinn}\left\{ |\Omega_k|^{1/2} \int_0^{z_1} [(1+z)^2(1+\Omega_M z) - z(2+z)\Omega_\Lambda]^{-1/2}\, dz \right\},$$

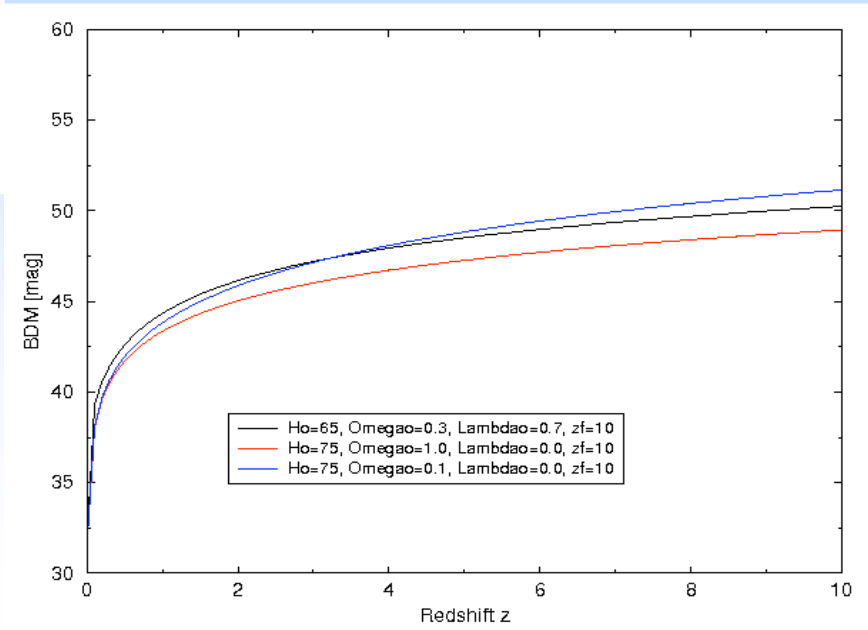
sinn = sinh for $\Omega_k > 0$ or sin for $\Omega_k < 0$

Bolometric distance modulus BDM(z) = 5 log D_L(z) + 25

High Redshift Galaxies

Galaxy age and BDM as a function of redshift





Cosmological Effects

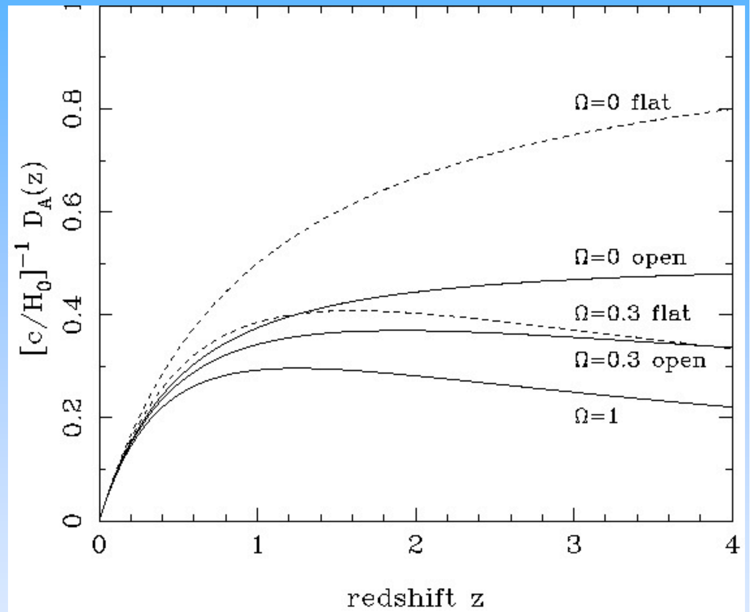
Angular diameter θ, distance d, linear size x

$$\tan(\theta) = \frac{x}{d} \qquad \theta = \frac{x}{d}$$

decreases with redshift until z~1,

then slightly increases again

$$D_L = (1 + z)^2 \, d_A$$



Angular size distance d_A

$$d_A = \frac{x}{\theta} \qquad d_A = \frac{r(\chi)}{1+z}$$

$$r(\chi) = \begin{cases} \sin\left(\sqrt{-\Omega_k} H_0 \chi\right) / \left(H_0 \sqrt{|\Omega_k|}\right) & \Omega_k < 0 \\ \chi & \Omega_k = 0 \\ \sinh\left(\sqrt{\Omega_k} H_0 \chi\right) / \left(H_0 \sqrt{|\Omega_k|}\right) & \Omega_k > 0 \end{cases}$$

curvature

density

$$d_a = \frac{c}{H_0 q_0^2} \frac{(z q_0 + (Q_0 - 1)(\sqrt{2 q_0 z + 1} - 1))}{(1+z)^2}$$

Cosmological Effects

Surface brightness decreases dramatically with increasing redshift

$$\mu(z) \sim (1+z)^{-4}$$

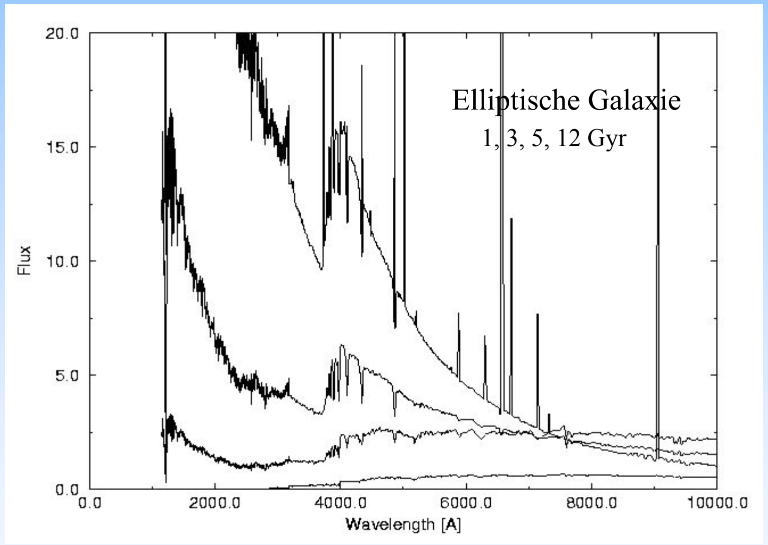
faint structures & faint objects vanish rapidly with increasing redshift

