



# **Evoluzione spettrale delle Galassie**

**Materiale didattico per gli studenti**

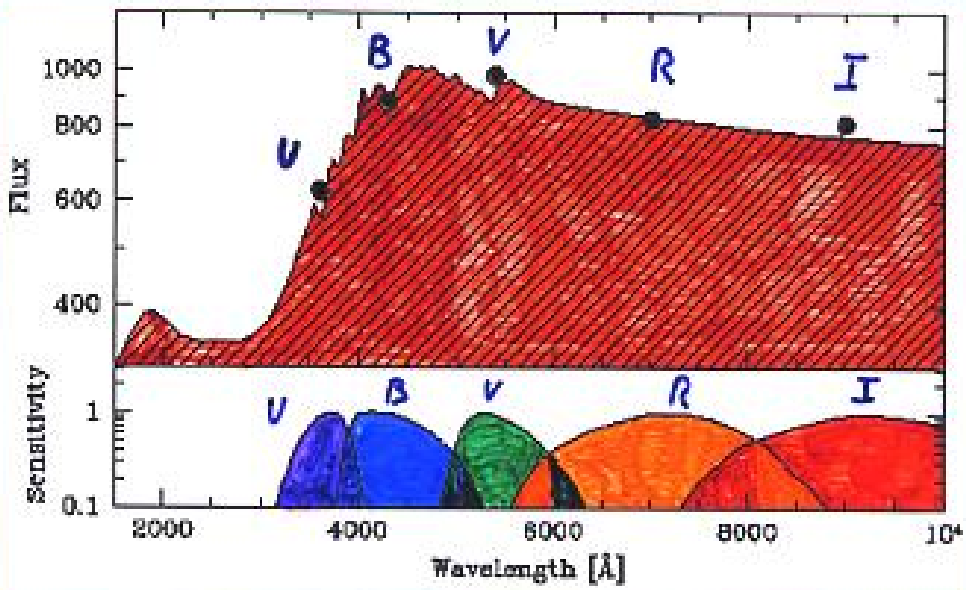
**A.A. 2014/15 - Laurea Magistrale in  
Astrofisica e Cosmologia**

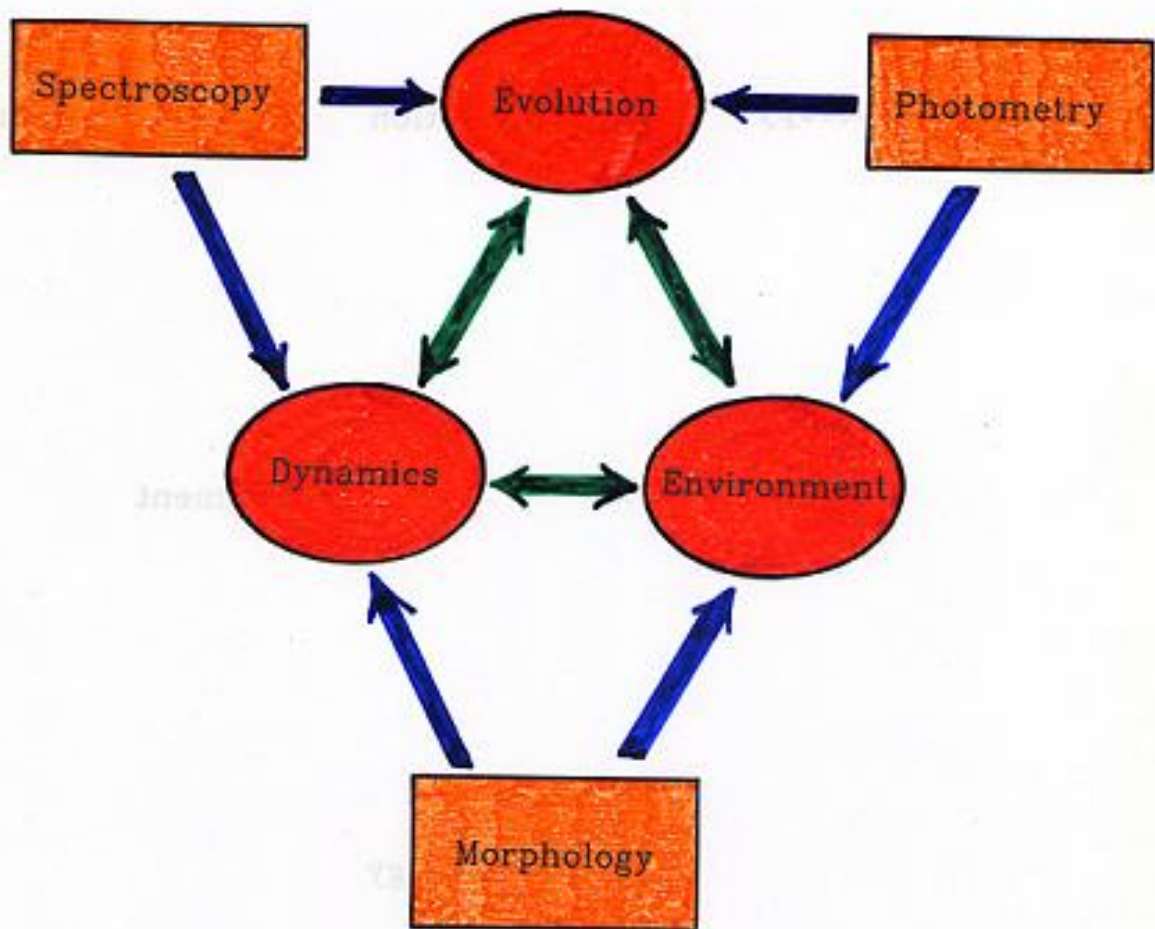
**Prof. Alberto Buzzoni**

**MORPHOLOGY**

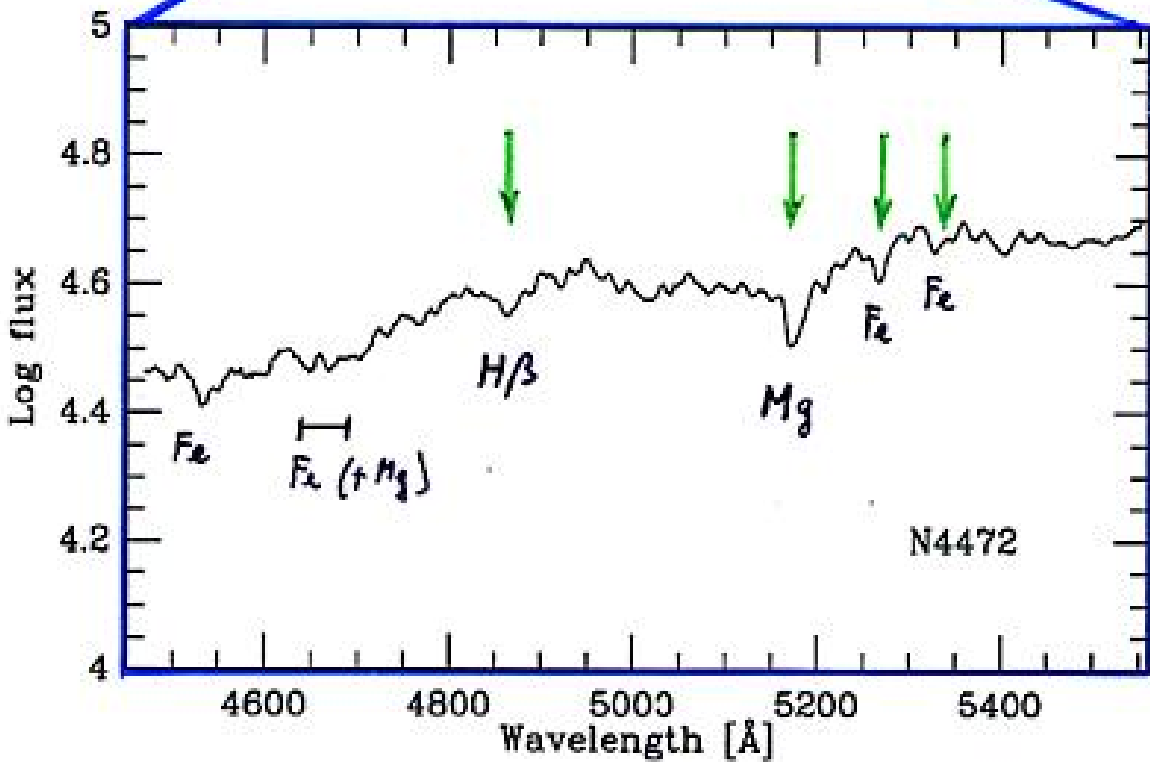
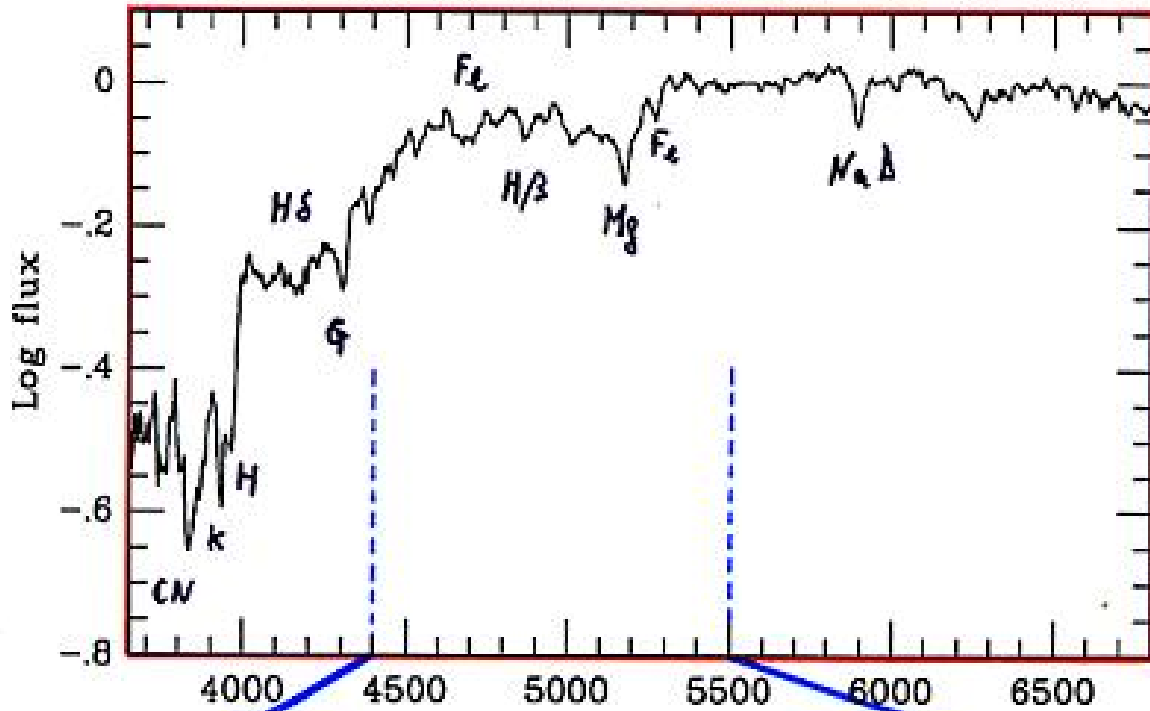


**PHOTOMETRY**





# SPECTROSCOPY



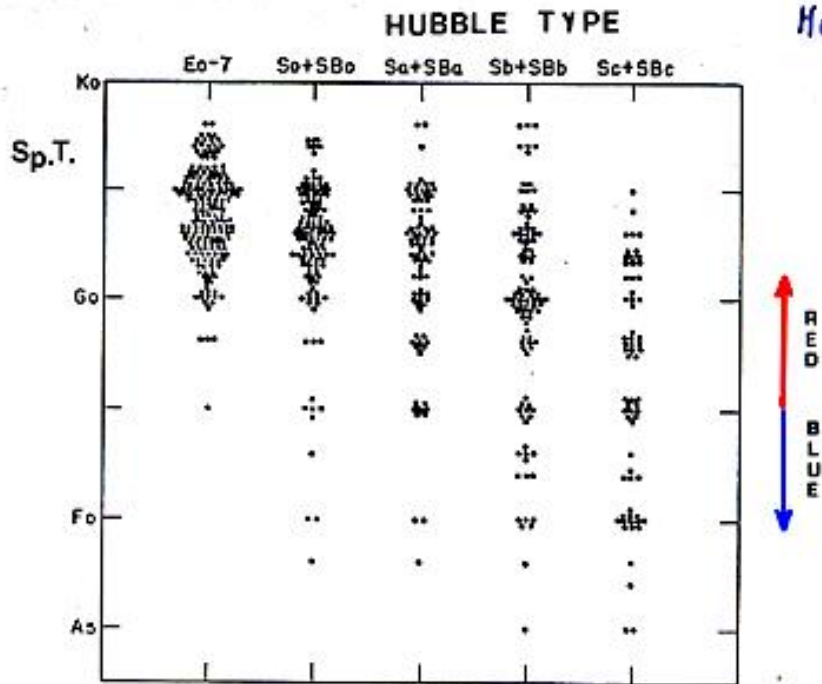
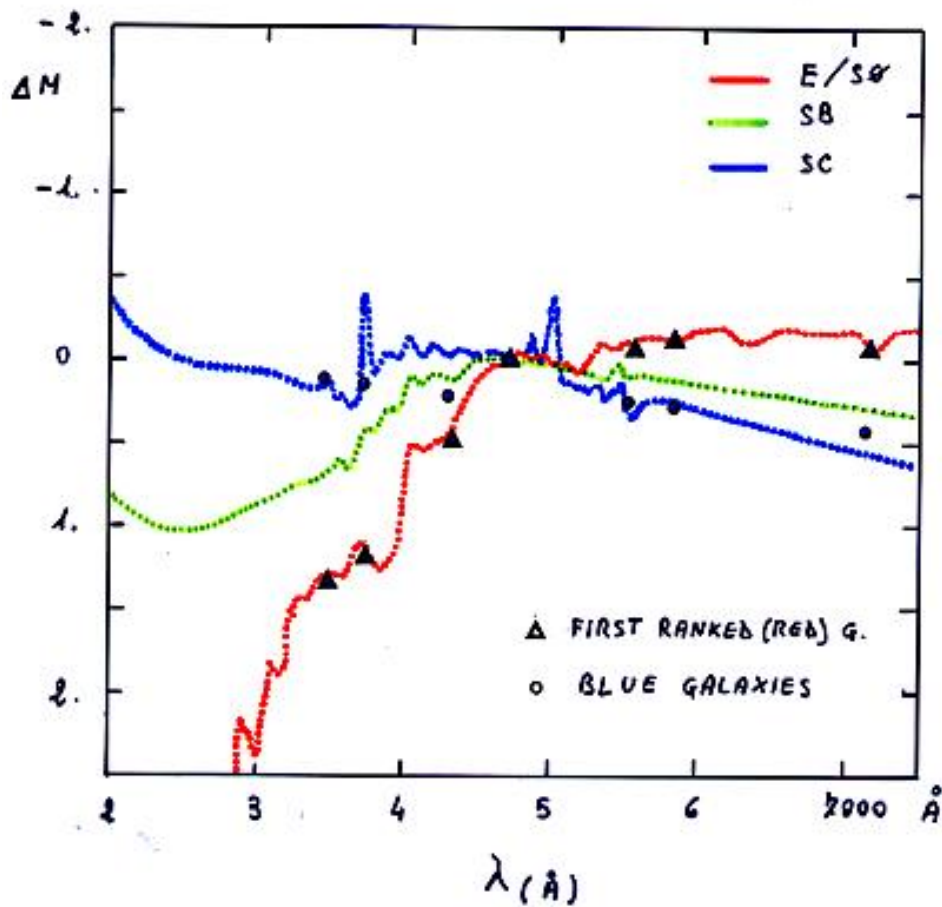
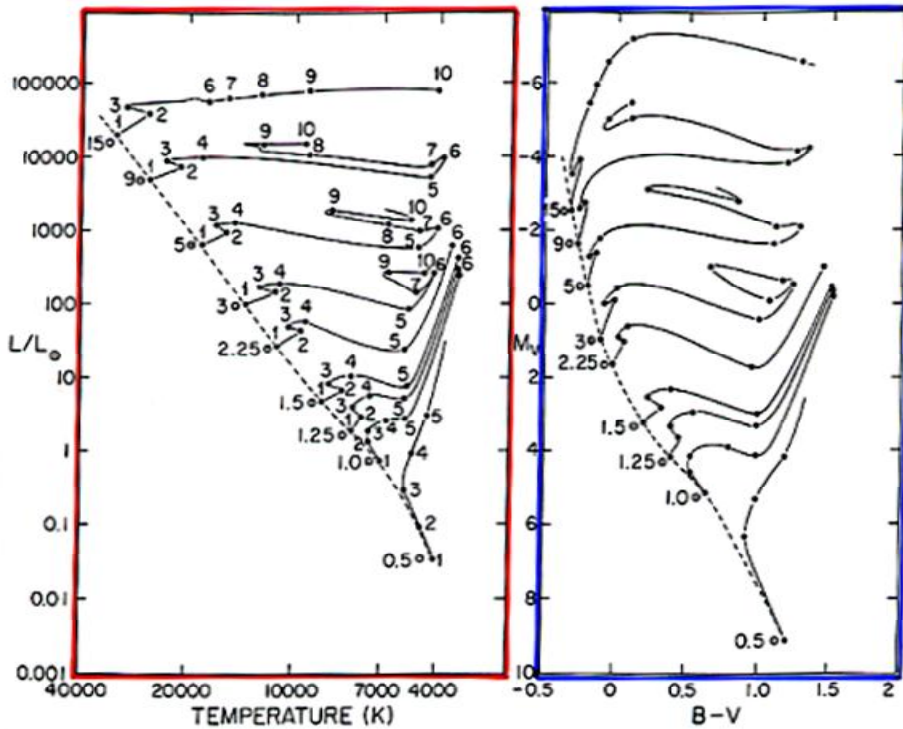


