# The Physics of Galaxies

## Observations versus Theory

## From the Early Universe to the Present

Part 5

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## Fundamental Questions about Galaxy Formation & Evolution

When and how did galaxies
- form their stars ? SFH (continuously – in starbursts)
- produce their heavy elements ? CEH (how much into ICM)
- assemble their masses ? MAH (stellar – gaseous)

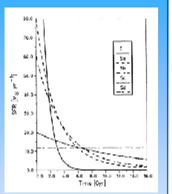
How did all this depend on
- galaxy mass / type ?
  (down-sizing, staged galaxy formation)
- environment (field, group, cluster) ?
  → role of mergers & galaxy transformation ?

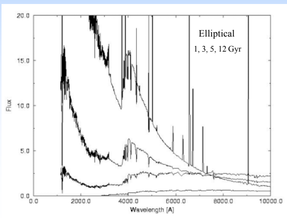
How is the formation & evolution of galaxies related to the formation & evolution of Large Scale Structure?

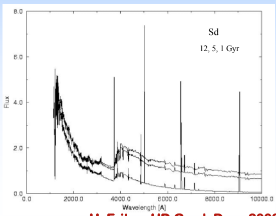


## Spectral Evolution of a Galaxy

Stellar population :
➜ Stellar Initial Mass Function
➜ Stellar evolutionary tracks (m, Z)
➜ Star Formation Histories of various galaxy types








## Chemically Consistent Evolutionary Synthesis GALEV

simultaneous modeling 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

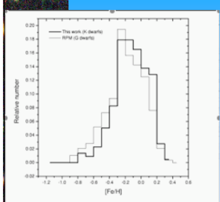
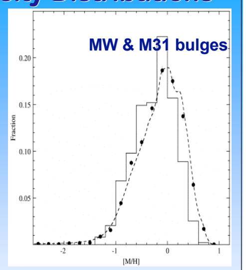



Fig. 2. Comparison between the metallicity distributions for K dwarfs (this work) and G dwarfs (RPM).

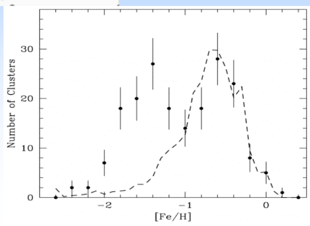
Solar neigh-bourhood
G-, K-, M- stars

(Rocha-Pinto & Maciel 1998)

Δ[Fe/H] ~ 2 dex




(Sarajedini & Jablonka 05)



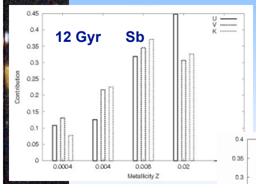

E : NGC 5128 halo

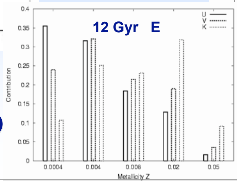
(Harris & Harris 2000)

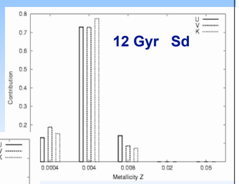
## Chemically Consistent Evolutionary Synthesis

**Stellar metallicity distributions in model galaxies**

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



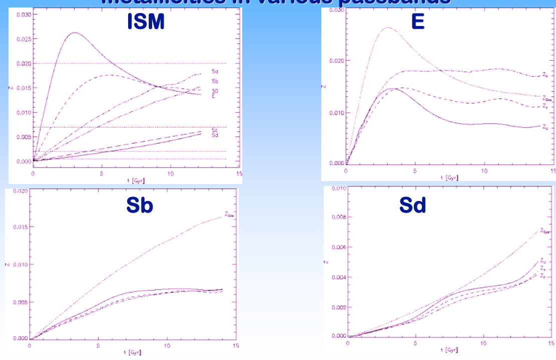

(Bicker et al. 2004)

**Elliptical ≠ SSP**



## Chemically Consistent Evolutionary Synthesis

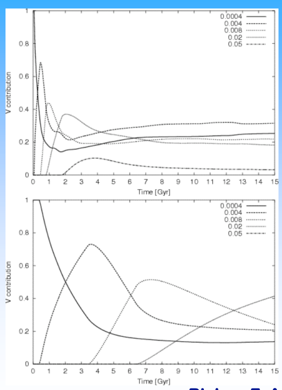
ISM abundances and luminosity weighted stellar metallicities in various passbands




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 & Distant Galaxies

**SFRs from $H_\alpha$, O[II], UV severely overestimated for low metallicity galaxies**

| | Z=0.0004 (I ZW 18, SBS 0335) | $Z_\odot$ | Z=0.05 |
|---|---|---|---|
| $H_\alpha$ | 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 valid for $Z \sim Z_\odot$**

(Kennicutt 98, Gallagher et al. 89)

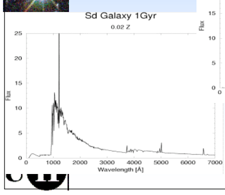
(Bicker & Fritze 2005)

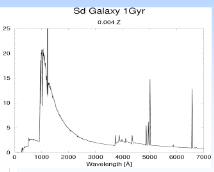


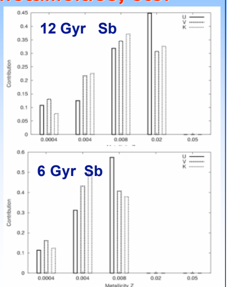
## Chemically Consistent Evolutionary Synthesis

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 $z_1$

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

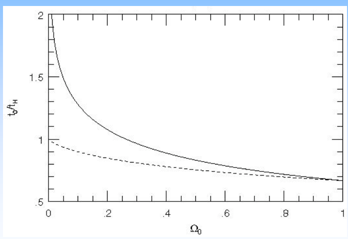
| | | | | | |
|---|---|---|---|---|---|
| z = | 0 | 1 | 2 | 4 | 6 |
| age = | 14 | 5 | 3 | 1 | 0.5 Gyr |

## 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

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

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

Bolometric distance modulus

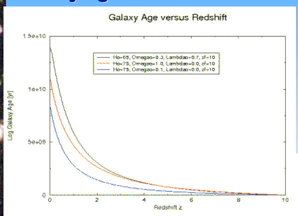
BDM(z) = 5 log $D_L(z)$ + 25 = m - M

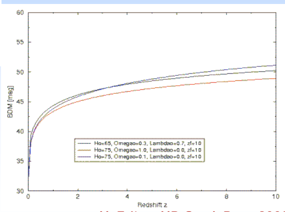
$M_\lambda = m_\lambda$ - BDM(z)