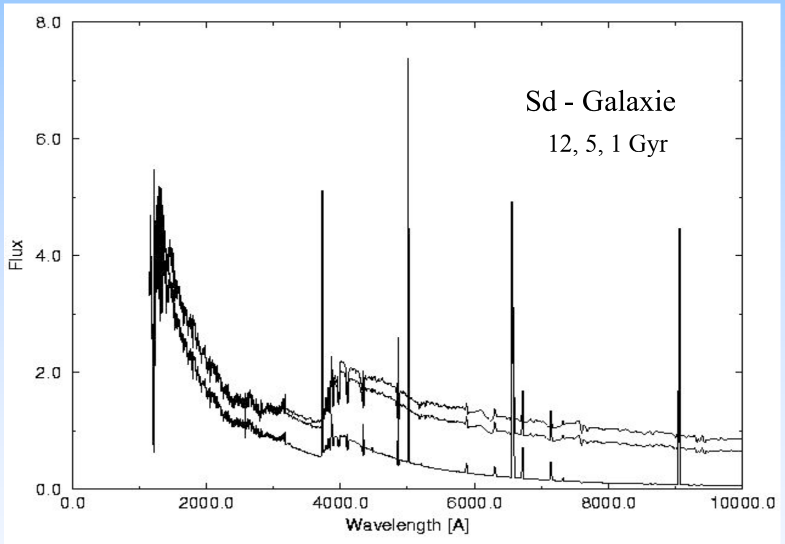
High Redshift Galaxies

★ Distant galaxies are seen in younger stages :

→ evolutionary correction

$$e_\lambda := M_\lambda(z, t_{gal}(z)) - M_\lambda(z, t_0) \quad \text{(galaxy type)}$$



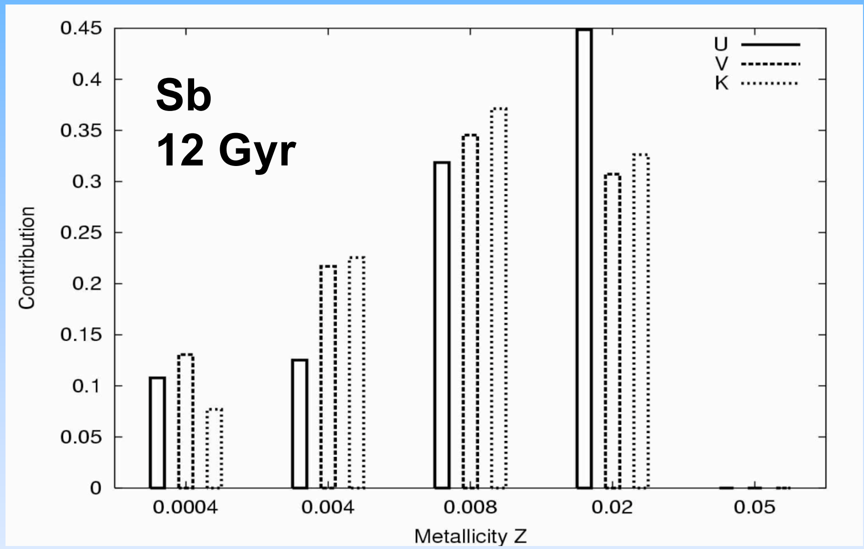


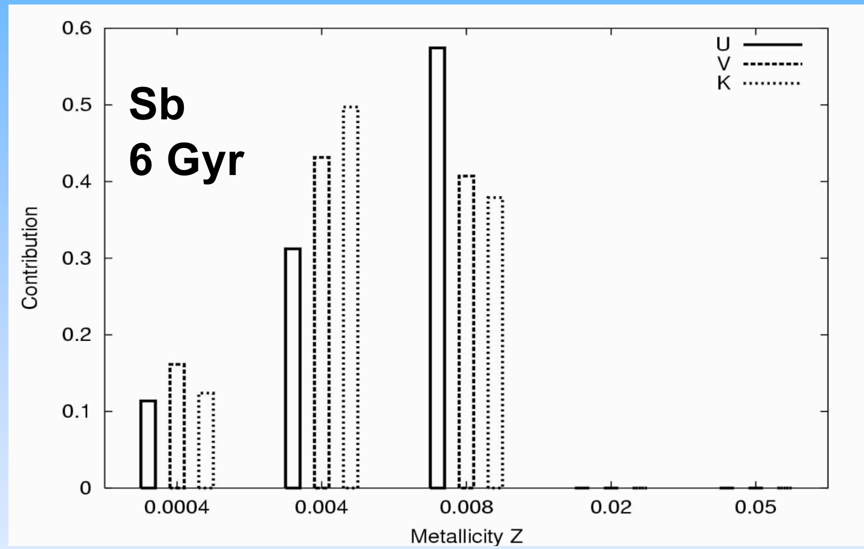
evolutionary correction strong for galaxies with

strongly variable SFR(t)

High Redshift Galaxies

★ Distant galaxies less enriched : chemically consistent models





(Bicker et al. 2004)

High Redshift Galaxies

Light from distant galaxies :

★ redshifted & diluted in expanding Universe

$$\lambda_{obs} = \lambda_0 \cdot (1+z) \qquad F_\lambda^{obs} = F_\lambda^0 \; / \; (1+z)$$

Opt. observations of galaxy at z > 1 show restframe UV
NIR observations - " - - " - opt.

→ cosmological correction :

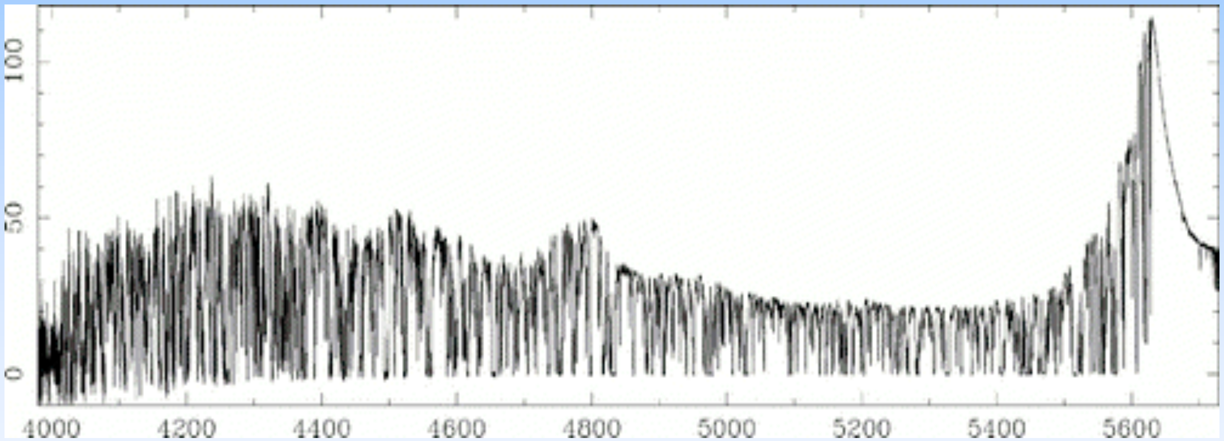
$$k_\lambda := M_\lambda(z, t_0) - M_\lambda(0, t_0) \text{ (gal. type)}$$

★ reddened & attenuated by intergalactic HI (Madau 1995)

"Attenuation" for wavelengths $\lambda_{restframe} < 1216$ A
seen in the optical for galaxies at z > 2.5
seen in the UV for galaxies at z > 1
→ GALEX data