Figure 2. The distribution of spectral type as a function of nebular type for 546 nebulae from Tables I and II.



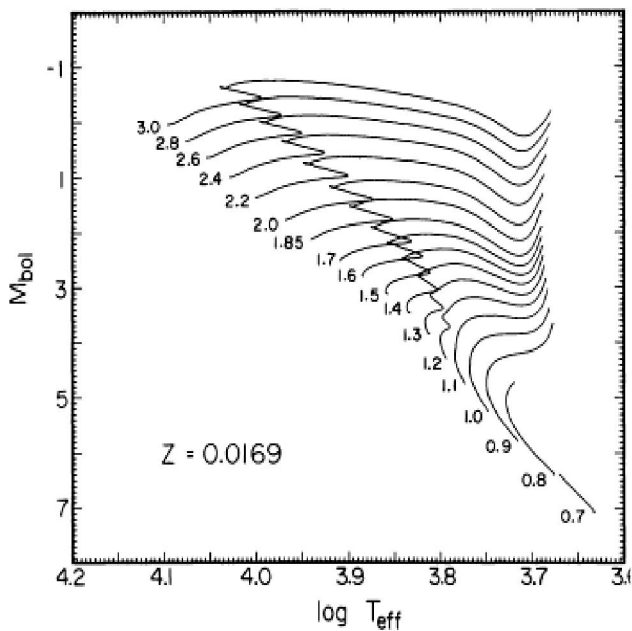
# Stellar Evolution

## Le prime tracce evolutive

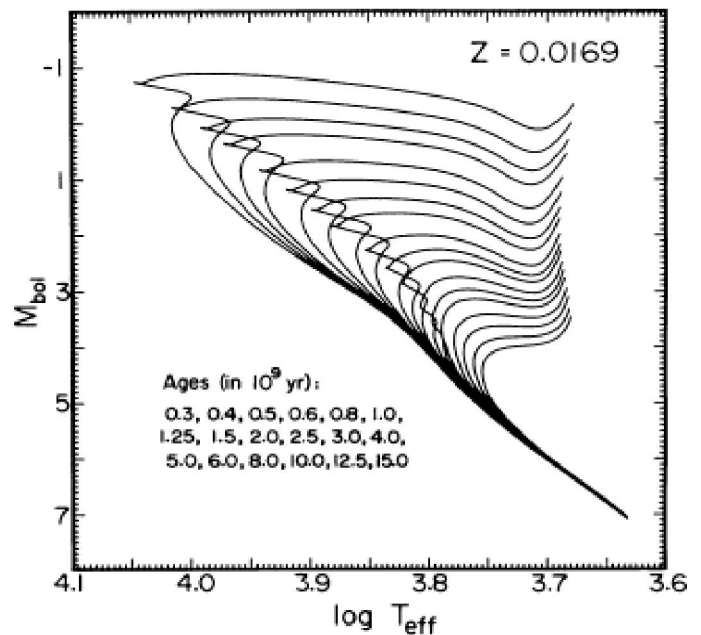


Iben (1967)

## Tracce stellari

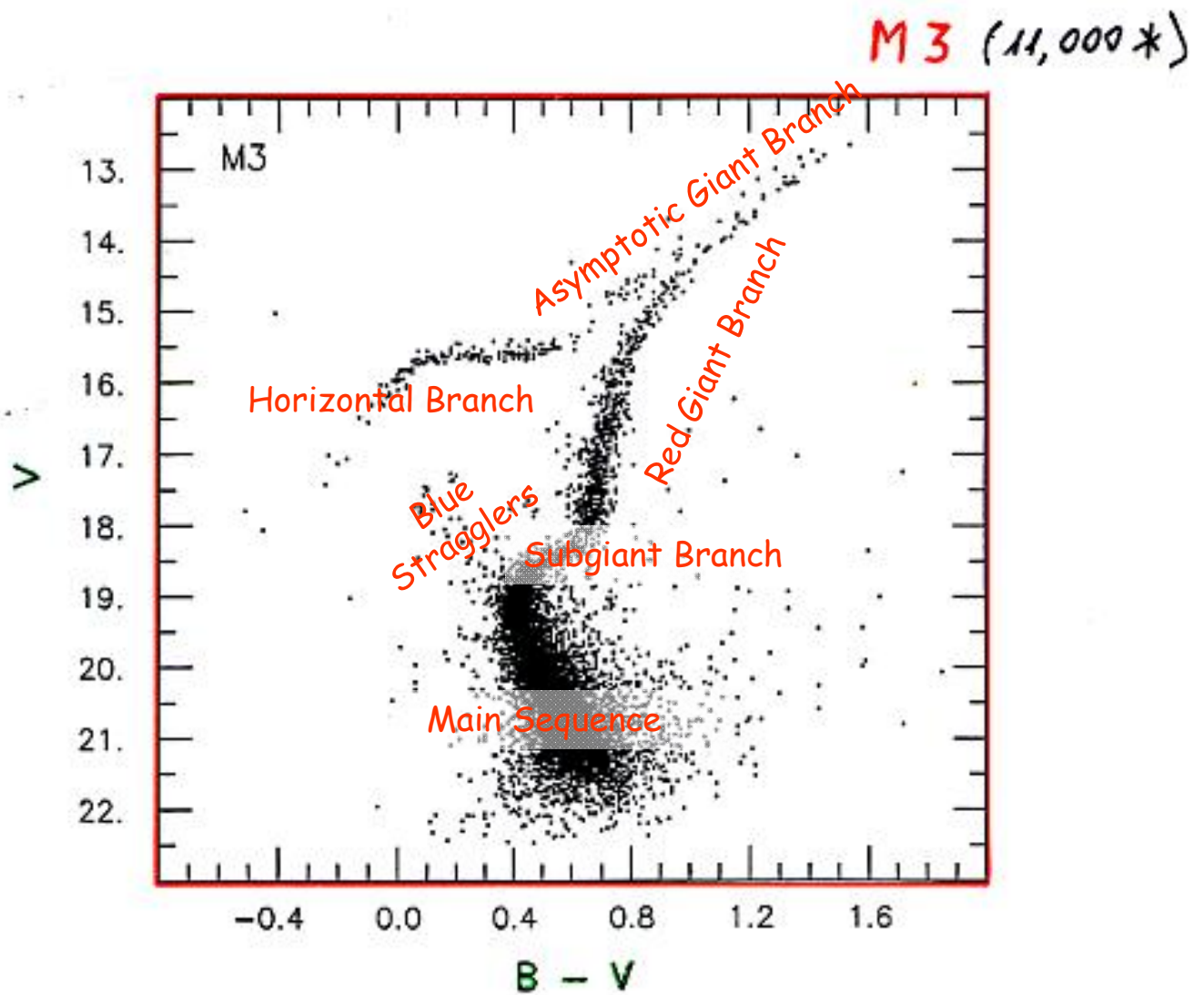


## Isocrone



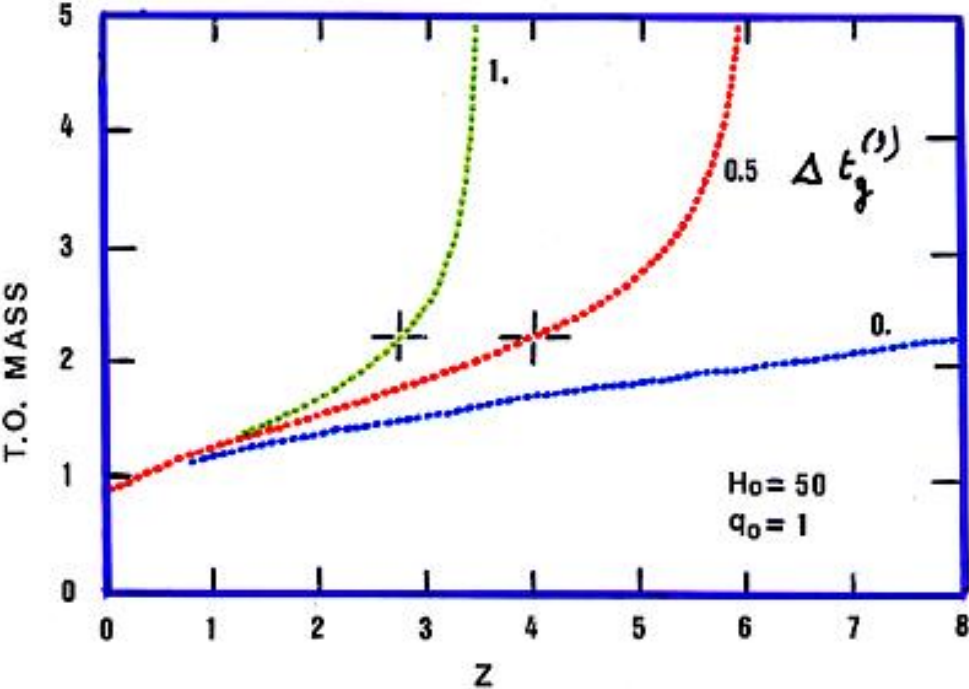
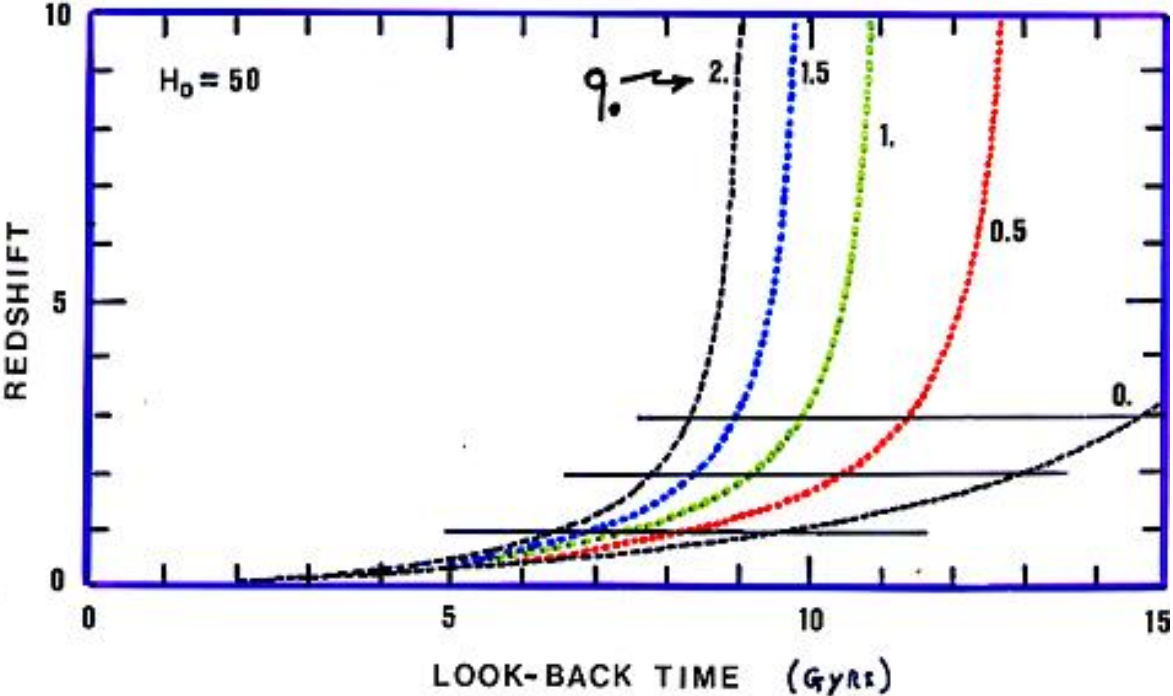
Vandenberg (1985)

# Un diagramma colore-magnitudine tipo (l'ammasso globulare M3)



Buonanno et al.  
(1994)