## High Redshift Galaxies

Galaxy age and BDM as a function of redshift



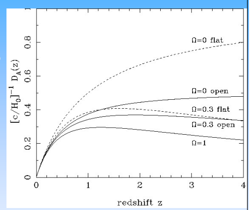






## Cosmological Effects

Angular diameter $\theta$, distance d, linear size x

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




decreases with redshift until z~1,

then slightly increases again

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

Angular size distance $d_A$

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

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

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

$\mu(z) \sim F/\alpha^2 \sim [L/(4\pi D_L^2)] / [D^2/D_A^2] \sim (1+z)^{-4}$

F flux, $\alpha$ angular diameter, D linear diameter,

$D_L$ luminosity distance, $D_A$ angular diameter distance

faint structures & faint objects vanish rapidly with increasing redshift

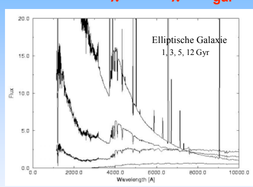


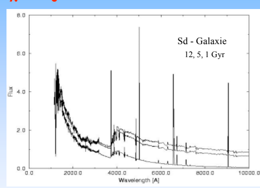
## High Redshift Galaxies

★ Distant galaxies are seen in younger stages :

→ evolutionary correction

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



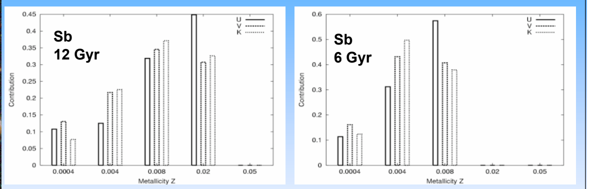




evolutionary corrections

- strong for galaxies with strongly variable SFR(t)
- only obtainable from evolutionary synthesis modeling

## 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

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

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

→ cosmological correction :

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

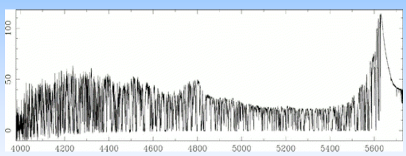
★ reddened & attenuated by intergalactic HI (Madau 1995)

"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

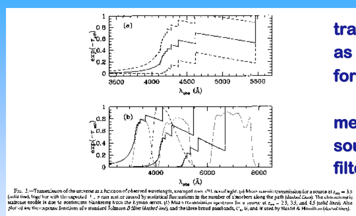
Intergalactic HI, in the form of Lyα clouds, Lyman Limit Systems and galaxy haloes causes a forest of absorption lines shortward of Lyα @ 1215 A in the spectra of distant galaxies



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)



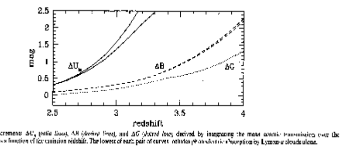
## High Redshift Galaxies : Attenuation



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)

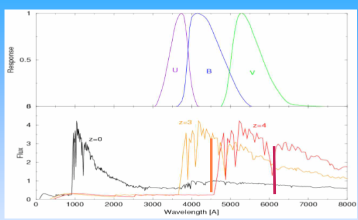
mean attenuation [mag] in different filters as a function of redshift. lower curves Lyα only, upper curves: all Ly lines.



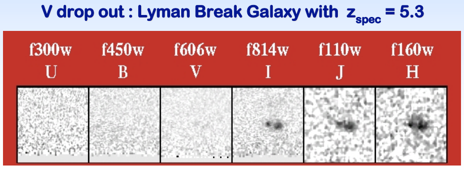

(Madau 1995)



## Drop Out Technik - Lyman Break Galaxies




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



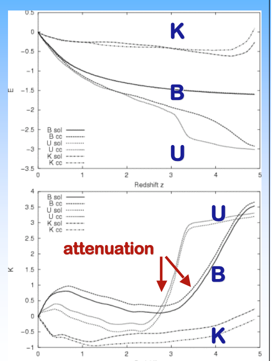



## High Redshift Galaxies

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

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

(Bicker et al. 2004)



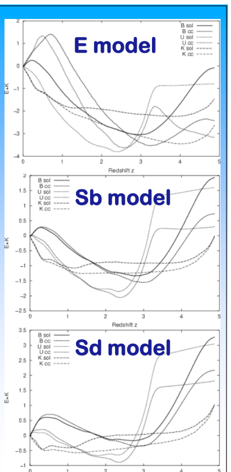
## High Redshift Galaxies

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

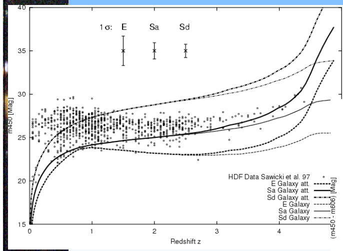


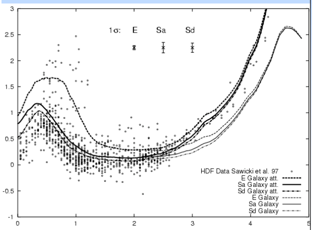



## High Redshift Galaxies

Luminosity & colour evolution of E, Sb, Sd models with evolutionary + cosmological corrections (Bicker et al. 04)

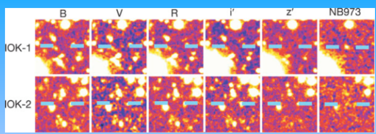
$m_\lambda(z) = M_\lambda(z{=}0,t_o) + BDM(z) + e_\lambda(z) + k_\lambda(z)$



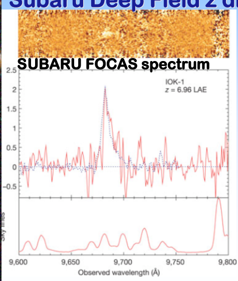





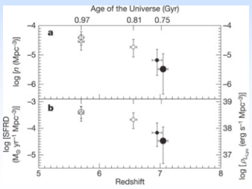

## Redshift Record 2006




Subaru Deep Field z dropout with $z_{spec}$=6.96 (Iye+06, Nat. 443, 186)



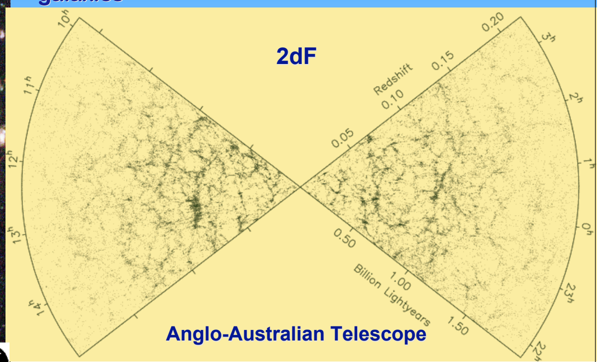

750 Myr after Big Bang, Lya line, SFR~10 Msun/yr






## Redshift Surveys

Center for Astrophysics Redshift Survey : 17,000 galaxies






## Redshift Surveys

Blue z < 0.01
green 0.01 < z < 0.04
red 0.04 < z < 0.1

Panoramic view of the entire near-infrared sky : distribution of galaxies beyond the Milky Way (from the 2MASS Extended Source Catalog XSC, >1.5 million galaxies). Projected with an equal area Aitoff in the Galactic system (Milky Way at center).
Galaxies color coded by redshifts from UGC, CfA, Tully NBGC, LCRS, 2dF, 6dFGS, and SDSS surveys.