High Redshift Galaxies : Attenuation

Intergalactic HI, in the form of Lyα clouds, Lyman Limit Systems and galaxy haloes causes a forest of absorption lines shortward of Lyα @ 1215 A in the spectra of distant galaxies



High resolution (FWHM~6.6 km/s) spectrum of the z=3.2 QSO 1422+23 with Keck HIRES @ S/N~150 /resolution element (Fig. from Rauch 1998, ARAA)

High Redshift Galaxies : Attenuation

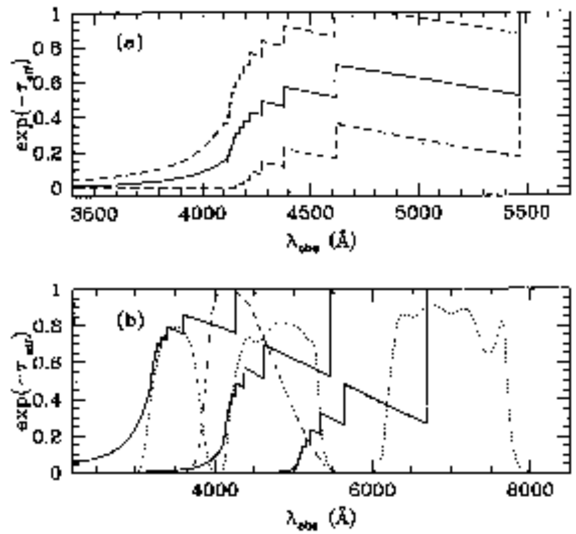


FIG. 3.—Transmission of the universe as a function of observed wavelength, averaged over [illegible] lines of sight. (a) Mean cosmic transmission for a source at $z_{em} = 3.5$ (solid line), together with the expected 1 σ rms scatter caused by statistical fluctuations in the number of absorbers along the path (dashed lines). The characteristic staircase profile is due to continuum blanketing from the Lyman series. (b) Mean transmission spectrum for a source at $z_{em} = 2.5$, 3.5, and 4.5 (solid lines). Also plotted are the response functions of a standard Johnson B filter (dashed line), and the three broad passbands, $\mathcal{U}_n$, $\mathcal{G}$, and $\mathcal{R}$ used by Steidel & Hamilton (dotted lines).

transmission of the universe as a function of wavelength for source @ z=3.5

mean transmission for sources @ z=2.5, 3.5, 4.5 with filters $\mathcal{U}$, $\mathcal{G}$, $\mathcal{R}$ (Steidel)

mean attenuation [mag] in different filters as a function of redshift.
lower curves Lyα only,
upper curves: all Ly lines.

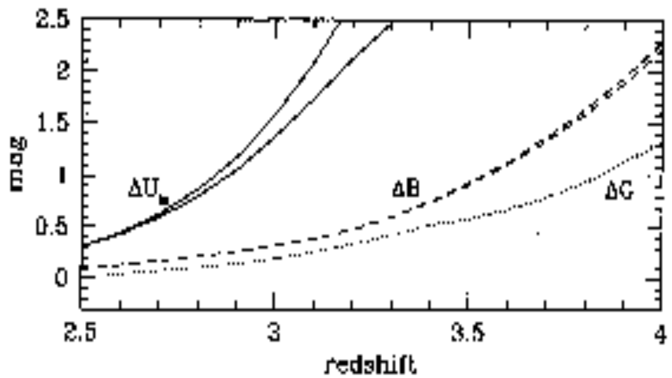
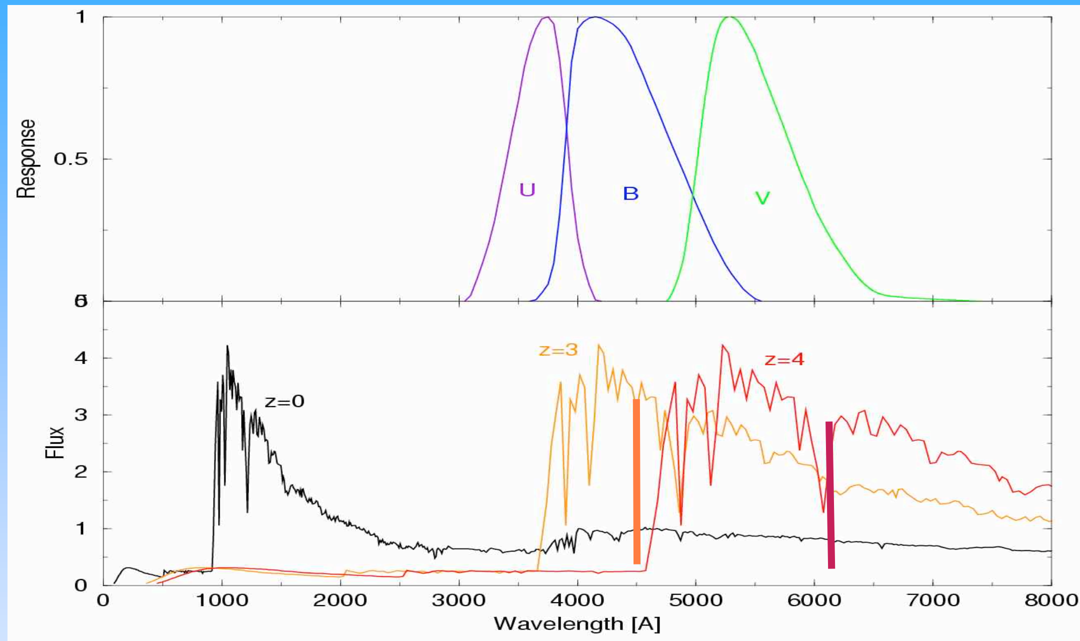


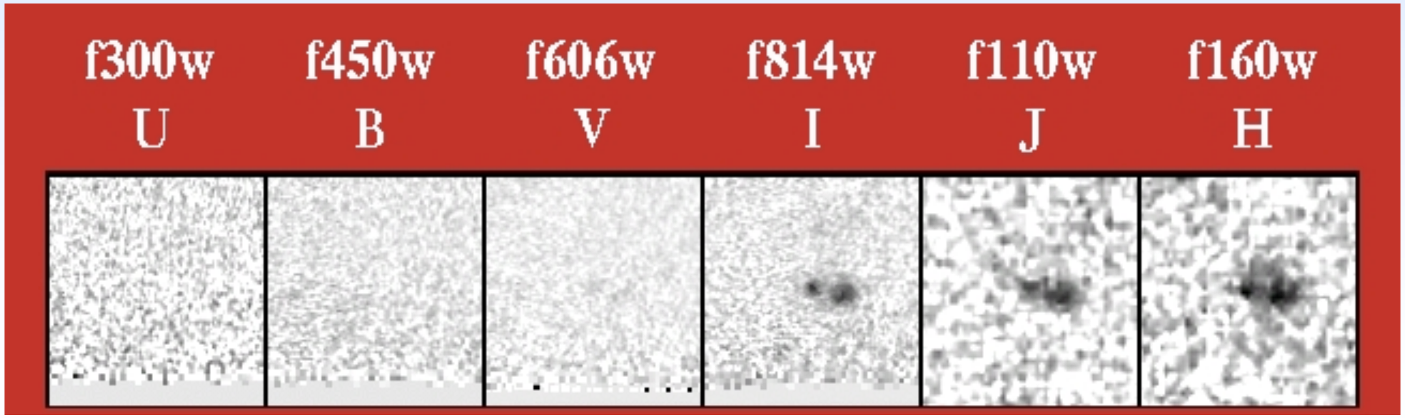
FIG. 4.—Magnitude increments ΔU_n (solid lines), ΔB (dashed lines), and ΔG (dotted lines), derived by integrating the mean cosmic transmission over the corresponding bandpass, as a function of the emission redshift. The lowest of each pair of curves includes [illegible] absorption by Lyman-α clouds alone.