# Cosmologia & Look-back time



[http://en.wikipedia.org/wiki/Distance\\_measures\\_\(cosmology\)](http://en.wikipedia.org/wiki/Distance_measures_(cosmology))



$$\begin{aligned}
 * & \left\{ \begin{array}{l} 1) \quad \nabla P = -\rho g \Rightarrow \frac{P}{R} \propto \rho \frac{M}{R^2} \Rightarrow P \propto \rho \frac{M}{R} \\ 2) \quad \nabla M = 4\pi R^2 \rho \\ 3) \quad \nabla L = 4\pi R^2 \epsilon \end{array} \right. \\
 * & \left\{ \begin{array}{l} 4) \quad \nabla T = -\frac{3\rho k L}{16\pi a c T^3 R^2} \Rightarrow \frac{T}{R} \propto \frac{\rho L}{T^3 R^2} \Rightarrow T^4 \propto \frac{\rho L}{R} \end{array} \right. \\
 * & \left\{ \begin{array}{l} 5) \quad P = \frac{\rho k T}{\mu H} \Rightarrow P \propto \rho T \end{array} \right.
 \end{aligned}$$

$$\rho T \propto \rho \frac{M}{R}$$



$$\left\{ \begin{array}{l} T \propto \frac{M}{R} \end{array} \right.$$

$$\left\{ \begin{array}{l} T^4 \propto \frac{\rho L}{R} \end{array} \right. \Rightarrow \frac{M^4}{R^4} \propto \frac{M}{R^4} L \Rightarrow \boxed{L \propto M^3}$$

$$L t \propto M$$



$$\left\{ \begin{array}{l} t \propto \frac{M}{L} \end{array} \right. \Rightarrow$$

$$\left\{ \begin{array}{l} L \propto M^3 \end{array} \right.$$

$$\boxed{\begin{array}{l} t \propto M^{-2} \\ t \propto L_{T.O.}^{-2/3} \end{array}}$$

# Relazioni di scala per le stelle in Sequenza Principale

$$\left\{ \begin{array}{l} \nabla P = -\rho g \\ \rho = \frac{\rho k T}{\mu H} \end{array} \right. \Rightarrow \frac{\rho k T}{\mu H R} \propto -\rho \frac{GM}{R^2}$$

$$\Downarrow$$

$$T \propto \frac{M}{R} \mu$$

$$\nabla T = \frac{-3\rho \tilde{\kappa} L}{16\pi a c R^2 T^3}$$

$$\Downarrow$$

$$\frac{T^4}{R} \propto \frac{M}{R^3} \frac{\tilde{\kappa} L}{R^2}$$

$$\frac{M^{\frac{3}{4}}}{R^4} \mu^4 \propto \frac{M}{R^4} \tilde{\kappa} L$$

$$\Downarrow$$

$$L \propto M^3 \frac{\mu^4}{\tilde{\kappa}}$$

$$\left\{ \begin{array}{l} T \propto \frac{M}{R} \mu \\ L \propto R^2 T^4 \end{array} \right. \Rightarrow R \propto \frac{L^{\frac{1}{2}}}{T^2}$$

$$T \propto \frac{M T}{L^{\frac{1}{2}} \mu}$$

$$\Downarrow$$

$$\frac{L^{\frac{1}{2}}}{M \mu} \propto \mu$$

$$\left\{ \begin{array}{l} L \propto \frac{M^3 \mu^4}{\tilde{\kappa}} \\ T \propto \frac{M^{\frac{1}{2}} \mu}{\tilde{\kappa}^{\frac{1}{2}}} \end{array} \right. \Rightarrow L \propto T^6 \left( \frac{\tilde{\kappa}}{\mu} \right)^2$$

$$\left( \frac{M^3 \mu^4}{M^2 \tilde{\kappa} \mu} \right)^{\frac{1}{2}} \propto \left( \frac{M^{\frac{1}{2}} \mu}{\tilde{\kappa}^{\frac{1}{2}}} \right)^6 \left( \frac{\tilde{\kappa}}{\mu} \right)^2$$

$$\Downarrow$$

$$T \propto \sqrt{\frac{M}{\tilde{\kappa}}} \mu$$

# Energetica nucleare e rapporto M/L delle galassie

## METAL ABUNDANCE

$$X + Y + Z = 1$$

Hydrogen      Helium      "OTHERS"

$$\left[ \frac{Fe}{H} \right] = \log \frac{Fe}{Fe_{\odot}} - \log \frac{H}{H_{\odot}}$$

IF  $Fe \propto Z$

$$\left[ \frac{Fe}{H} \right] = \log \frac{Z}{0.017} - \log \frac{1-Z-Y}{0.71} \approx \log Z + 1.8$$

$$(X, Y, Z)_{\odot} = (0.70, 0.28, 0.017)$$

$$1 \text{ gr } H \rightarrow 1 \text{ gr } Z$$

$$6.6 \cdot 10^{18} \text{ ergs}$$

ENERGETICS

IN A GALAXY:  $M_Z \sim 3 \cdot 10^5 M_{\odot} \sim 4 \cdot 10^{42} \text{ gr}$

$$M_Z = \frac{\int L \times t}{6.6 \cdot 10^{18}} \sim \frac{\langle L \rangle \cdot 10^{10} \text{ yr}}{6.6 \cdot 10^{18} \text{ ergs}}$$

$$\langle L \rangle \sim 2.2 \cdot 10^{10} L_{\odot}$$

$$\frac{M}{L} \leq 5 \quad \text{in primordial galx}$$

# Clocks

$$L t = E$$

KELVIN-HELMHOLTZ  $E = \frac{GM^2}{R}$

$$t_{\odot} \sim \frac{E}{L} \sim \frac{GM^2}{RL} \sim \frac{6 \cdot 10^{-8} (2 \cdot 10^{33})^2}{7 \cdot 10^{10} \cdot 4 \cdot 10^{33}} \text{ sec.}$$

$$t_{\odot} \sim \frac{6 \cdot 10^{25}}{7 \cdot 10^{10} \cdot 3 \cdot 10^7} \text{ yr} \Rightarrow \frac{2}{7} \cdot 10^8 \text{ yr}$$

NUCLEARE  $E = \alpha M c^2$   
 $\downarrow$   
 0.007

$$t_{\odot} \sim \frac{E}{L} \sim \frac{\alpha M c^2}{L} \sim \frac{7 \cdot 10^{-3} \cdot 2 \cdot 10^{33} \cdot 9 \cdot 10^{20}}{4 \cdot 10^{33}} \text{ sec.}$$

$$t_{\odot} \sim \frac{63}{2} \frac{10^{17}}{3 \cdot 10^7} \text{ yr} \sim \frac{63}{6} \cdot 10^{10} \sim 10^{11} \text{ yr}$$

DIPENDENZA DALLA CHIMICA

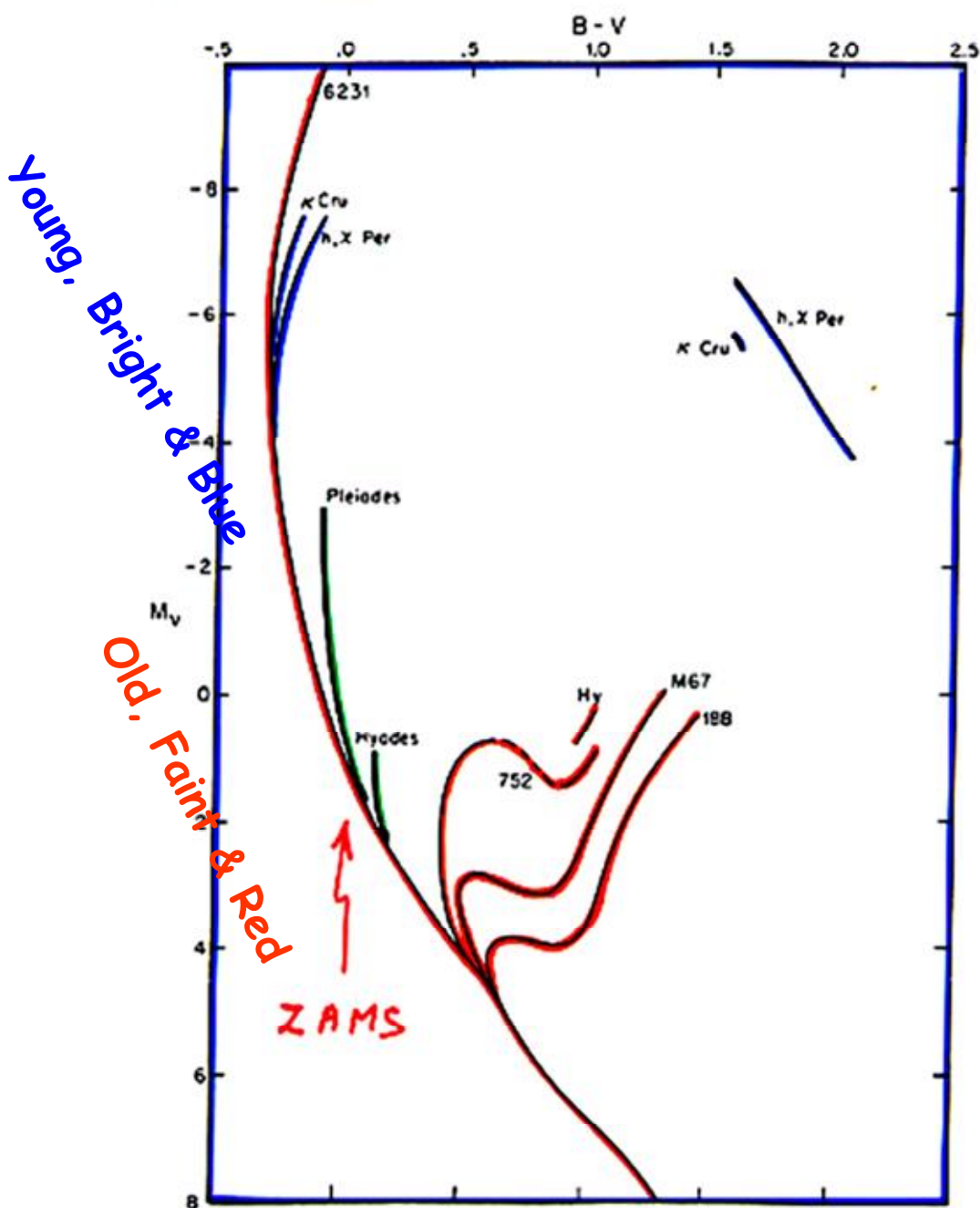
$$\begin{cases} t \propto \frac{M}{L} \\ L \propto \frac{M^3 \mu^4}{R} \end{cases} \Rightarrow t \propto \frac{M \tilde{K}}{M^{\frac{3}{2}} \mu^4} \propto \frac{1}{M^{\frac{1}{2}}} \left( \frac{\tilde{K}}{\mu^4} \right)$$

quindi: se  $M = \text{fix}$   $t \uparrow$  se  $Z \uparrow$   
 $t \downarrow$  se  $Y \uparrow$

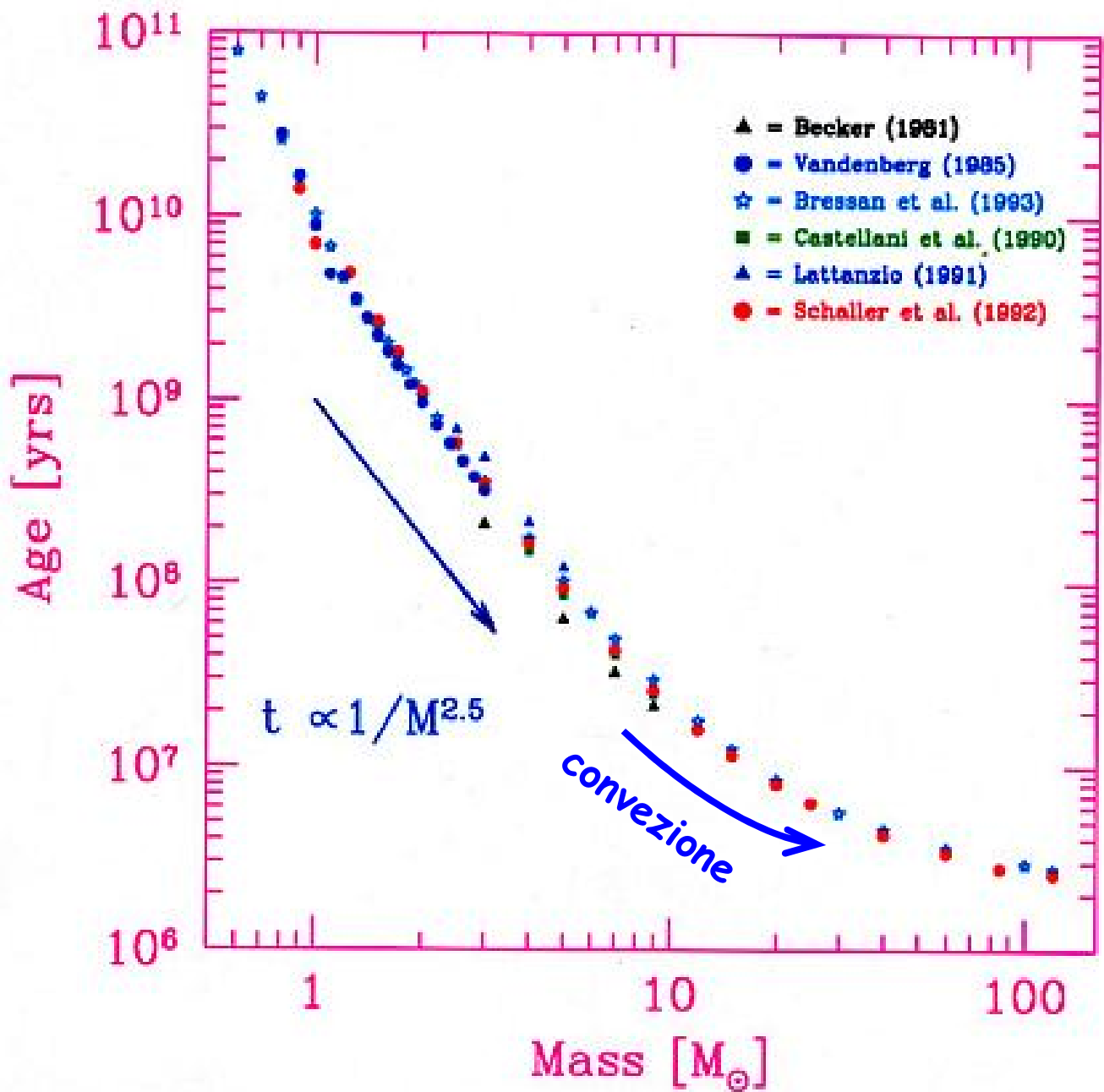
se  $t = \text{fix}$   $M_{T0} \uparrow$  se  $Z \uparrow$   
 $M_{T0} \downarrow$  se  $Y \uparrow$

# Il punto di Turn Off come indicatore di eta'

Figure 2.5. Course of the color-magnitude array for a number of well-known open clusters of different ages. From top to bottom: NGC 6231,  $\kappa$  Crucis (NGC 4755),  $\eta, \chi$  Persei (NGC 864, 886), Pleiades, Hyades, NGC 752, Messier 67 (NGC 2682), and NGC 188.