## 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 gals
$17.5 < I_{AB} < 22.5$ , $0 \le z \le 1.3$, $\langle z \rangle = 0.56$

**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 #6)

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

## Beyond Redshift Surveys

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

Look for other strategies to find high – z galaxies :

- -- Lyman - $\alpha$ searches
- -- QSO fields
- -- optical identifications of QSO absorbers
- -- drop out technique
- -- exploit gravitational lensing/magnification
- -- color selection criteria for SFing and passive galaxies
- -- photometric redshifts



## Gravitational Lensing : a Great Telescope

Mass concentrations change 4-dim. space-time

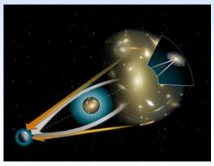
$$G_{\mu\nu} = \kappa T_{\mu\nu}$$

Forground galaxy clusters deflect & magnify light from distant background galaxies,

can produce multiple images, arcs, …

but do not change the spectrum !

Gravitational telescope!






## Gravitational Lensing : a Great Telescope

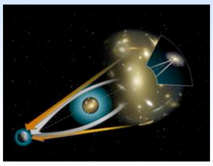
Mass concentrations c…

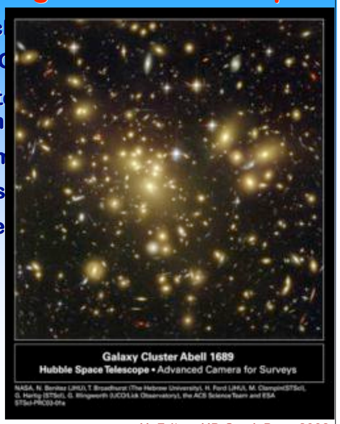
Forground galaxy clust… from…

can produce multiple i…

but do not change the s…

Gravitational telescope…

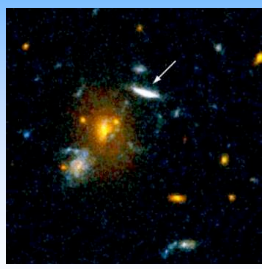







## cB58 : a gravitationally lensed galaxy @ z=2.72

magnification factor ~30
(Teplitz+02) : NIRSPEC@KeckII : NIR spectrum:
restframe optical spectrum





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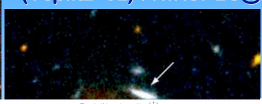

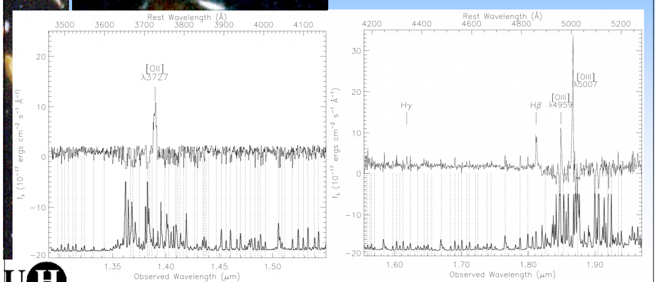




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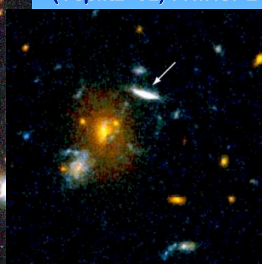
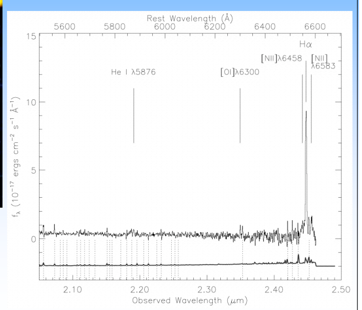




## cB58 : a gravitationally lensed galaxy @ z=2.72

NIR spectrum: restframe optical spectrum

Balmer decrement Hα/Hβ ➜ E(B-V)=0.27

Hα ➜ SFR=620 ± 18 $M_\odot$/yr

width of Balmer lines, UV continuum ➜ $M_{dyn}$=1.2 × $10^{10}$ $M_\odot$

12 + log(O/H) = 9.2 ➜ Z ~ 1/3 $Z_\odot$

Pettini+02 : optical spectrum : 48 rest-UV ISM abs. lines (1134 - 2576 Å), due to elements from H to Zn.

Abundance pattern: O, Mg, Si, P, and S are all ~2/5 solar,

N and the Fe-peak elements Mn, Fe, and Ni are underabundant by a factor of ~3

➜ metal enrichment in cB58 has taken place within the last ~300 Myr, ok with stellar population age!



## cB58 : a gravitationally lensed galaxy @ z=2.72

NIR spectrum: restframe optical spectrum

TABLE 1
EMISSION LINES

| Line | $\lambda_{obs}$ ($\mu$m) | $z_{em}$ | $W_{rest}$ (Å) | $F^a$ |
|---|---|---|---|---|
| [O II] λλ3726, 3728 ...... | 1.3898 | 2.72897 | 37 ± 3 | 12.74 ± 1.22 |
| Hγ λ4340 ................ | 1.61828 | 2.72875 | 9 ± 1 | 1.61 ± 0.17 |
| Hβ λ4861 ................ | 1.81217 | 2.72774 | 26 ± 4 | 4.07 ± 0.57 |
| [O III] λ4959[b] ............ | 1.84913 | 2.72890 | 26 ± 8 | 4.01 ± 1.30 |
| [O III] λ5007 ............. | 1.86678 | 2.72845 | 97 ± 5 | 14.73 ± 0.78 |
| He I λ5876 ............... | 2.19100 | 2.72873 | 3 ± 1 | 0.35 ± 0.09 |
| [O I] λ6300 .............. | 2.34949 | 2.72935 | 25 ± 4 | 3.06 ± 0.46 |
| [N II] λ6548 ............. | 2.44204 | 2.72944 | 7 ± 2 | 0.86 ± 0.21 |
| Hα λ6563 ................ | 2.44750 | 2.72935 | 106 ± 3 | 12.56 ± 0.37 |
| [N II] λ6583 ............. | 2.45566 | 2.73031 | 10 ± 2 | 1.14 ± 0.26 |

[a] Observed line flux in units of $10^{-16}$ ergs $s^{-1}$ $cm^2$.
[b] The blue wing of the 4959 Å line is in a deep atmospheric absorption trough.



## cB58 : a gravitationally lensed galaxy @ z=2.72

Optical spectrum : 48 rest-UV ISM abs. lines (1134 - 2576 Å), due to elements from H to Zn.