Madau 1995

Drop Out Technik - Lyman Break Galaxies



V drop out : Lyman Break Galaxy with $z_{spec} = 5.3$

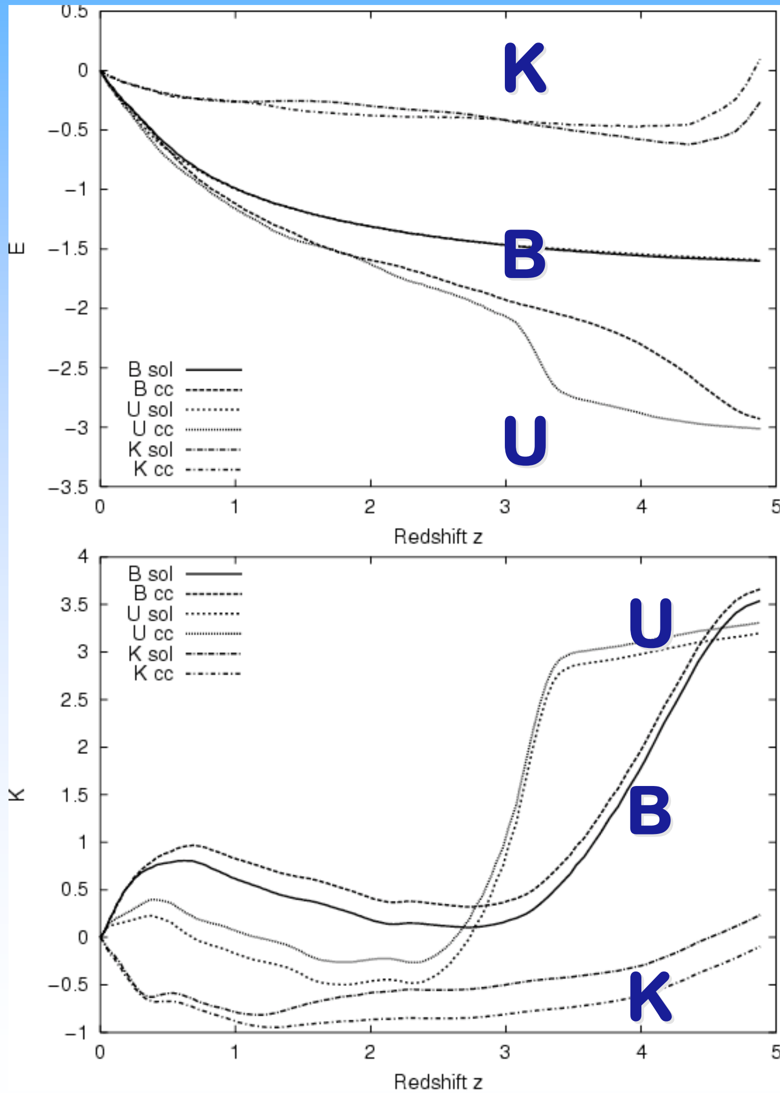


High Redshift Galaxies

$$m_{\lambda}(z)=M_{\lambda}(z=0,t_{o})+BDM(z)+e_{\lambda}(z)+k_{\lambda}(z)$$

Evolutionary and cosmological corrections : Sb model $Z_{\odot}$ only vs. chem. cons. model

(Bicker et al. 2004)