# The Clock



# Peso Molecolare Medio

$$\mu = \frac{\sum n_j m_j}{\sum n_j}$$

$\forall j =$  tutte le specie chimiche

## GAS NEUTRO

$$\mu_N = \frac{\rho_X + \rho_Y + \rho_Z}{\frac{\rho_X}{H} + \frac{\rho_Y}{4H} + \frac{\rho_Z}{2Z H}} \sim \frac{H}{X + \frac{Y}{4} + \frac{Z}{2Z}}$$

$\downarrow$   
 $\sim 0$

## PLASMA TOT IONIZZATO

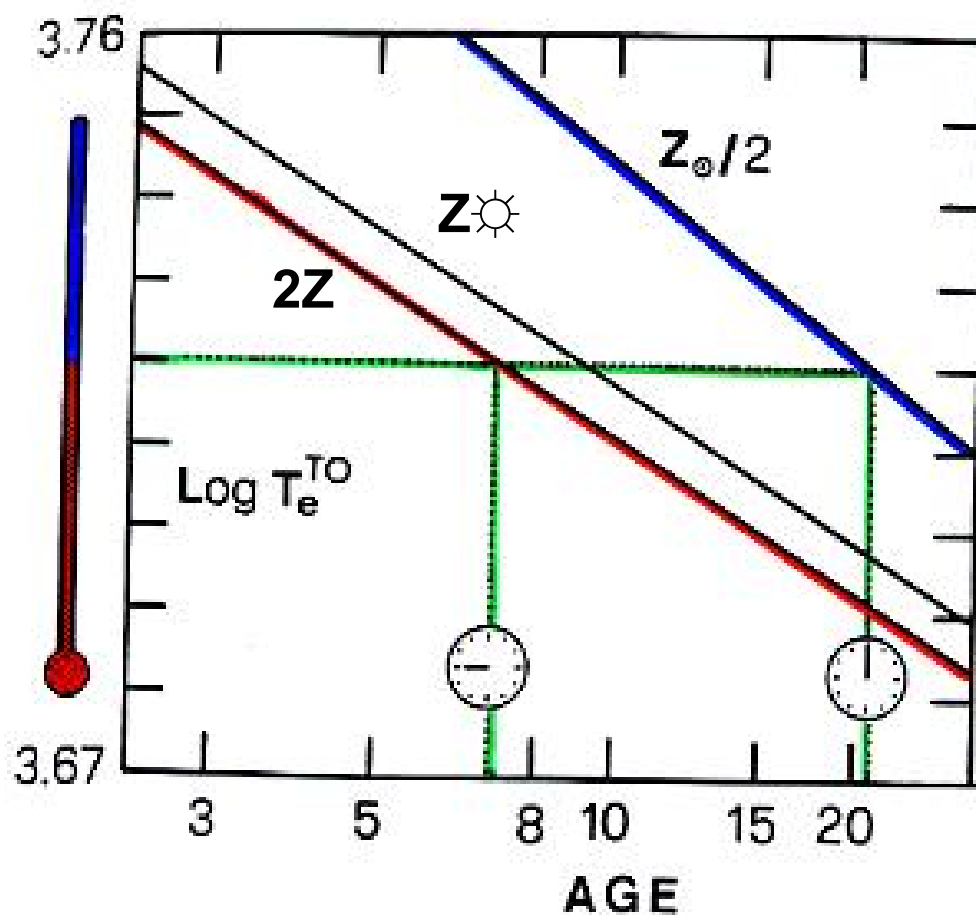
$$\mu_i = \mu_N + \frac{\rho}{\frac{\rho_X}{H} + \frac{2\rho_Y}{4H} + \frac{Z\rho_Z}{2Z}} = \mu_N + \frac{H}{X + \frac{Y}{2} + \frac{Z}{2}}$$

$$\mu_i = \frac{H}{\left(X + \frac{Y}{4} + \frac{Z}{2Z}\right) + \left(X + \frac{Y}{2} + \frac{Z}{2}\right)} = \frac{H}{2X + \frac{3}{4}Y + \underbrace{\left(\frac{1+1}{2}\right)\frac{Z}{2}}_{\sim 0}}$$

$$\mu_i \sim \frac{H}{2X + \frac{3}{4}Y + \frac{Z}{2}}$$

# Thermometers & Clocks (effetto della metallicita')

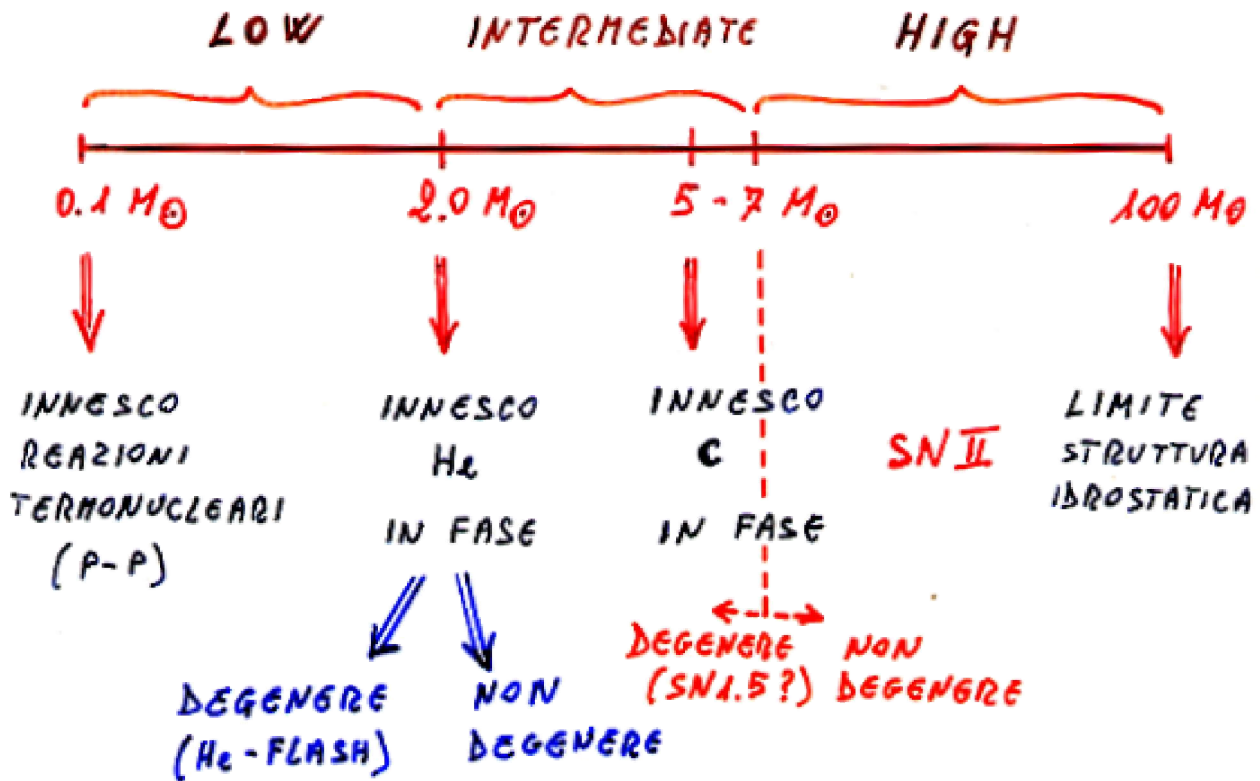
GLOBAL PROPERTIES OF STELLAR POPULATIONS



Renzini & Buzzoni (1986)



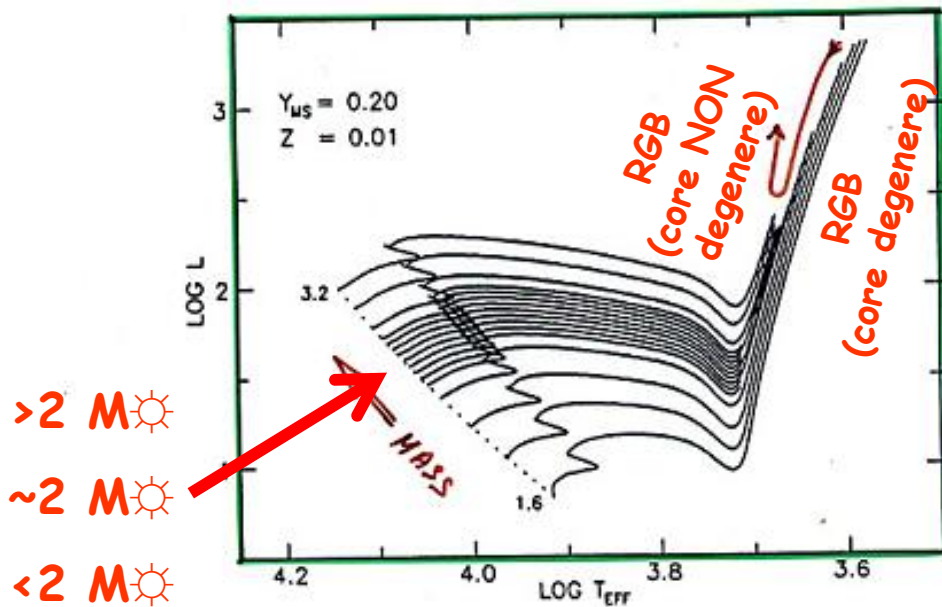
# STELLAR MASSES



FASE	LOW-MASS	HIGH-MASS
CORE H-BURNING	MS	MS
SHELL H-BURNING	{ SGB RGB	1-ST GB
CORE He-BURNING	HB	1-ST BLUE LOOP
DOUBLE (MULTIPLE) SHELL BURNING	AGB	2-ND, 3-RD etc. GBs

# L'effetto della "transizione di fase" in RGB

SWEIGART, GREGGIO & RENZINI (1989)



RENZINI & BUZZONI (1986)

GLOBAL PROPERTIES OF STELLAR POPULATIONS

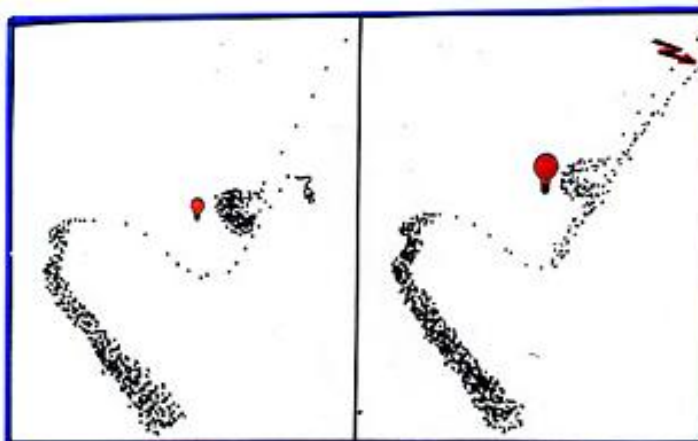


Figure 14. An artist view of the RGB phase transition. On the left panel the HR diagram of a cluster slightly younger than  $t(M_{\text{HeF}})$ . On the right panel the same cluster when slightly older than

$t(M_{\text{HeF}})$ . Note the virtual identity of the main sequences, and, by contrast, the development of the RGB. The plug indicates the point when helium ignites (non degenerately). The jagged arrow indicates the helium flash location. The growing light bulb emphasizes the brightening of the clump giants across the RGB phase transition. The AGB stays nearly the same across the transition.

## DISTINCTIVE PARAMETERS IN A STELLAR POPULATION

- 1) AGE  $\Rightarrow t$
- 2) CHEMICAL COMPOSITION  $\Rightarrow Z, [Fe/H]$
- 3) STAR MASS DISTRIBUTION  $\Rightarrow IMF$
- 4) STAR FORMATION HISTORY  $\Rightarrow SFR$

## CANONICAL ASSUMPTIONS

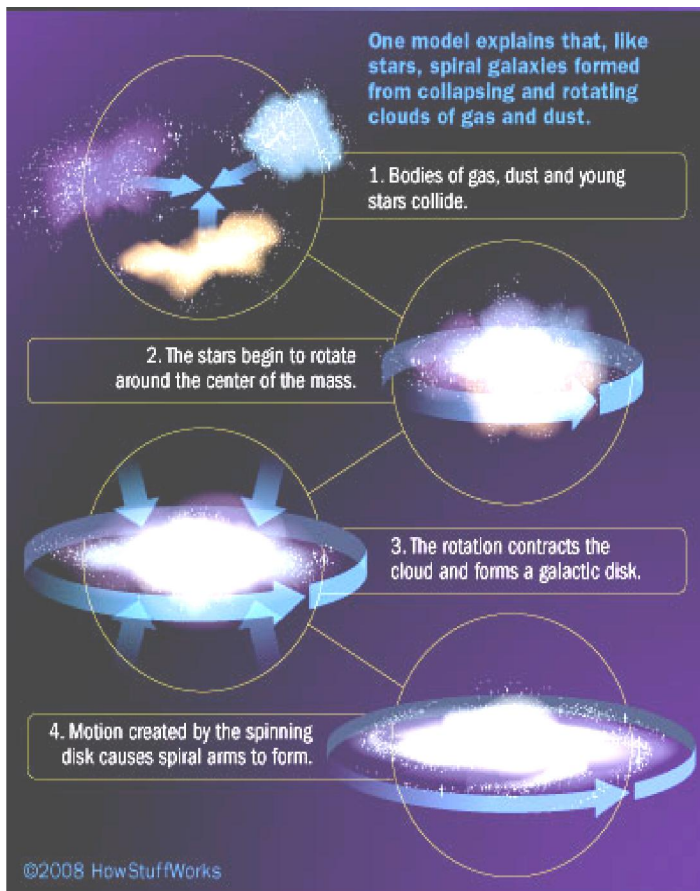
- 1) IMF  $N(M) \propto M_*^{-s}$  ( $s = 2.35$ )
- 2) SFR  $\begin{cases} \delta(t) \rightarrow SSP \\ f(t) \rightarrow CSP. \end{cases}$