Bulk outflow of the ISM at a speed of ~255 km/s and at a rate that exceeds the star formation rate.

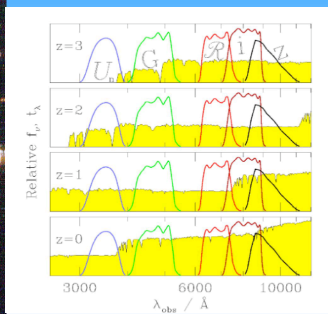
Unclear whether this gas will be lost or retained by the galaxy

Baker+04 : Iram: CO(3-2): $M_{CO}$ ~ 7 × $10^9$ $M_\odot$

➜ consumption timescale $10^7$ yr, unless replenished from HI



## Lyman Break Galaxies : Colour Selection Techniques



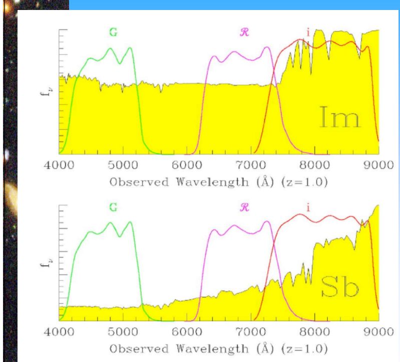

(Adelberger+04)

SFing galaxy spectrum @ z=0, 1, 2, 3

Spectroscopic redshifts only for SFing emission line galaxies ! Lyman Break technique also for passive galaxies !



## Color Selection Criteria

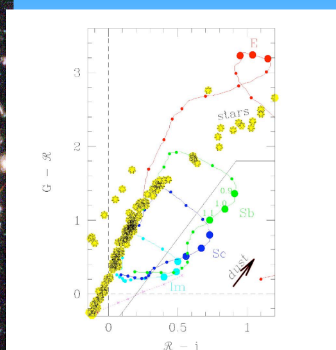



Balmer break 3700 A

4000 A break



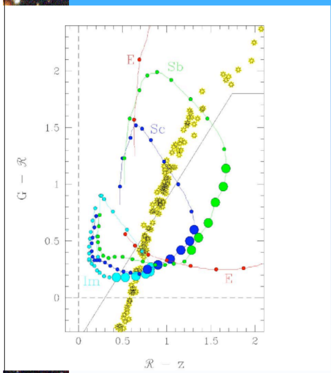
## Color Selection Criteria




Expected locations of stars and star-forming galaxies at z>1.

(Adelberger+04)

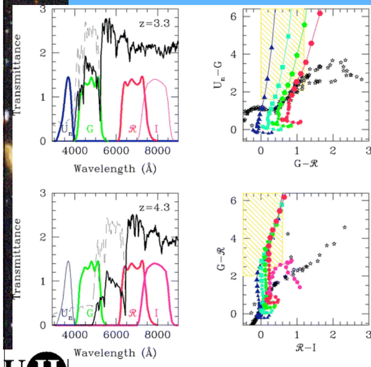
## Color Selection Criteria




Expected GRz colors
of galaxies
small circles: dust-free
big circles: E(B-V)=0.15
@ z=1.0, 1.1, 1.2,
1.3, 1.4, 1.5
stars: Gunn & Stryker 83



## Lyman Break Galaxies : Colour Selection Techniques

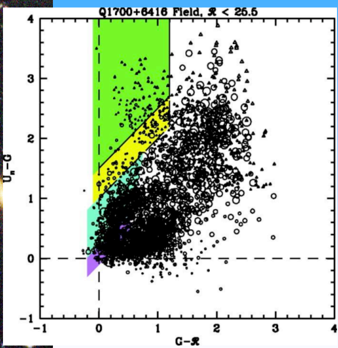



(Giavalisco 04, ARAA)

Galaxy with const. SFR
@ various redshifts from
z=0.5 in steps of $\Delta z$=0.1
with diff. amounts of dust
▲ E(B-V)=0, ■ E(B-V)=0.15,
★ E(B-V)=0.3, ✲ E(B-V)=0.45
(using Calzetti+97's
starburst extinction law)



## Color Selection Criteria for Galaxies in the Redshift Desert

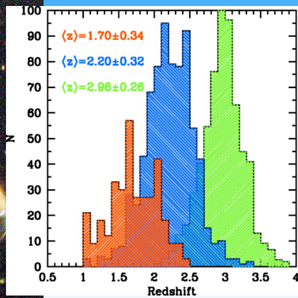



$U_n$GR colors of galaxies
symbol sizes scale w.
brightness
triangles: $U_n$ dropouts
cyan: z = 2.20+/-0.32
magenta: z = 1.70+/-0.34
green/yellow: LBGs @ z~3

(Steidel+04)



## Color Selection Criteria



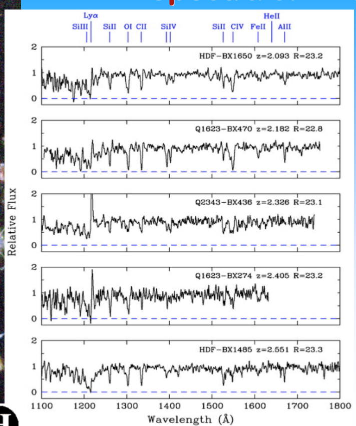

Redshift distribution of
spectroscopically confirmed
galaxies

green: LBGs @ z~3, scaled by 0.7
blue: gals @ z = 2.20+/-0.32 (749)
red: gals @ z = 1.70+/-0.34 (114),
scaled by 3

(Steidel+04)



## Spectra of LBGs




Example spectra
(restframe)

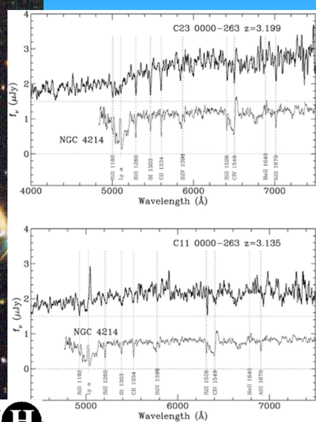
LBGs @ 2 < z < 2.6

interstellar
absorption lines

(Steidel+04)



## Spectra of Lyman Break Galaxies



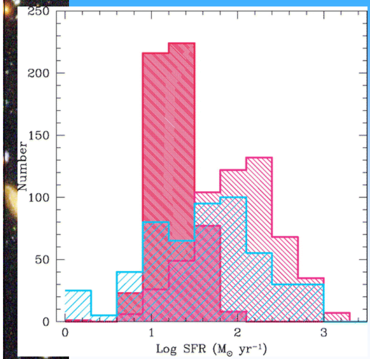

(Giavalisco 04, ARAA)

Comparison with spectra of
a local starburst galaxy

LBG spectra: Keck-LRIS
NGC 4214 spectrum: HST-GHRS

both spectra in observer's
frame @ z(LBG).