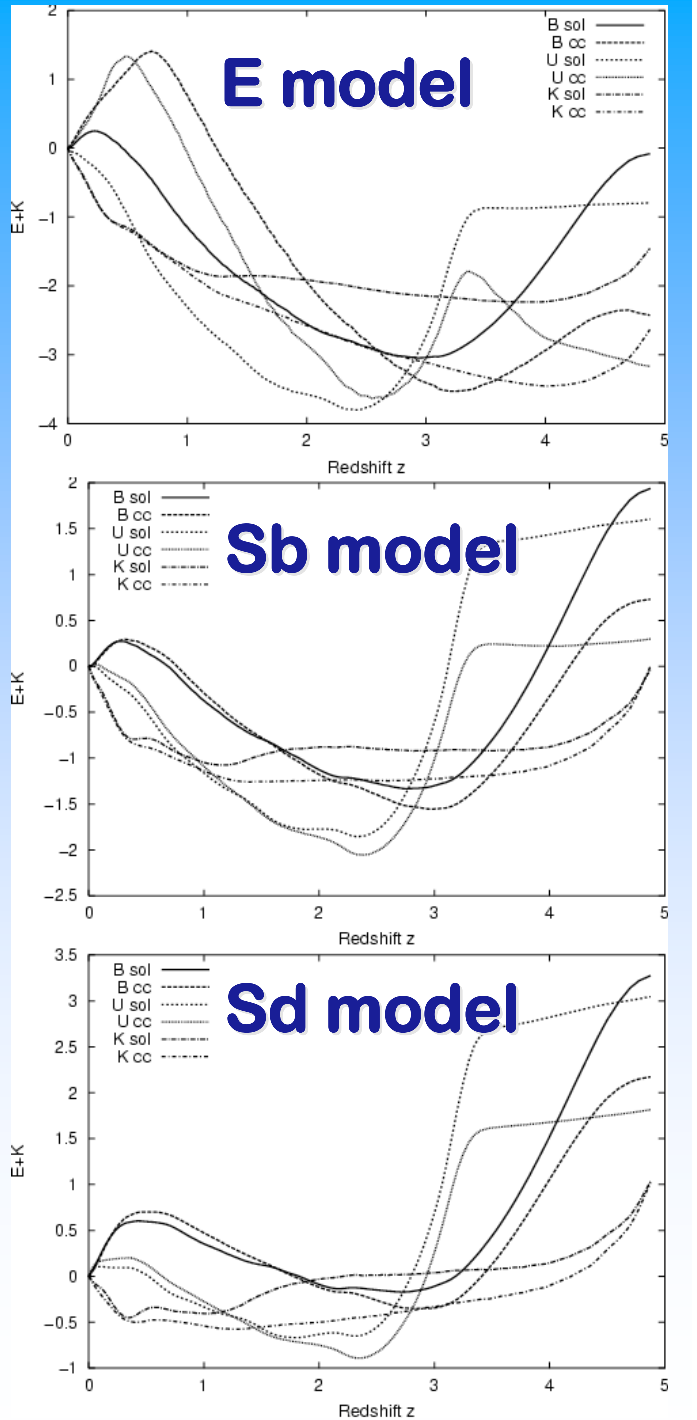
High Redshift Galaxies

Evolutionary + cosmological corrections :
E, Sb, Sd models

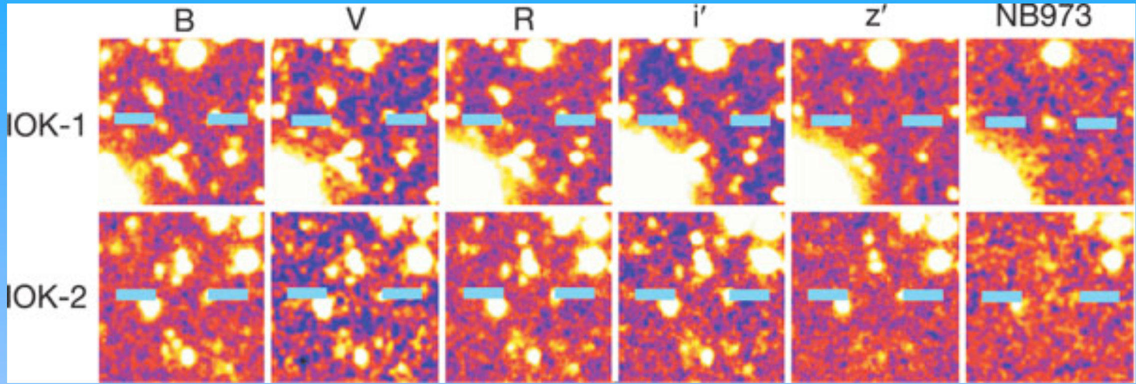
(Bicker et al. 2004)

$$m_\lambda(z)=M_\lambda(z=0,t_o)+BDM(z)+e_\lambda(z)+k_\lambda(z)$$

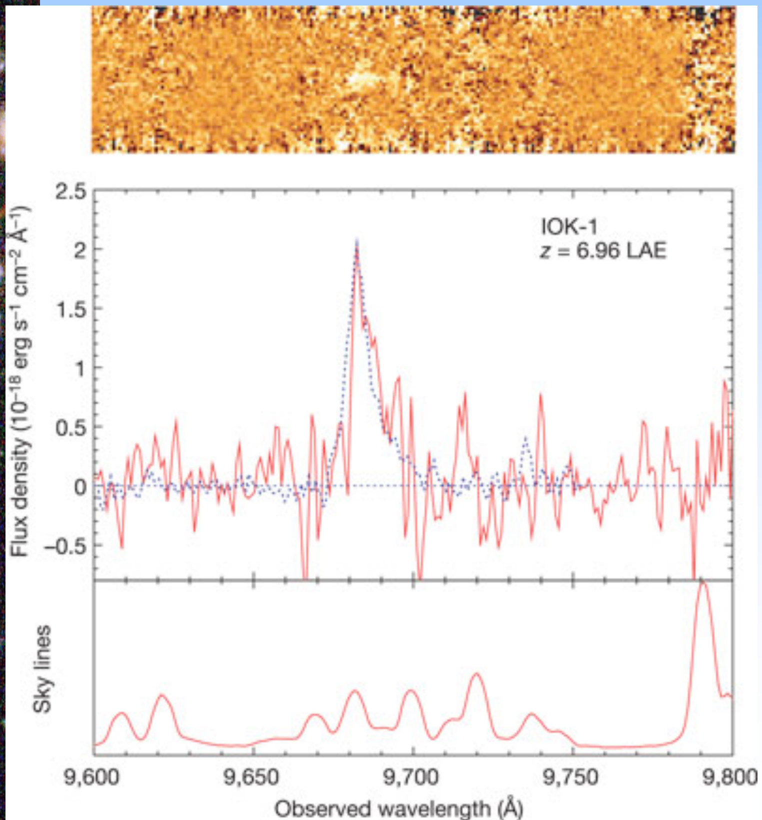
(e+k) > 0 ➜ galaxies fainter,
(e+k) < 0 ➜ galaxies brighter



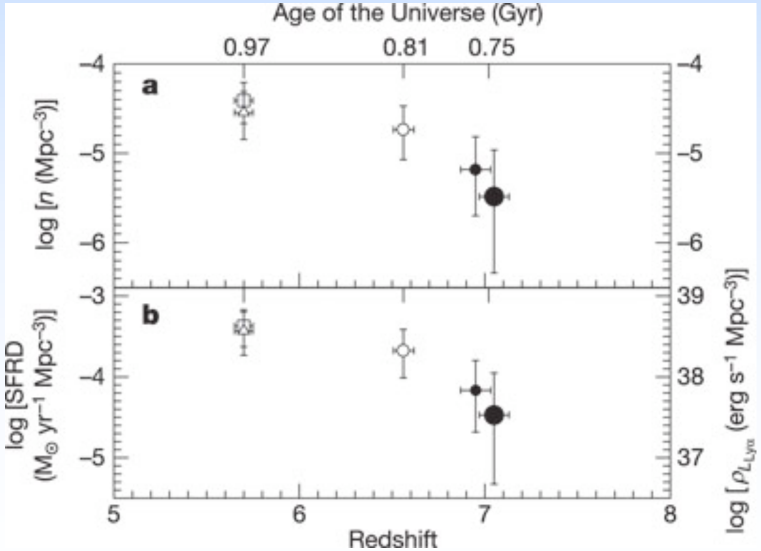
Redshift Record 2006



Subaru Deep Field z dropout at z=6.96 (Iye+06, Nat. 443, 186)



750 Myr after Big Bang, Lya line, SFR~10 Msun/yr



Redshift Surveys

Center for Astrophysics Redshift Survey : 17,000 galaxies

to $z < 0.05$

Large Scale Structure: Cosmic web :

voids, groups, clusters, filaments

galaxy groups : Ø ~ 1 Mpc

galaxy clusters : Ø ~ 3 – 10 Mpc

voids : Ø ~ 50 – 100 Mpc

Great Wall : L ~ 100 Mpc = largest structure

no structures on scales > 200 Mpc

--> universe homogeneous : cosmological principle !