**Articoli consigliati (vedi Webpage):**

<http://www.bo.astro.it/~eps/lezioni/lezioni.html>

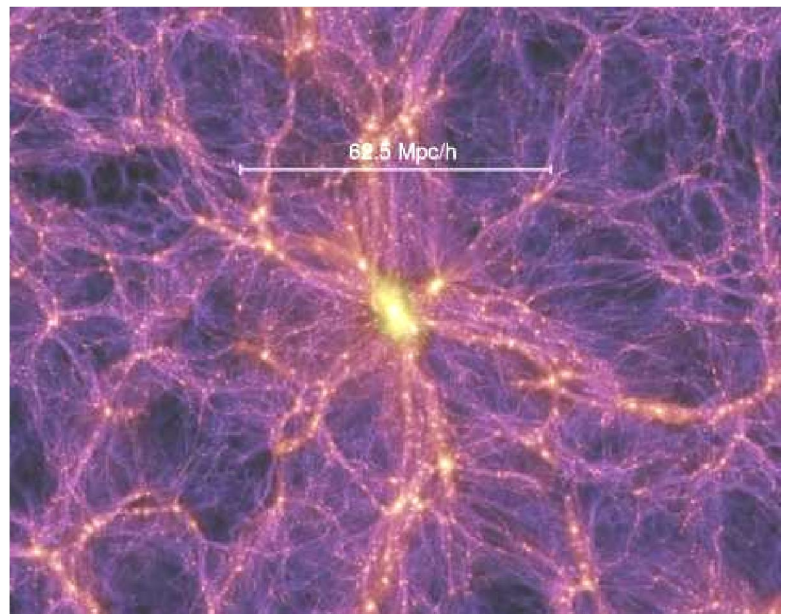
- SSPs (Tinsley)
- SSPs (Renzini & Buzzoni)
- M/L clusters (Girardi)
- Galaxy Colors (Buzzoni)
- Galaxy Spectral Atlas (Kennicutt1)
- Galaxy Spectral Atlas (Kennicutt2)
- Energetica e Metallicita'
- Chemical evolution of spiral galaxies (Buzzoni)

# Come nascono le galassie?



**Scenario  
"monolitico"  
(Larson 1974, 1975)**

**Scenario  
"gerarchico"  
(Kauffmann &  
White 1993)**

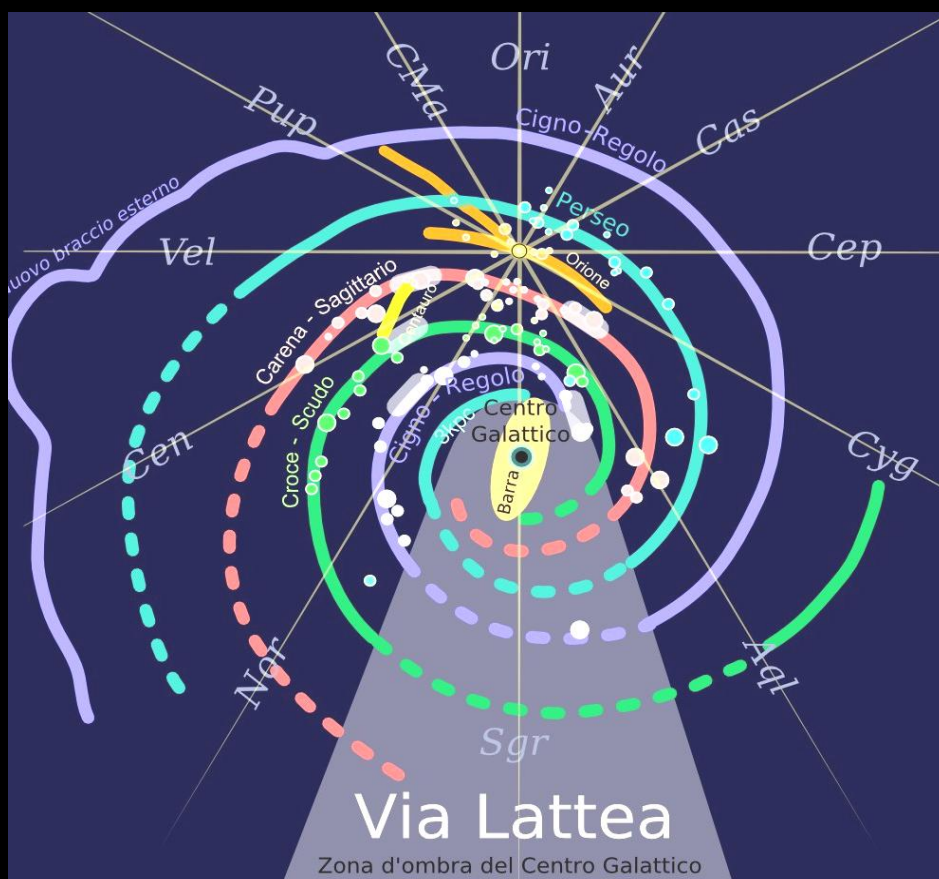


[http://en.wikipedia.org/wiki/Galaxy\\_formation\\_and\\_evolution](http://en.wikipedia.org/wiki/Galaxy_formation_and_evolution)

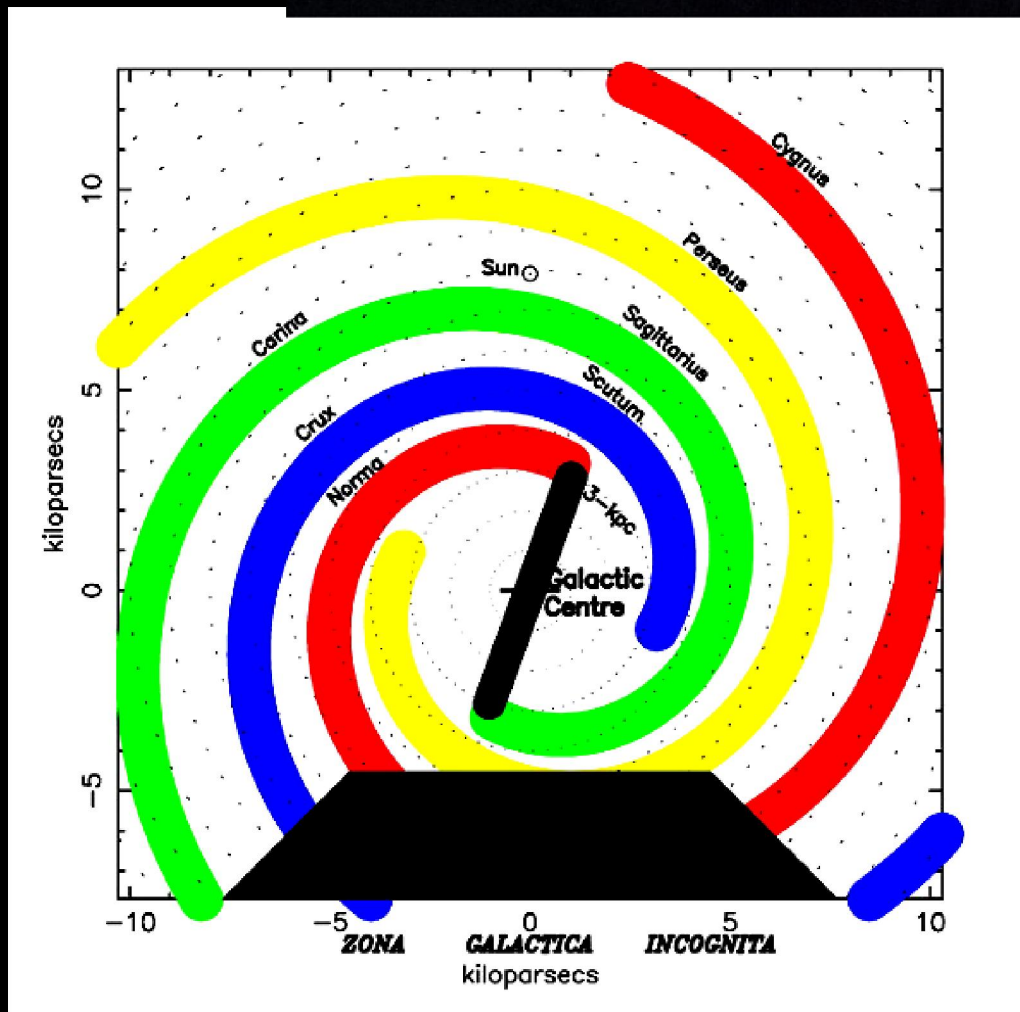
[http://en.wikipedia.org/wiki/Dwarf\\_galaxy\\_problem](http://en.wikipedia.org/wiki/Dwarf_galaxy_problem)

[http://it.wikipedia.org/wiki/Via\\_Lattea](http://it.wikipedia.org/wiki/Via_Lattea)

# La Via Lattea



# I vari bracci della Via Lattea (schematico)

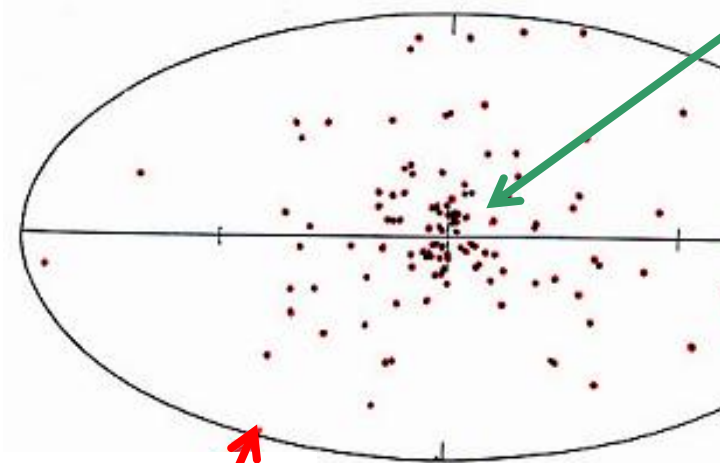


Vallée (2005)

# I diversi sistemi stellari nella Via Lattea

Ammassi aperti

Verso il centro galattico



(da "dentro") (in sezione)

Ammassi globulari

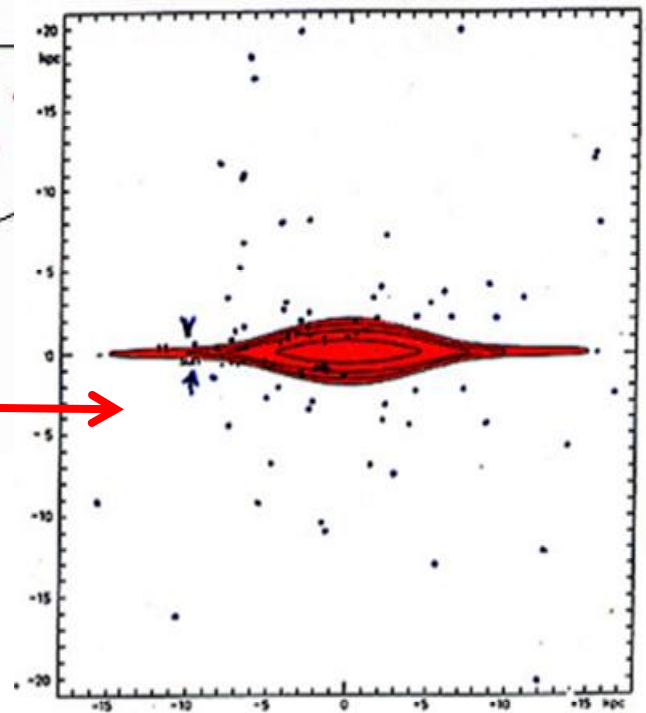
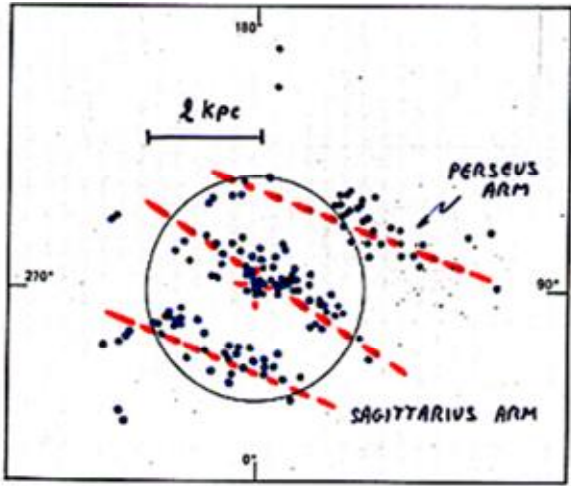


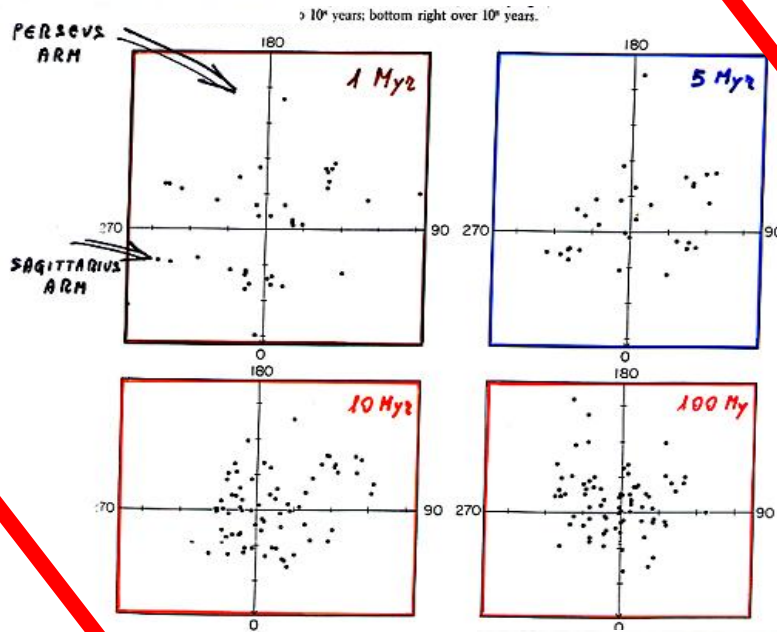
Fig. 23.6: Il sistema galattico: distribuzione spaziale degli ammassi globulari, proiettata su di un piano passante per il sole e perpendicolare al piano galattico, ed aree di uguale densità (riferite alle vicinanze del sole). Nel piano galattico è rappresentato, punteggiato, il sottile strato di materia interstellare con popolazione I estrema (braccio della spirale) (secondo J. H. Oort).