## SFRs of Lyman Break Galaxies




(Giavalisco 04, ARAA)

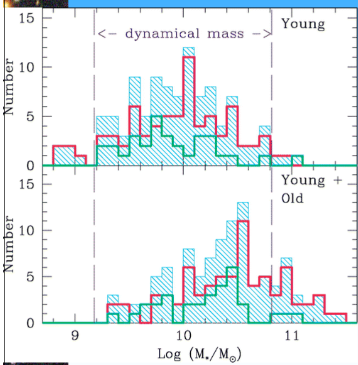
SFRs of LBGs range from few $M_\odot$/yr (like Milky Way) through >> 100 $M_\odot$/yr (enough to form $10^{11}$ $M_\odot$ of stars in 1 Gyr).

Extinctions are small/ moderate:

$0.15 < E(B-V) < 0.2$



## Masses of LBGs




(Giavalisco 04, ARAA)

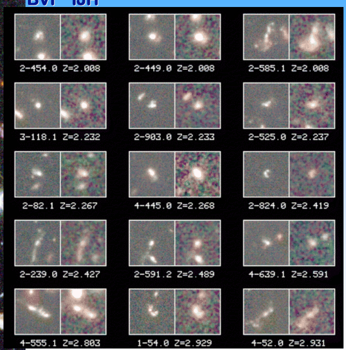
Photometric = stellar masses of LBGs

$10^9$ - $10^{10}$ $M_\odot$

$M_{dyn}$ marks the mass range obtained from emission lines



## Morphologies of LBGs



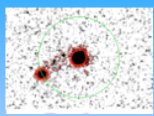

small compact, relatively regular

. . . highly fragmented, diffuse, irregular.

HST images of LBGs (Dickinson 1998)

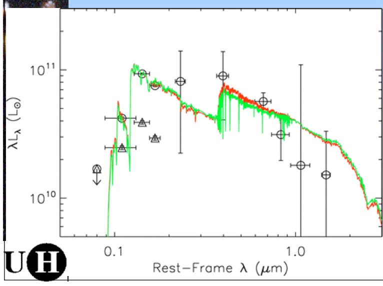


## Spectrum of a lensed LBG@z=4.42



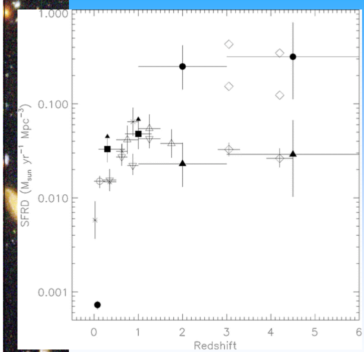
SED of HDF-G4 ❍ & its companion △ (d=7 kpc). Rest-frame UV to the NIR, with the best-fit Bruzual & Charlot (2003) models for exponential & continuous SFRs

(Younger+07)






## Cosmic SFR Density




(Giavalisco 04, ARAA)

**Madau diagram**

*open diamonds* with error bars: LBGs @ *z* = 3 & 4 (Steidel+99) without dust correction,

*filled triangles* & *circles*: SCUBA galaxies,

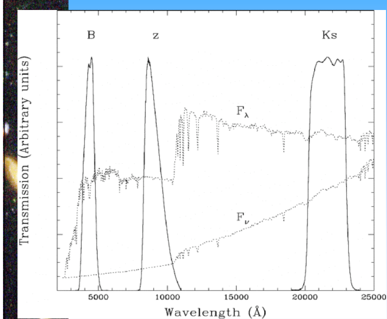
*open diamonds* without errors: two different estimates of the dust obscuration correction for the LBGs.

How to detect dust-obscured galaxies ?

➜ NIR (NIR = better tracer of mass!)



## Colour Selection for Galaxies : NIR

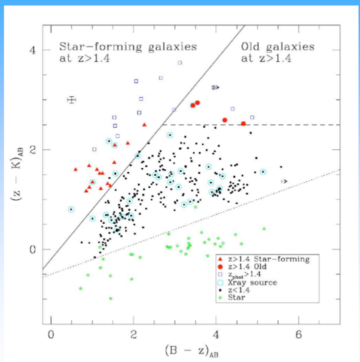



ESO VLT K20 survey

BzK filters + gal. @ z=1.73

(Daddi+04)

# Colour Selection for Galaxies : NIR




(Daddi+04)



# K20 Galaxy Survey

Colour selection for SFing & passive galaxies

ESO VLT: 500 gals to Ks<20 mag,

~ complete spectroscopic coverage
+ deep UBVRIJKs imaging

ideal to study massive (passive) galaxies to z~2.

(Cimatti+02)



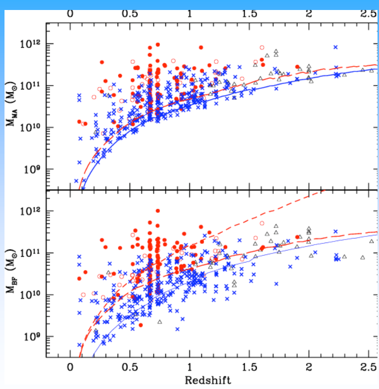
# K20 Galaxy Survey

Galaxy masses

maximal ages

best ages

(Fontana+02)



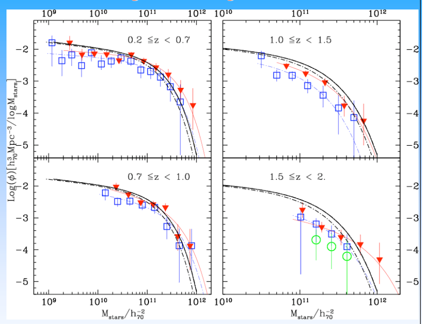



# K20 Galaxy Survey

Galaxy mass functions (z)

maximal ages
best ages
local (Cole+01)

(Fontana+02)



Only mild evolution (<30%) to z~1.
z~2 : ~35% of present mass in $10^{11}$ $M_\odot$ gals is assembled.



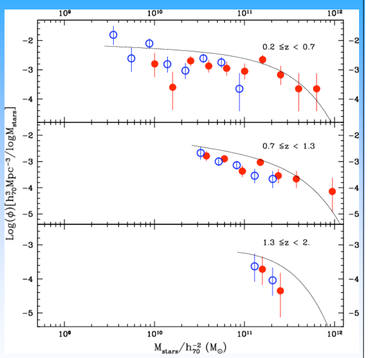
# K20 Galaxy Survey

Galaxy mass functions (z)

breakdown into spectral types

E/S0
spirals

(Fontana+02)



At z < 0.7, all gals > $10^{11}$ $M_\odot$ are E/S0,
at z >> 0.7 many massive gals are SFing.