$R_{Hubble} = c/H_o = 3000\ h^{-1}$ Mpc

Redshift Surveys

Las Campanas Redshift Survey : R-band 26,418 redshifts
over total field of 700 deg^2 , (N & S Galactic Caps),
Large Scale Structure: voids, groups, clusters, filaments
$\langle z \rangle = 0.1$

Canada France Redshift Survey CFRS : I-band 591 galaxies $17.5 < I_{AB} < 22.5$, $0 \leq z \leq 1.3$, $\langle z \rangle = 0.56$

Sloan Digital Sky Survey SDSS : 3rd data release:
spectra of 528,640 objects over 4188 deg^2 ,
2.5m Apache Point Telescope
QSOs and galaxies to z~6, but $\langle z \rangle = 0.03$
ongoing till 2008 (now @ data release #5)

huge amounts of observing time :
many galaxies @ low z, few @ high z

Redshift Surveys

huge amounts of observing time :

many galaxies @ low z, few @ high z

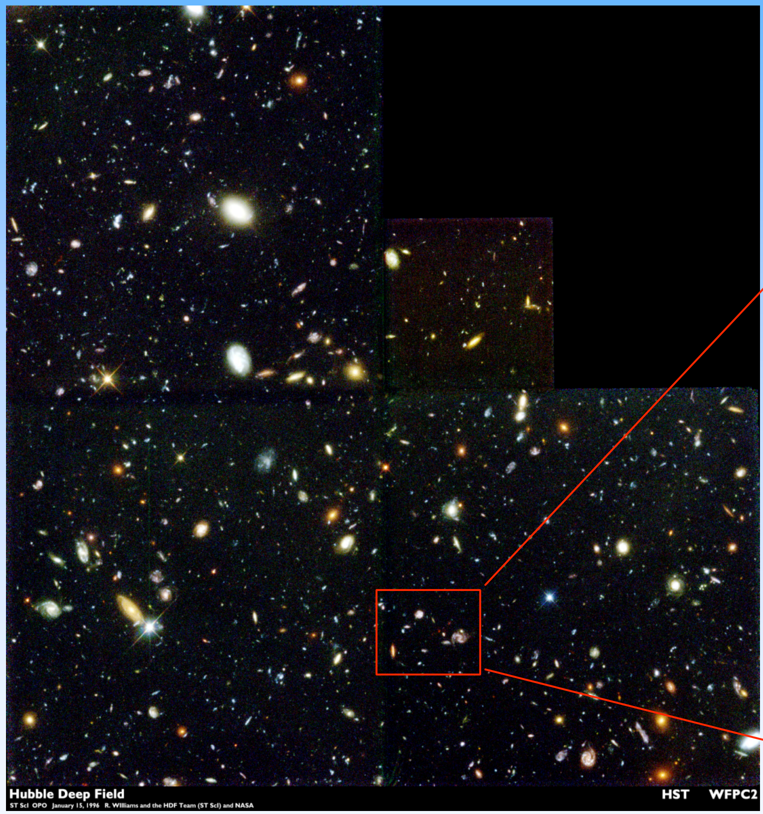
Look for other strategies to find high – z galaxies :

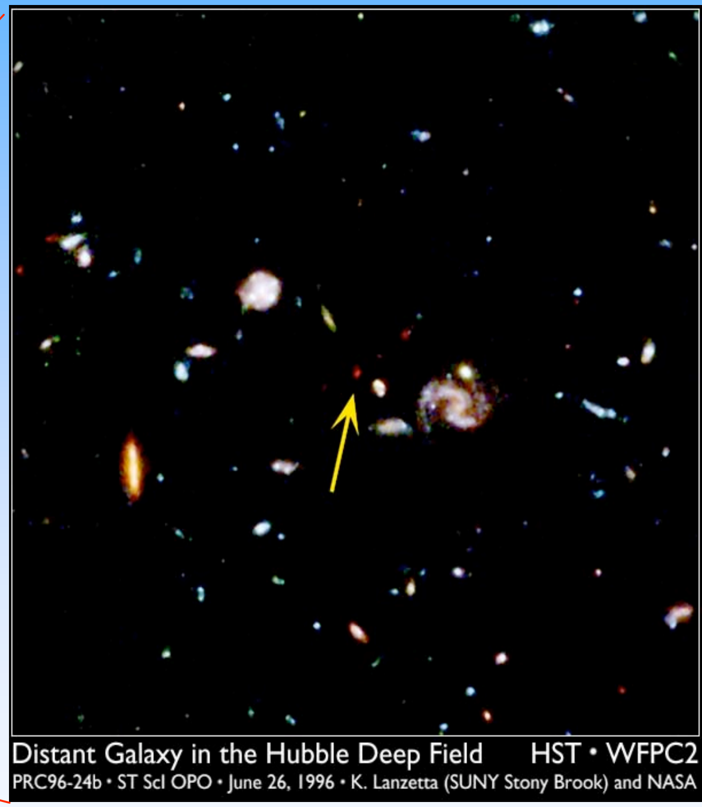
-- Lyman - α searches
-- QSO fields
-- optical identifications of QSO absorbers
-- drop out technique
-- color selection criteria for SFing and passive galaxies
-- photometric redshifts

Deep Fields

Faintest galaxies : 29 mag (UBVRIJHK)

Spectroscop. limit : 25 mag (= factor 40 brighter)

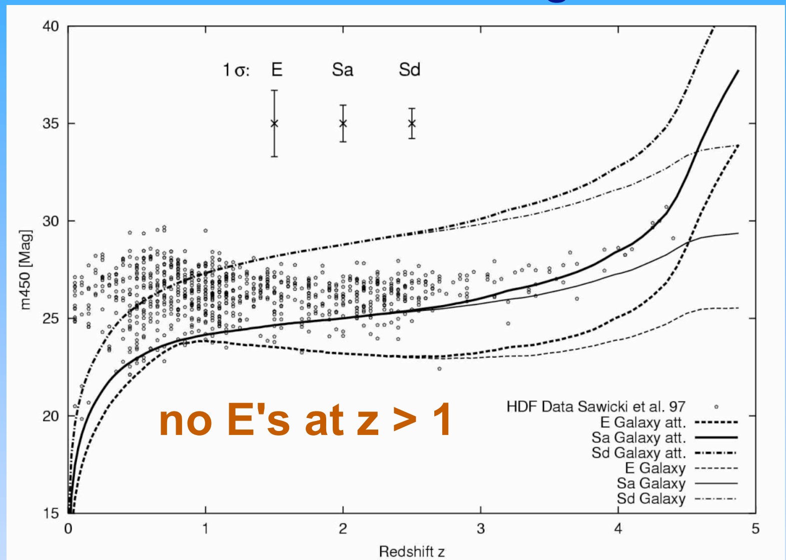




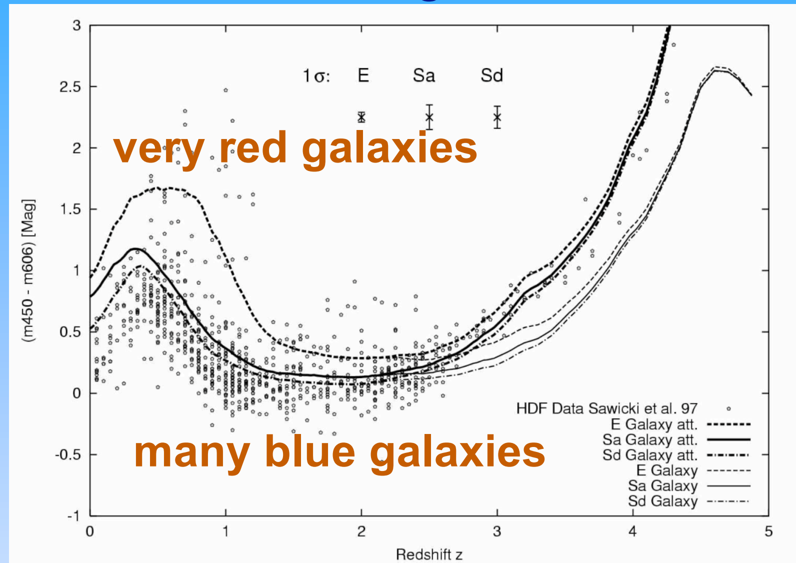
→ Drop Out technique & Photometric redshifts