# Gli ammassi aperti come traccianti dei bracci a spirale



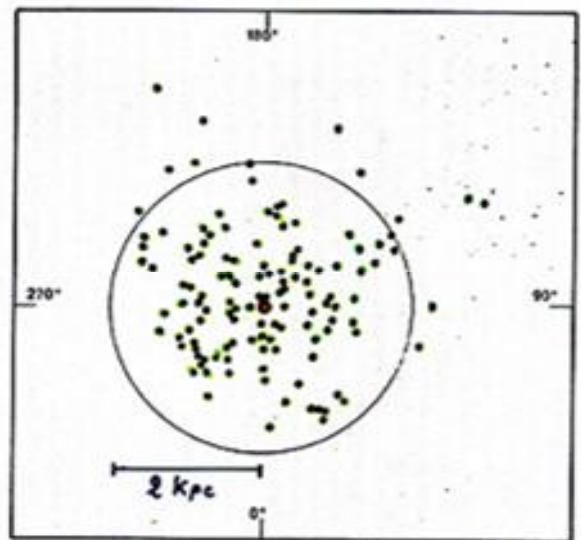
Associazioni O-B (<1Myr)



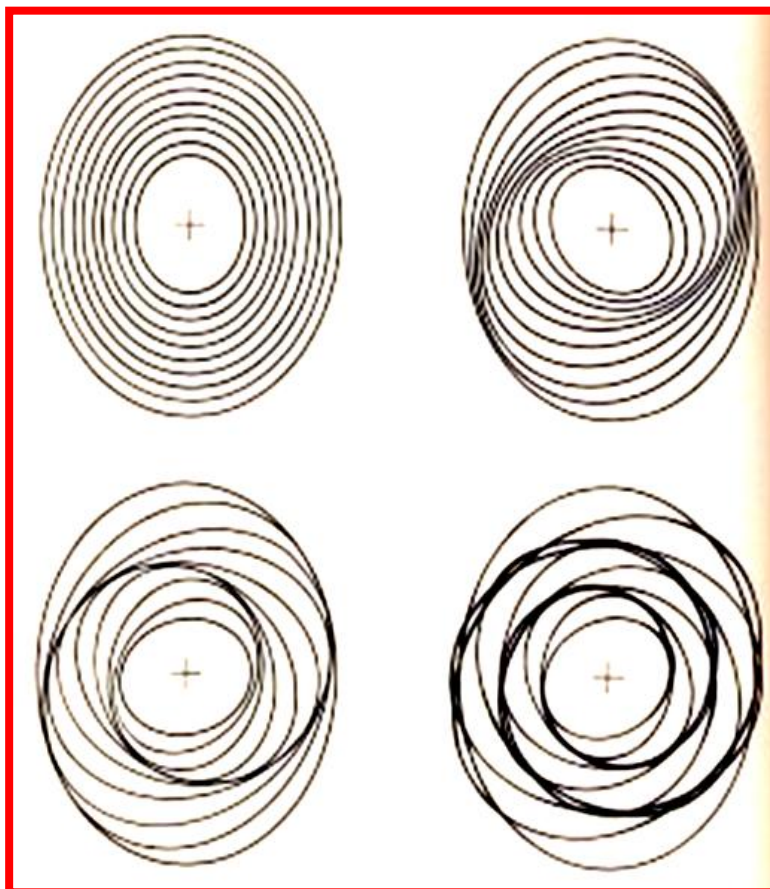
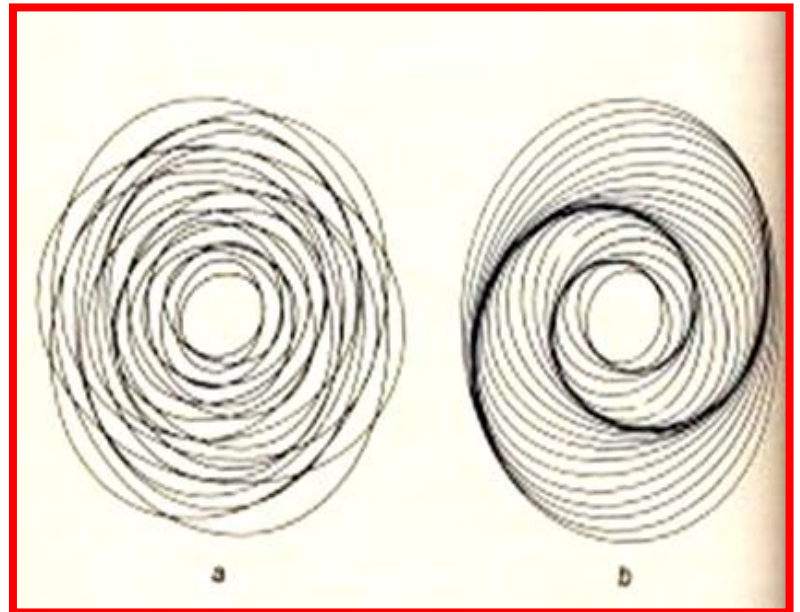
Eta'

Ammassi aperti (>1Gyr)

[http://it.wikipedia.org/wiki/Ammasso\\_aperto](http://it.wikipedia.org/wiki/Ammasso_aperto)



# Risonanze orbitali & genesi delle braccia a spirale

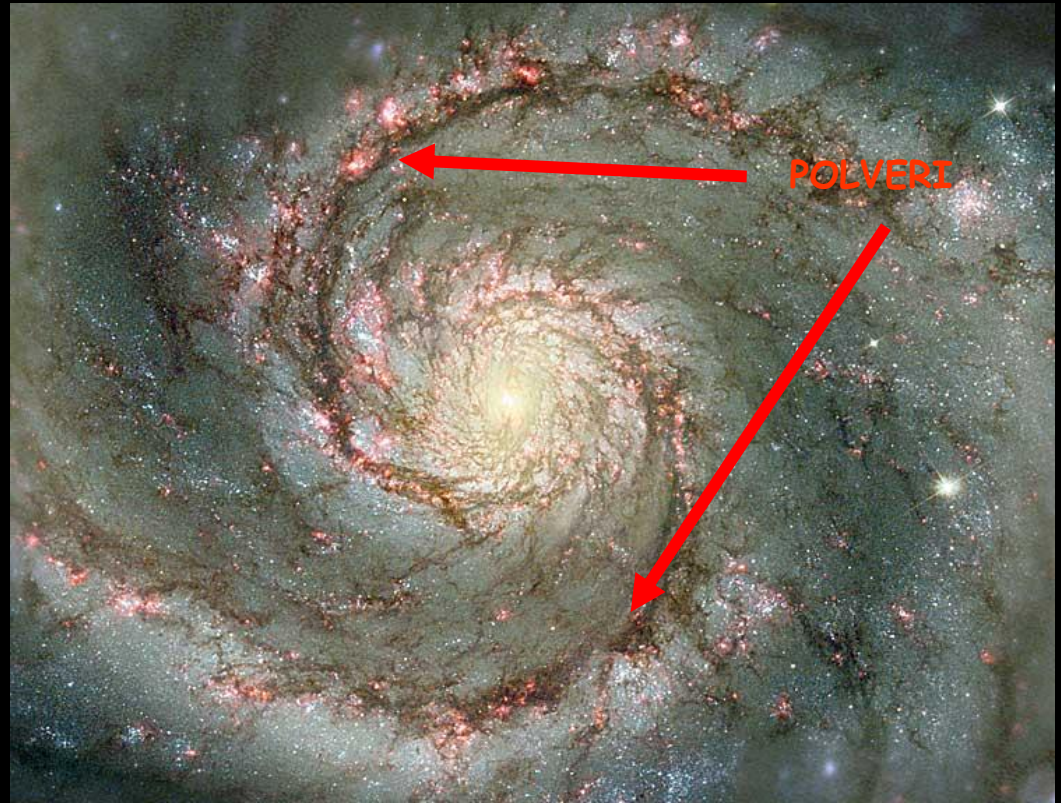


**Kalnajs  
(1986)**

# Il meccanismo di formazione stellare

## Il caso di M51

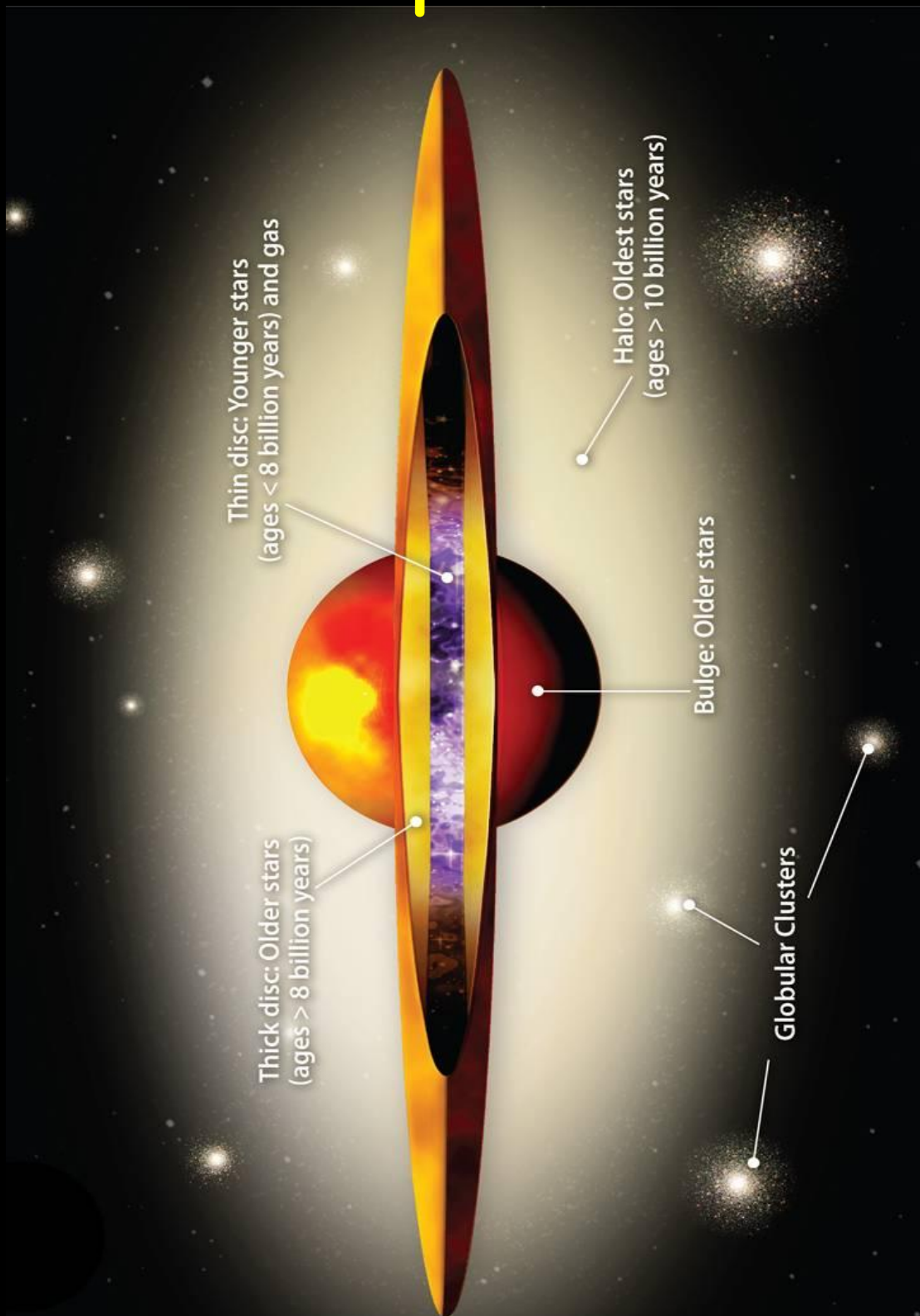
Ottico



Ultravioletto



# Struttura delle galassie a spirale



# Il Diagramma di Bottlinger e la diagnostica delle popolazioni stellari

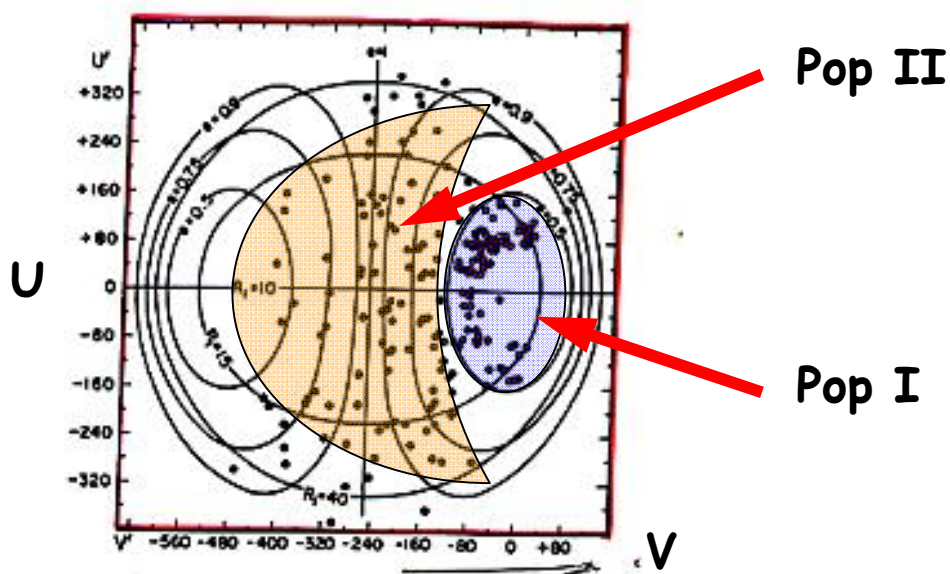
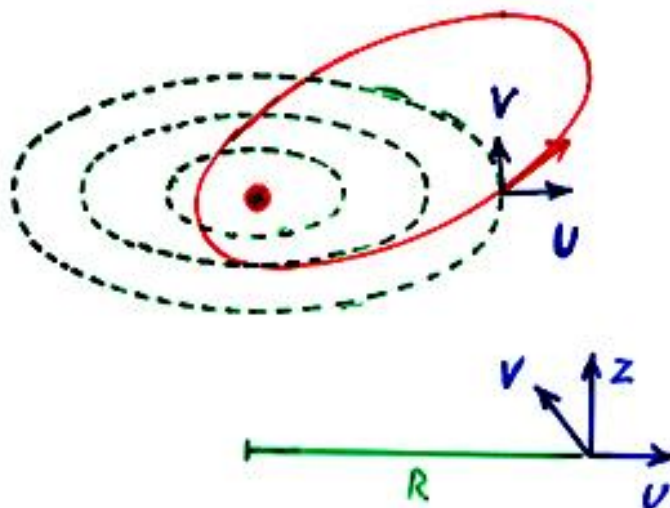
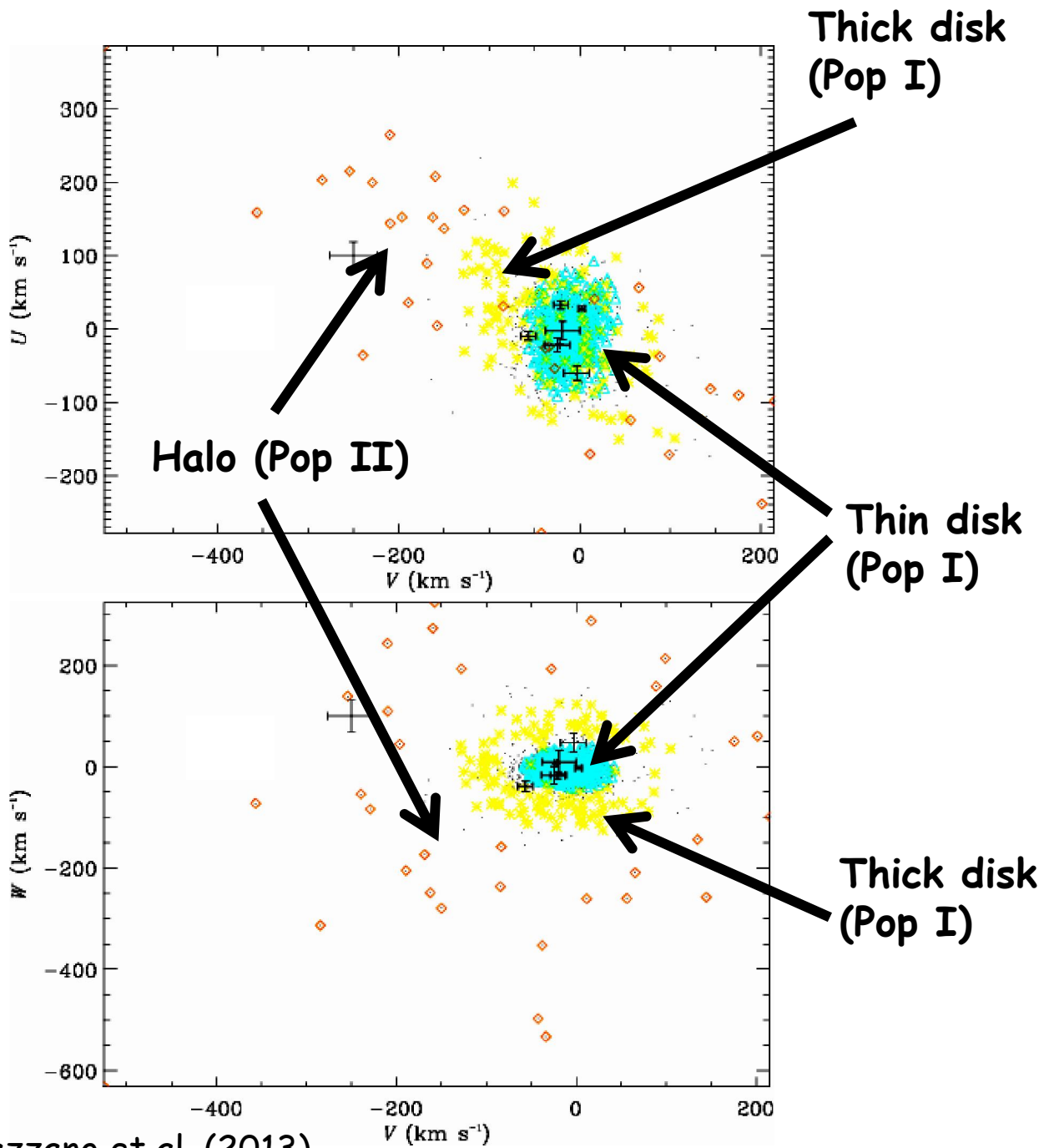
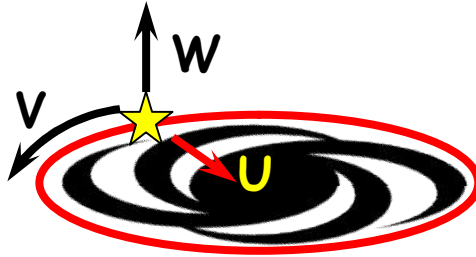