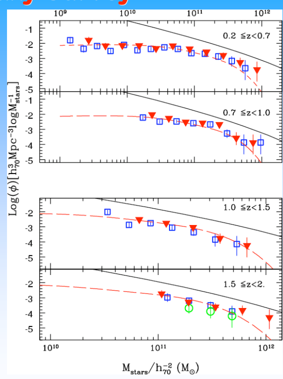
# K20 Galaxy Survey

Galaxy mass functions (z)

comparison with Λ-CDM models

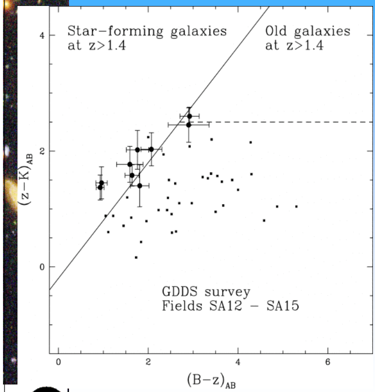
baryonic MF
total MF (baryons + DM)

(Fontana+02)



Λ-CDM models underpredict galaxies above $10^{11}$ $M_\odot$,
in particular at high redshifts.

## Colour Selection for Galaxies : NIR



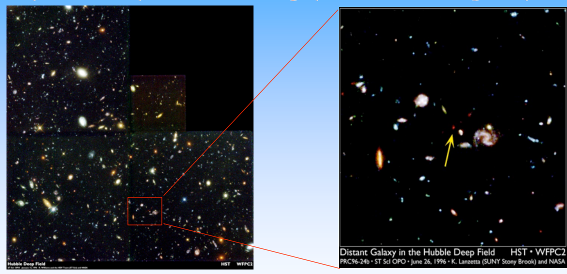

Gemini Deep Deep Survey gals
large squares: 1.4 < z < 2.2
small squares: z < 1.4

(Daddi+04)



## Deep Fields

Faintest galaxies : 29 mag (UBVRIJHK)
Spectroscop. limit : 25 mag ( = factor 40 brighter)




→ Drop Out technique → Colour Selection criteria

→ Photometric redshifts



## The Hubble Ultra Deep Field 2004

Deepest ever & largest optical field (+NIR+mid-IR+…)
ACS NICMOS Spitzer
SW of Orion, 1/10 ∅ full moon, 10.000 galaxies



## The Hubble Ultra Deep Field 2004

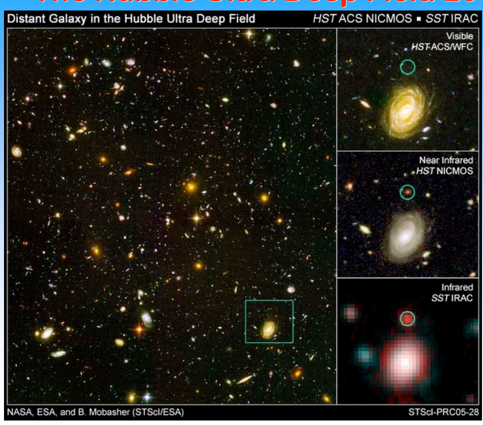
Deepest ever & largest optical field (+NIR+mid-IR+…)
ACS NICMOS Spitzer
SW of Orion, 1/10 ∅ full moon, 10.000 galaxies
exposure times 11.3 d ACS, 4.5d NICMOS
Faintest galaxies : 28.4 - 29 mag (BViz)
Spectroscop. limit : 25 mag ( = factor 40 brighter)

encircled : HUDF-JD2 among the most distant ever seen:
unusually massive and mature for its redshift z=6.5

$M_* \sim 8\ M_*(MW)$

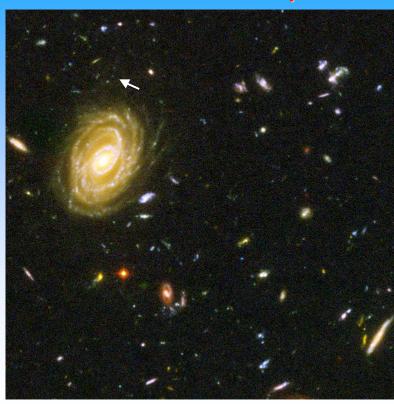


## The Hubble Ultra Deep Field 2004






## The Hubble Ultra Deep Field 2004



## Analysing High Redshift Galaxies via SEDs : Photometric Redshifts

Grid of model/template SEDs ⇔ observed SED

various galaxy types & all redshifts
E, ..., Sd, starbursts, post-starbursts
rest frame UV – K

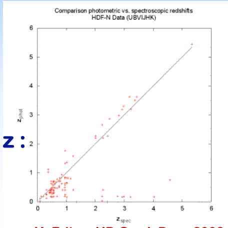
↕

multi-band imaging
opt. - Spitzer - FIR

SED analysis tool
$\chi^2$, neural network, ...

→ galaxy type + photometric redshift
( + SFR + age
+ gas/stellar masses
+ metallicities + . . . )

± 1σ



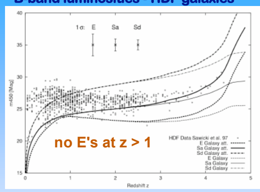

photometric z vs. spectroscopic z :
precision : $\Delta z / z \leq 5\,\%$ !
over full range in z !

(Kotulla & Fritze, in prep.)

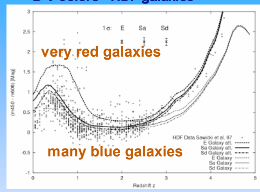


## High Redshift Galaxies

B-band luminosities - HDF galaxies




B-V colors - HDF galaxies




Chemically consistent GALEV models vs HDF galaxies:

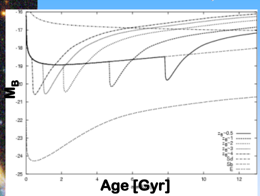
→ trace back spectral evolutionary paths to z > 4.5
i.e. over > 95 % $t_{Hubble}$
→ fair description of average properties of normal galaxies
→ identify high-z progenitors of local galaxy types
→ study mass assembly & chem. enrichment histories

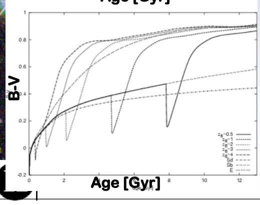
(Möller, Fritze, Fricke 98, Fritze, Möller, Fricke 99a,b, Bicker, Fritze, Möller 04)



## Starburst & Post-Starburst Galaxies at High Redshift

Starbursts on top of undisturbed galaxies



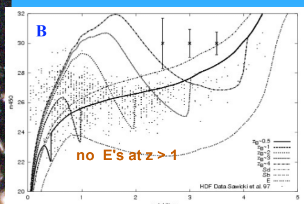



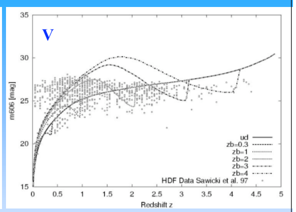

- of various types Sa, Sb, Sc, Sd
- starting at various ages
- with various bursts strengths
(- and various burst durations)

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

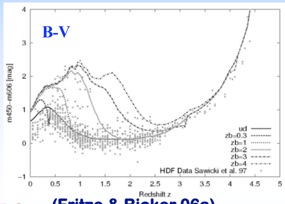


## High Redshift Galaxies : The Role of Starbursts




★ 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 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

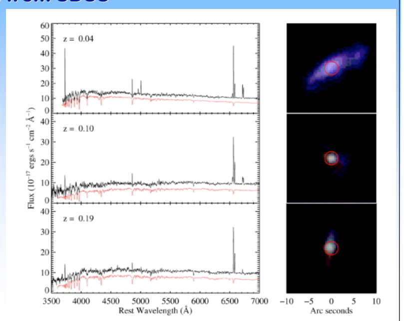
- wrong (type, redshift) combinations
- ages underestimated by × ~2
- $M_{phot}$ overestimated by × >5
- SFR overestimated by × >2
- . . . . .