High Redshift Galaxies

B-band luminosities - HDF galaxies



B-V colors - HDF galaxies



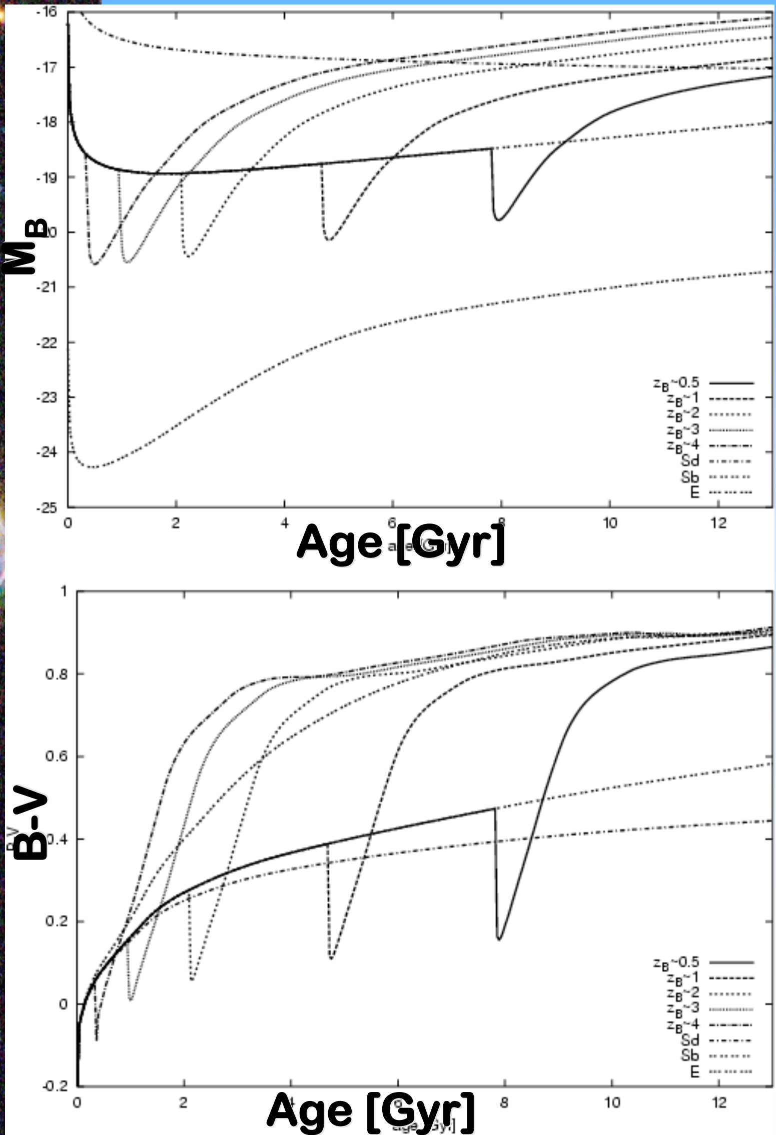
Chemically consistent GALEV models vs HDF galaxies:

- → trace back spectral evolutionary paths to $z > 4.5$
  i.e. over $> 95\ \%\ t_{Hubble}$
- → fair description of average properties of normal galaxies
- → identify high-z progenitors of local galaxy types
- → study mass assembly & chem. enrichment histories

(Möller, Fritze, Fricke 98, Fritze, Möller, Fricke 99a,b, Bicker, Fritze, Möller 04)

Starburst & Post-Starburst Galaxies at High Redshift

Starbursts on top of undisturbed galaxies

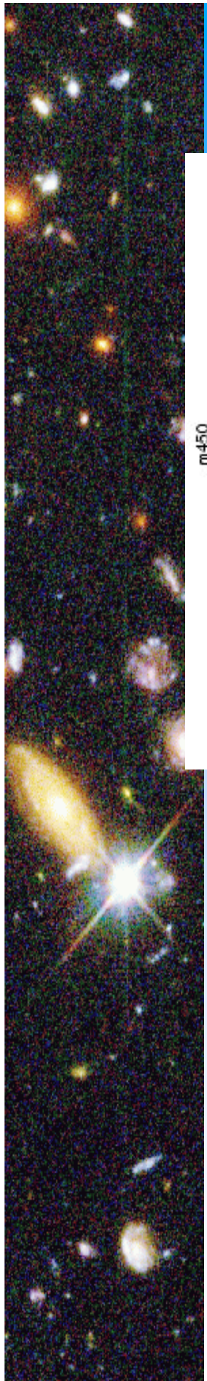


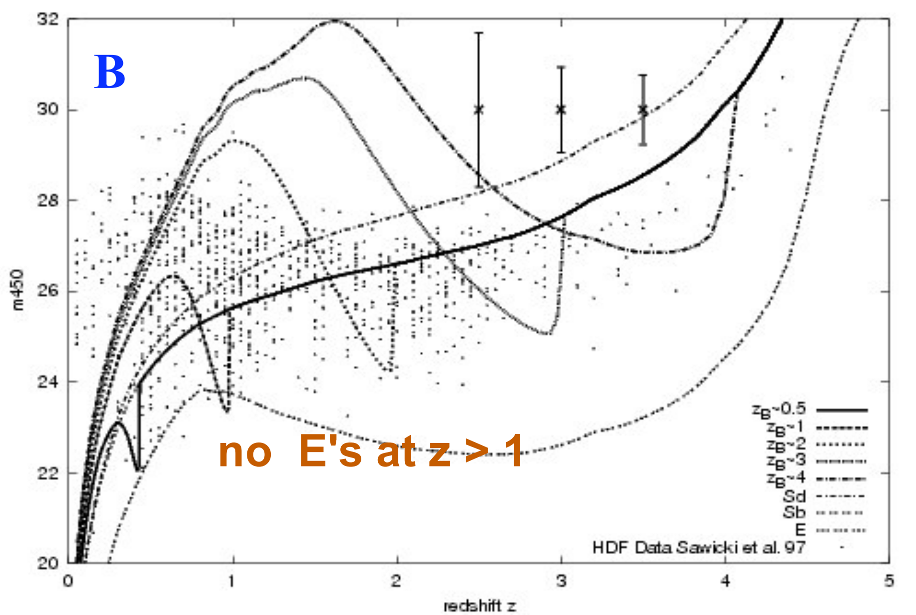
- of various types Sa, Sb, Sc, Sd
- starting at various ages
- with various bursts strengths