Fig. 23.10: Diagramma di Bottlinger. Sono riportate le componenti delle velocità galattiche  $U'$  (verso l'anticoentro) e  $V'$  (nel senso della rotazione) relative ai dintorni del sole. Gli assi ortogonali rappresentano le  $U$  e  $V$  assolute. Per ogni curva è data l'eccentricità orbitale  $e$  e la distanza apogalattica  $R_1$  in kpc. Nel capitolo 27 diremo sulle stelle (segnate con  $*$ ) aventi un eccesso nell'ultravioletto  $\delta(U-B) > +0^m.16$ , cioè le stelle povere di metalli della popolazione II di « halo ». Queste sono, incidentalmente, stelle veloci con grande velocità spaziale. Con  $o$  sono segnate le stelle con  $\delta(U-B) < +0^m.16$ , le quali costituiscono una transizione dalla popolazione II di halo alla popolazione del disco galattico, con orbite meno eccentriche (secondo O. J. Eccen).



# Il Diagramma di Bottlinger - 2



Gazzano et al. (2013)

# La struttura verticale del disco

SANBAGE (1982)

SANBAGE & FOOTS (1987)

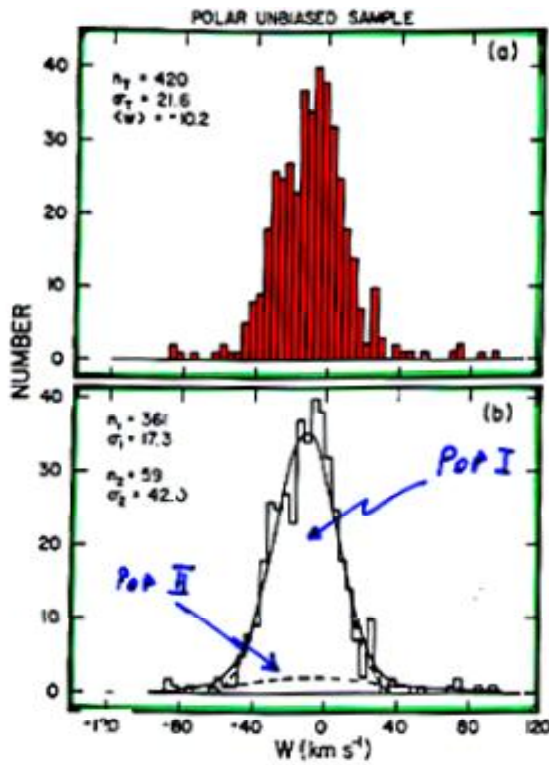


FIG. 2. (Top) Distribution of  $W$  velocities from Table VI for the 420-star sample, binned in  $4 \text{ km s}^{-1}$  intervals. (Bottom) Two-Gaussian fit to the observed distribution. The  $\langle W \rangle$ , and  $\sigma$ , values for the high-velocity component have been assumed.

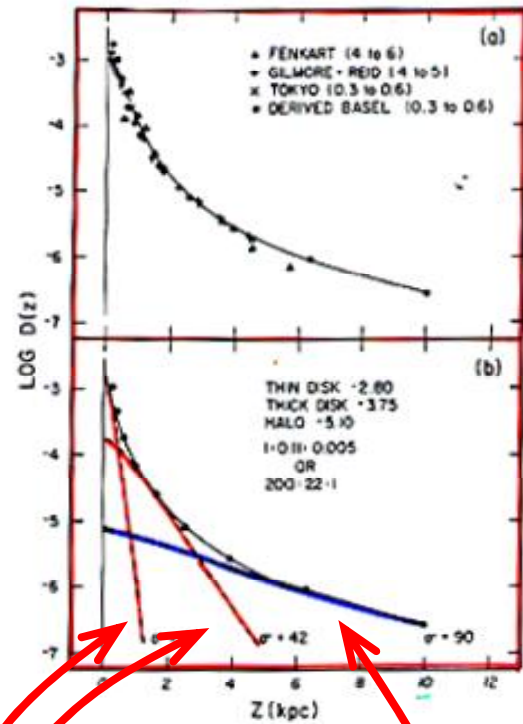


FIG. 2. (Top) The density  $D(Z)$  perpendicular to the galactic plane for the four data sets listed in Table II, III, and V. (Bottom) Decomposition of the observed  $\log D(Z)$  function into three components using the calculated densities shown in Fig. 1.

HALO 1

THICK DISK 22

THIN DISK 200

P/P HALO

# Le orbite delle Pop I e Pop II

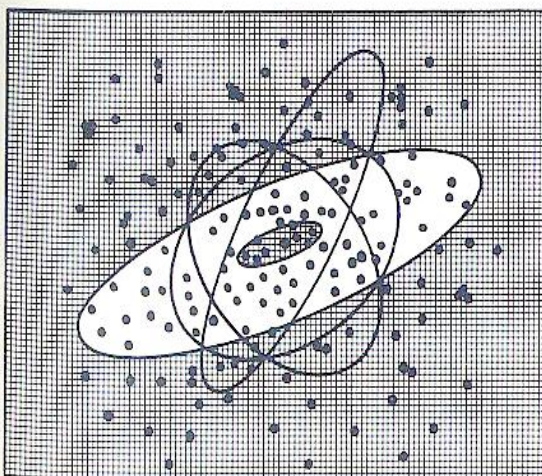
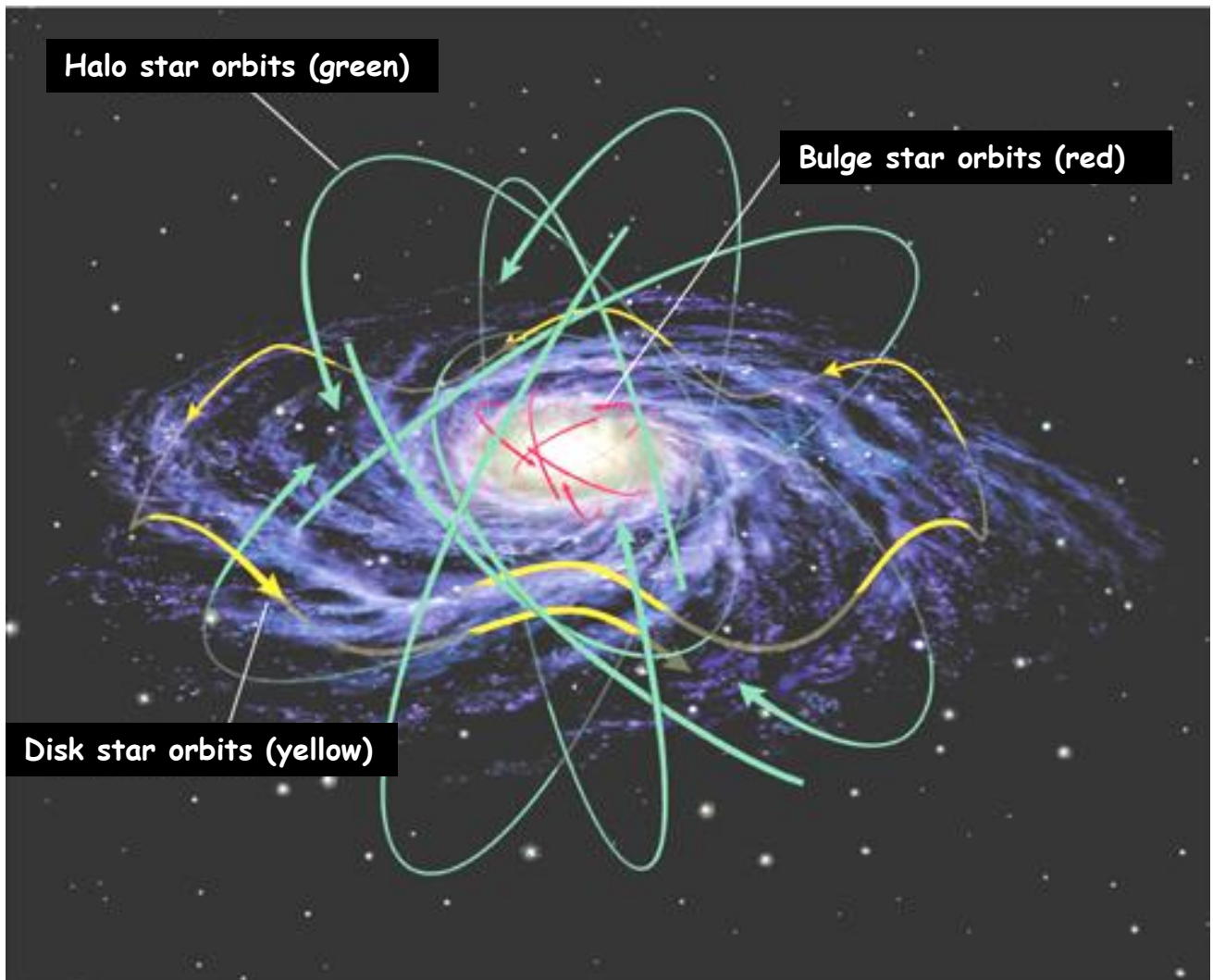


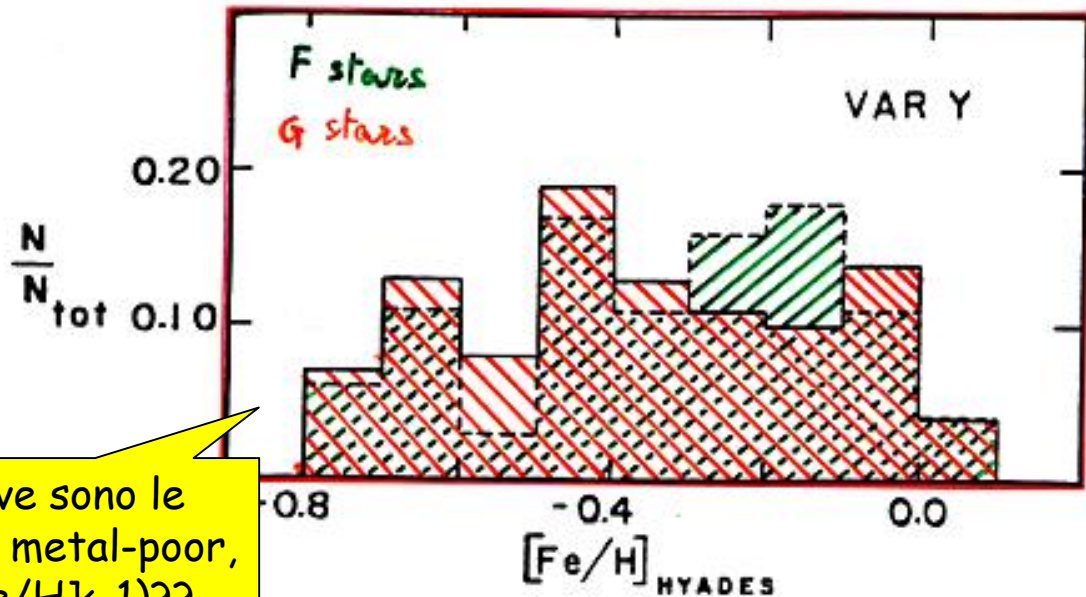
Fig. 11 Schema della costituzione della Galassia. Sono indicate alcune tipiche orbite delle stelle e degli ammassi dell'alone.