(Fritze & Kotulla, in prep.)



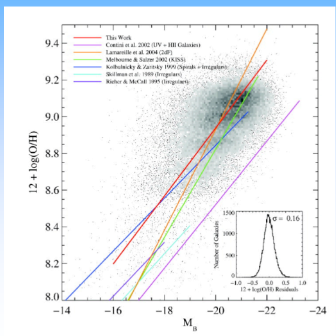
## Redshift Evolution of Fundamental Relations

L -- Z and M -- Z relations @ z~0.1
53000 SFing gals from SDSS
(Tremonti+04)



## Redshift Evolution of Fundamental Relations

Tremonti+04 : L -- Z relation for 53000 SFing gals @ z~0.1 vs. local gals




Conclusions ???

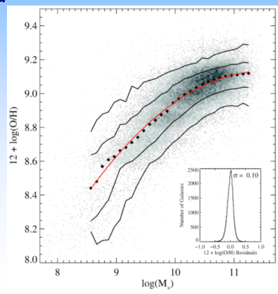
hampered by local controversy !



## Redshift Evolution of Fundamental Relations

Tremonti+04 : M* -- Z relation for 53000 SFing gals @ z~0.1 steep at log M*=8.5 -- 10.5, flatter for log M* >10.5

68 and 98% ranges indicated





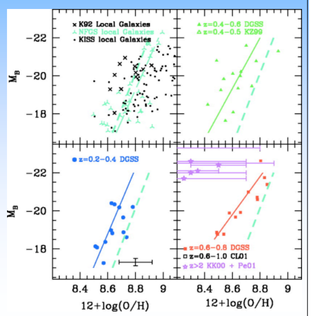

## Redshift Evolution of Fundamental Relations

Kobulnicky+03 : Redshift evolution of the L -- Z relation from z~0.26 to z~0.82 for gals from DEEP Groth Strip Survey

L -- Z relation @ higher z increasingly offset from local one :

gals get more metal-poor at given luminosity

effect stronger for fainter galaxies than for brighter ones.




## Redshift Evolution of Fundamental Relations

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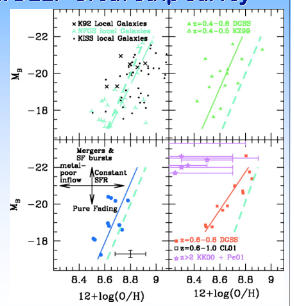
L -- Z relation @ higher z increasingly offset from local one



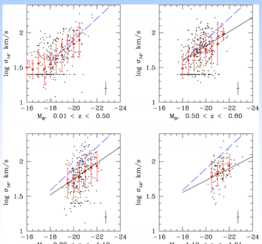


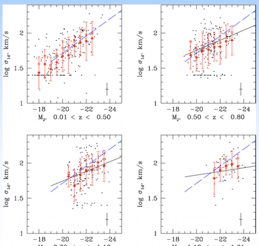

## Redshift Evolution of Fundamental Relations

Weiner+06 : Keck spectroscopy in GOODS - N field

TFRs for ~1000 gals (B-band) and ~670 gals (J-band) @ z~0. . . . 1.2

--> bright gals fade more between z~1.2 and z~0 than fainter ones in B. Little evolution in J.







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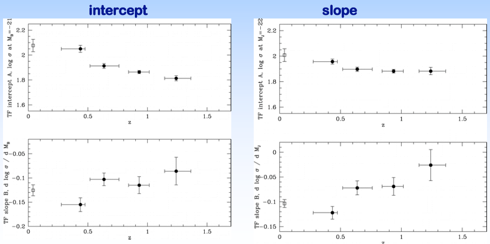
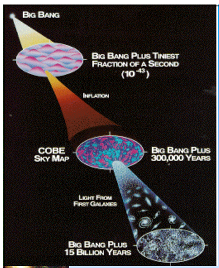
--> bright gals fade more between z~1.2 and z~0 than fainter ones in B. Little evolution in J.

intercept slope





## Universe formed in a Big Bang

Hot plasma, fully ionized

after ~300.000 yrs @ T~3000°:

H- (and He-) nuclei bind electrons

➜ Universe gets transparent (decoupling)

Since then, radiation spreads freely & cools down to ~ 3°K by today, photons travel straight

**Cosmic Background Radiation**
**&**
**Observational horizon**

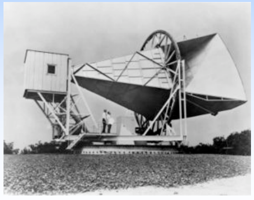


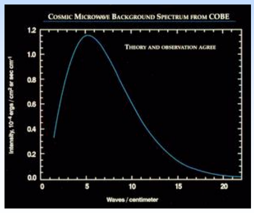
## Thermal History of the Universe

Predictions from Big Bang theory (G. Gamov, 1946) :

thermal radiation from decoupling (z~1000, age ~ 300.000 yr) : cosmic microwave background 2.7 K

observed 1965 by A. Penzias, R. Wilson

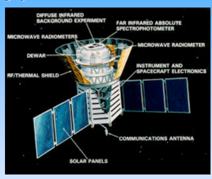


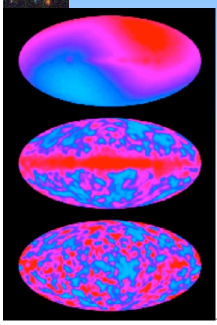


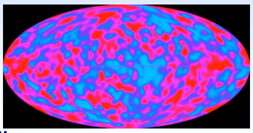


## Thermal History of the Universe

COBE satellite : launch 18. Nov. 1989





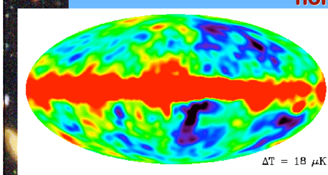


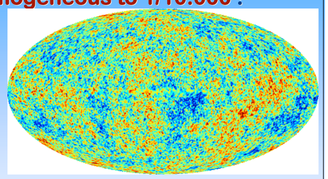
primordial fluctuations :
amplitude $\Delta T/T \sim 2\ 10^{-5}$



## Cosmic Background Radiation

At an age of 300.000 yrs, the Universe was homogeneous to 1/10.000 !