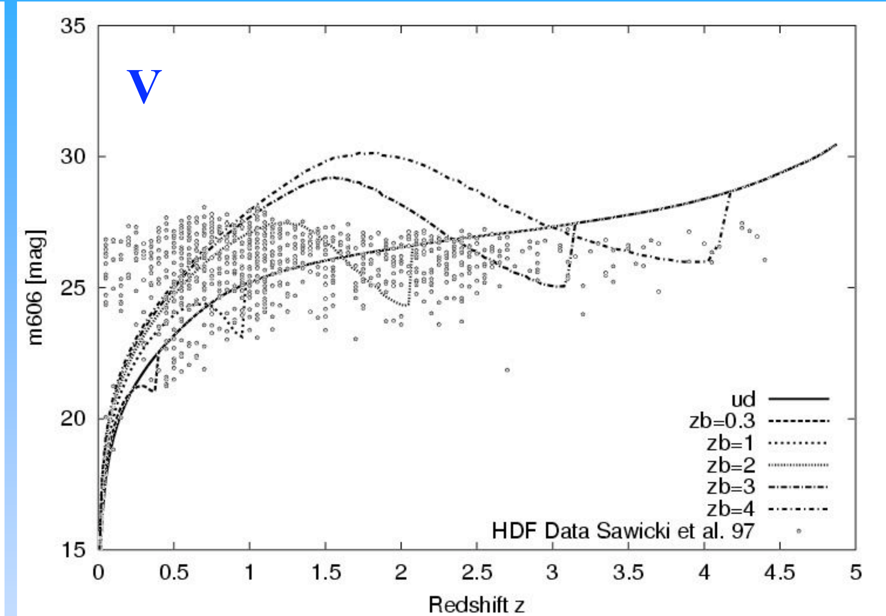
(- and various burst durations)

follow evolution of spectral and chemical properties through starburst & post-starburst phases to final stage (E, S0, ... ?)

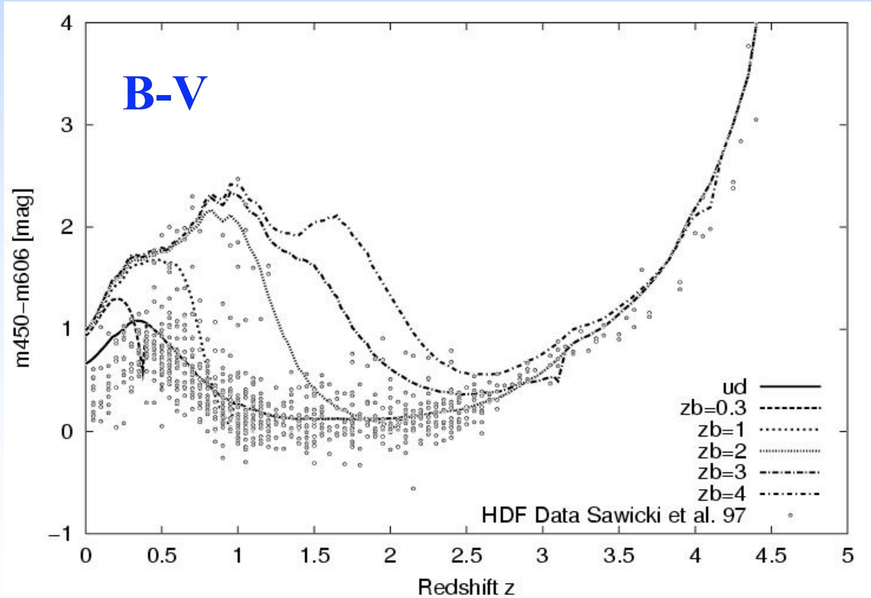
High Redshift Galaxies : The Role of Starbursts







- ★ many starburst galaxies at z > 1
- ★ bursts very strong : $\Delta S/S > 0.3$
- ★ postburst phases much longer than bursts !!!
- ★ galaxies very red after early bursts : (dust-free) EROs



(Fritze & Bicker 06a)

Analysing High Redshift Galaxies via SEDs

Grid of model/template SEDs ⇔ **observed SED**

various galaxy types & all redshifts — multi-band imaging

E, ..., Sd, starbursts, post-starbursts

rest frame UV – K ↕ opt. - Spitzer - FIR

SED analysis tool

χ^2, neural network, ...

→ galaxy type + photometric redshift

(+ SFR + age

+ gas/stellar masses

+ metallicities + . . .)

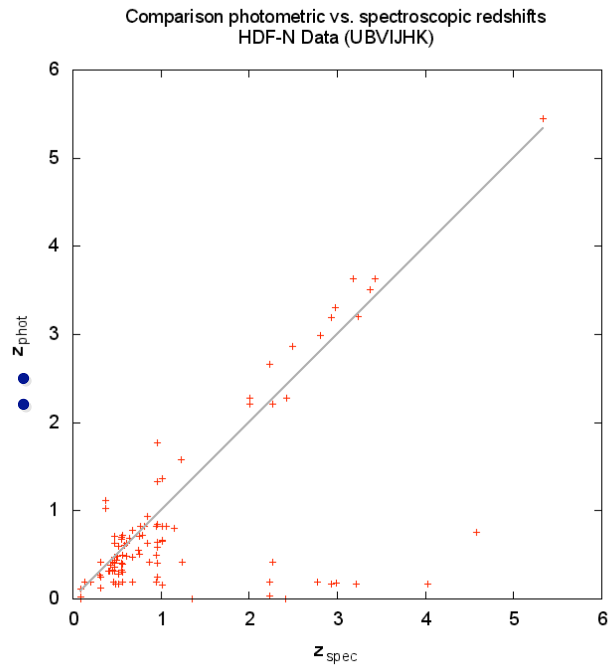
± 1σ

photometric z vs. spectroscopic z :

precision : $\Delta z / z \leq 5\,\%$!

over full range in z !

(Kotulla & Fritze, in prep.)



Analysing High Redshift Galaxies via SEDs

Grid of spectral energy distributions (SED)
↔ observed SED

(Papovich+01, Shapley+05, Erb+06, Reddy+06
using $Z_\odot$ Bruzual & Charlot models)

Chemically consistent vs $Z_\odot$ models :

analysis with $Z_\odot$ models often yields

- ☛ wrong (type, redshift) combinations
- ☛ ages underestimated by × ~2
- ☛ M_{phot} overestimated by × >5
- ☛ SFR overestimated by × >2

. . . . .

(Fritze & Kotulla, in prep.)