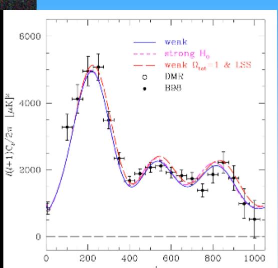



COBE Satellit WMAP Satellit

From these tiny inhomogeneities the galaxies, the galaxy clusters and the Large Scale Structure must have formed — how ?



## Density of the Universe



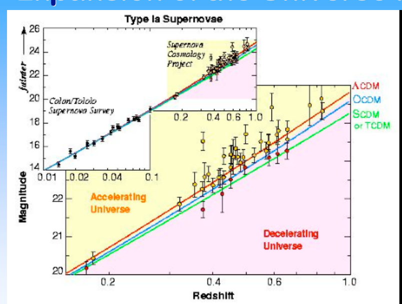
Boomerang balloon experiments measured fluctuations on much smaller angular scales than COBE: analysis of these spectra, combined with theoretical models, yield parameters:

$\Omega_m + \Omega_\Lambda = 1.02 \pm 0.06$ ,
$\Omega_b\ h^2 = 0.020 \pm 0.004$ ,

independent confirmation of conclusions from Big Bang nucleosynthesis!



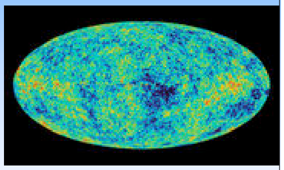
## Dark Energy : Acceleration of the Expansion of the Universe : $\Omega_\Lambda$




Measuring the flux of SN Ia as a function of redshift
-> distances out to large redshifts
-> two teams : SN Ia fluxes require a non-zero $\Omega_\Lambda$

# WMAP - Concordance Cosmology

WMAP high accuracy measurements
of many cosmological parameters:
Age of the universe : 13.7 ± 0.2 Gyr
Hubble constant :
70 (km/s)/Mpc +2.4/-3.2

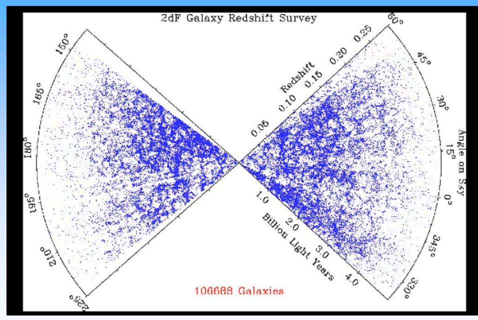


Composition of the universe :
4% ordinary baryonic matter
22% dark matter
74% dark energy

Total density (matter + energy)
consistent with flat geometry.

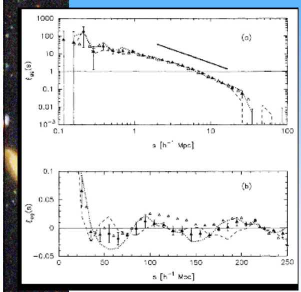


# Density Fluctuations -- Galaxy Correlation Function






# Density Fluctuations -- Galaxy Correlation Function



Galaxy correlation function from Las Campanas Redshift Survey.
Filled triangles = combination of northern & southern data.
Power law $\gamma = 1.52$ for comparison (solid line)
(cf. Tucker et al. 1997, MNRAS 285, L5)



# Density Fluctuations -- Galaxy Correlation Function

Power spectrum P(k) gives amplitude of density fluctuations as a function of length scale L = 1 / k.
Power spectrum P(k) is the Fourier transform to the galaxy correlation function ξ(r) :

$$P(k) = 2\pi \int_0^\infty dr\, r^2 \,(\sin kr) / kr\ \xi(r)$$



# Gravitational Instability

Structure in the Universe evolves via gravitational instability:
starting from very tiny initial fluctuations (e.g., inflated quantum fluctuations), slightly overdense regions
- have higher gravity field,
- expand slower than rest of Universe,
- increase their density relative to rest of Universe further,
- slows relative expansion down more,
- etc.

This gravitational instability is predictive:
density evolution in the Universe can be calculated with an impressive accuracy.



# Gravitational Instability

Models are predictive in their statistical properties, given:
- the cosmological parameters, $\Omega_m$, $\Omega_\Lambda$, $H_0$, and $\Omega_b$;
- the density fluctuation spectrum at early times, e.g, at the time of recombination,

which depends on the nature of dark matter:
Cold Dark Matter (CDM) : non-relativistic particles at $t_{eq}$
Hot Dark Matter (HDM) : relativistic particles at $t_{eq}$ (e.g. light neutrinos)

HDM : large structures form first, smaller ones by fragmentation; no agreement with today's structures.
CDM : small structure forms first, larger ones later by merging; better agreement with observations.

## Galaxy Formation Epoch

**Highest redshift QSO at present : z = 6.28 (SDSS)**
**Highest redshift galaxy : z ~ 6.96 (Iye+06)**

**The Universe (IGM) must be mostly ionized at z < 6:**

**Reionization by the first stars or AGNs around z~6.**

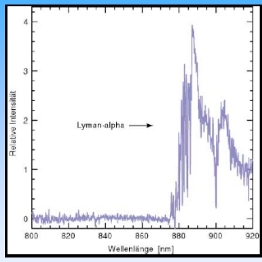
**A small fraction of the hydrogen in the Universe burning to helium is enough to generate energy for reionization (4 H → $^4$He + 7 MeV per nucleon; ionization energy per H is 13.6 eV)**

**Reionization of the IGM is directly visible in QSO spectra : Gunn Peterson trough due to HI seen in spectrum of QSO@ z=6.28 (Becker 01), not seen in spectra of QSOs @ z<6.**

**Most of the baryons at redshifts z > 2 are in highly ionized intergalactic medium with T ~ $2 \times 10^4$ K.**



## (Re-)ionization




VLT spectrum of the highest-redshift QSO at z = 6.28 (Becker 2001)



## Summary & Outlook

**Galaxy formation & evolution :**

- boost of knowledge in past years + tons of new ????
- synergy from diff. wavelengths, HST/satellites + ground-based large telescopes
- will continue: ALMA, Herschel, adaptive optics, IFS, ….
  + numerical techniques & computing power
- spectral, chemical & dynamical aspects interrelated
- observations + numerical modeling
- galaxies not isolated: role of mergers !
  galaxy evolution related to Large Scale Structure formation/evolution
- galaxy evolution related to stellar evolution & nucleosynthesis

**This course could only give a 1st glimpse, much more not dealt with than dealt with…**

**Thank you for your interest !**