Castellani (1986)



# Thick & Thin disk: The G-dwarf problem

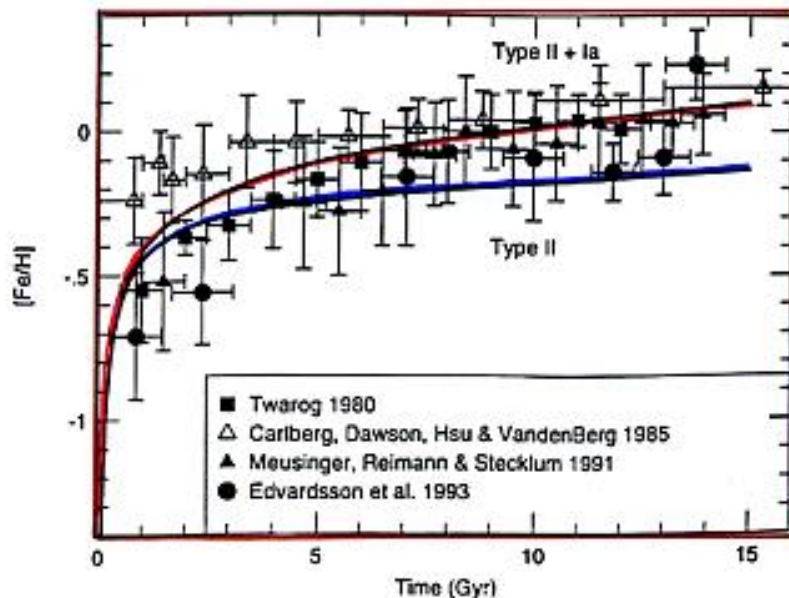
TWAROG (1980)



Dove sono le  
stelle metal-poor,  
([Fe/H] <-1)??

FIG. 8.—F dwarf metallicity distribution (*dashed line*) including corrections for stellar evolution and scale height effects which produce a constant SFR compared to the G dwarfs (*solid line*).

TIMMES et al. (1995)



# Thick & Thin disk e SFR

PARBI & FERRINI (1994)

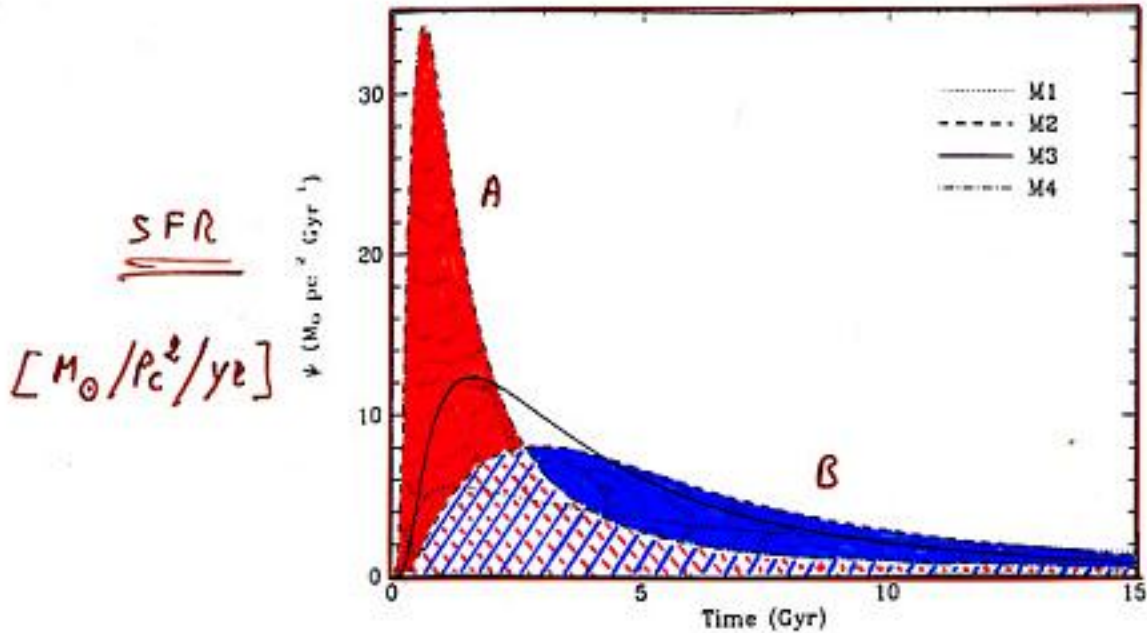


FIG. 3.—SF rate vs. time (M1–M4)

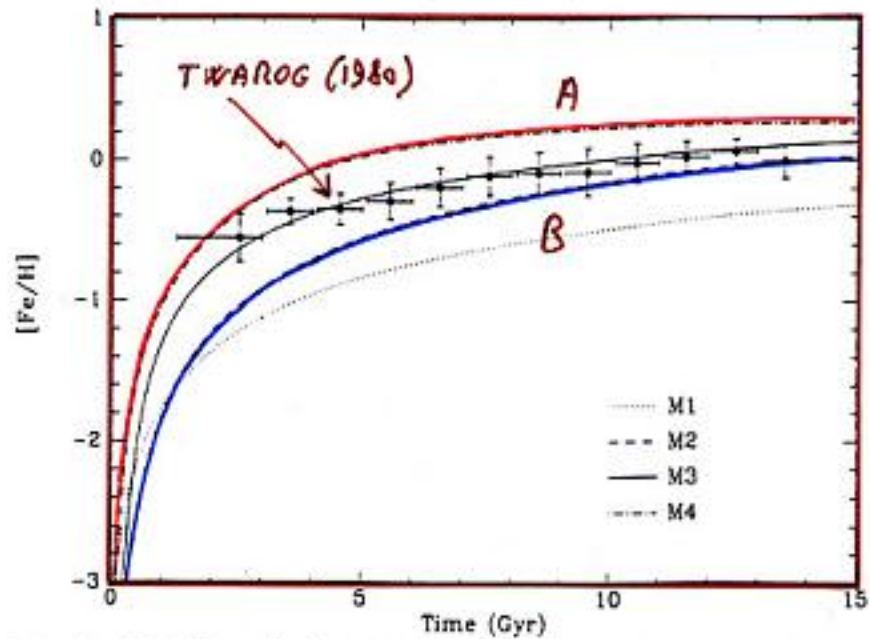
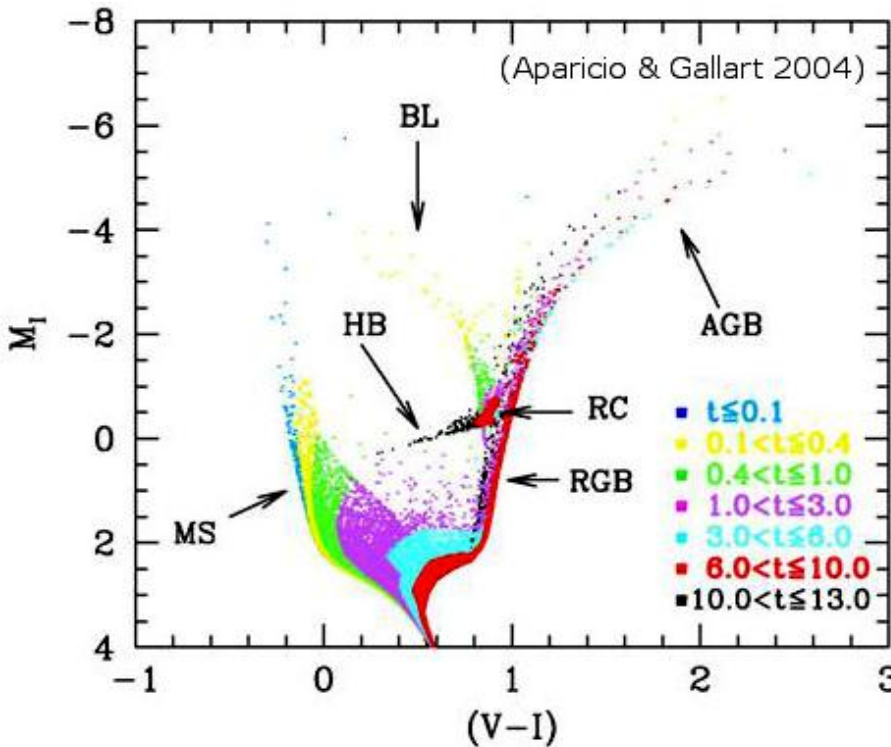
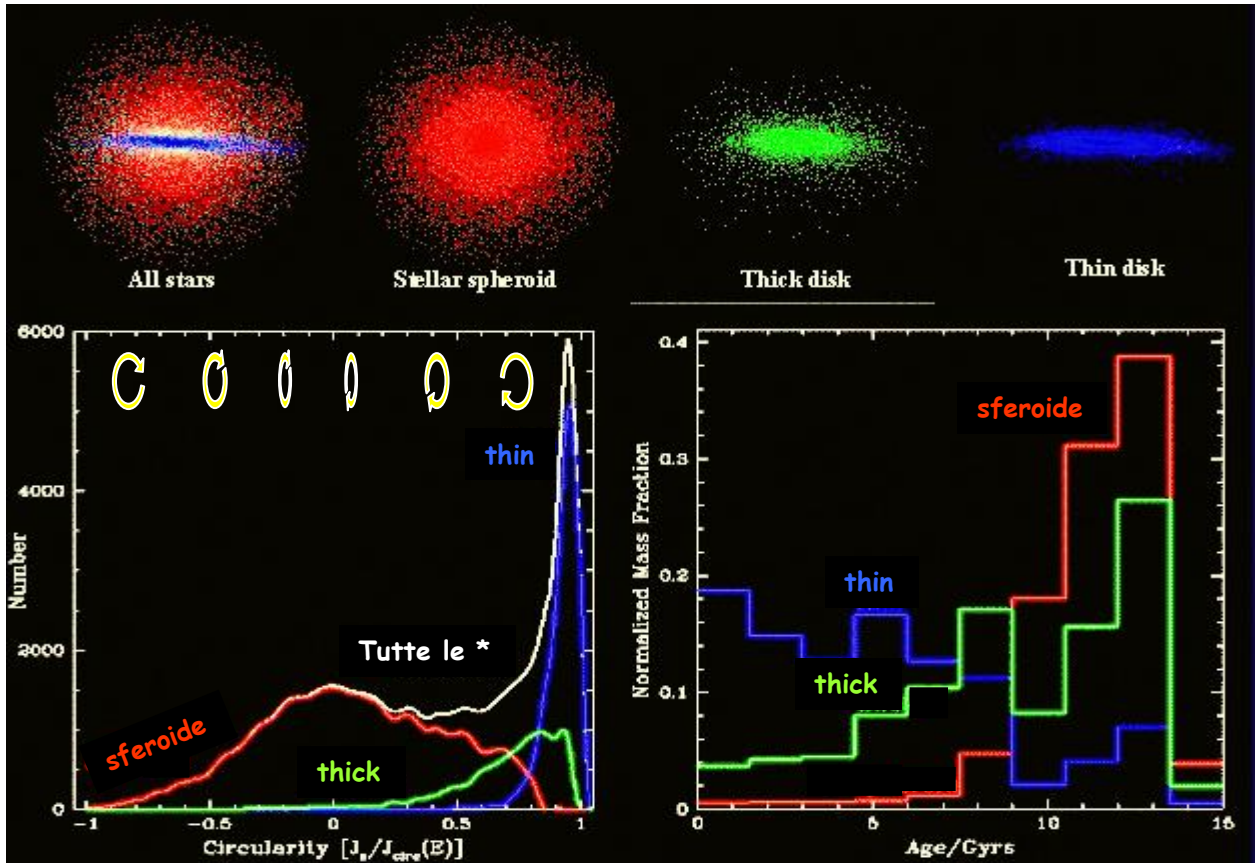


FIG. 4.— $[Fe/H]$  vs. time for the same models of Fig. 3, superposed on data of Twarog (1980).

# Le popolazioni stellari composite nel disco di M31



Collins & the RAVE coll. (2010)

$M_I$  apparente

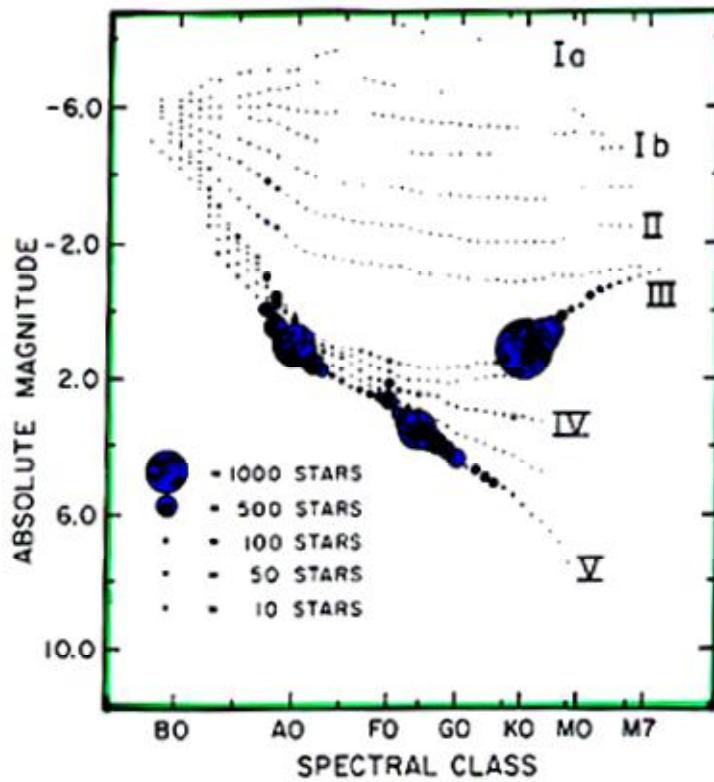
+21.0

+23.0

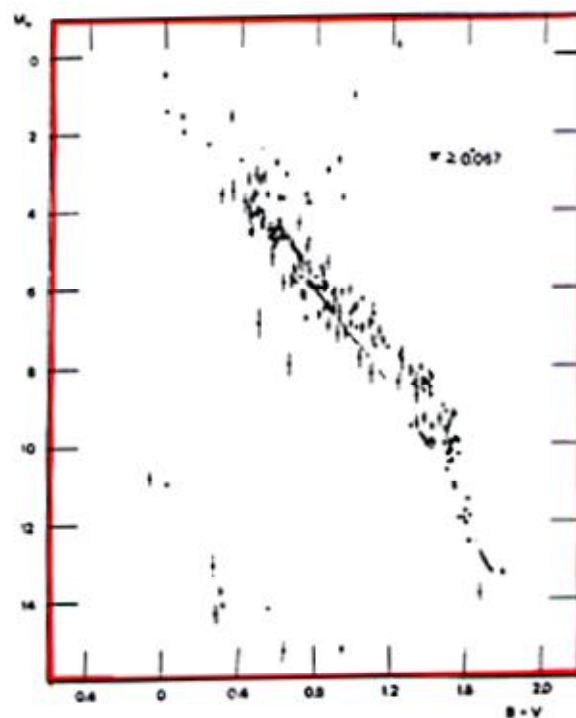
+25.0

+27.0

# I conteggi stellari e la determinazione della IMF



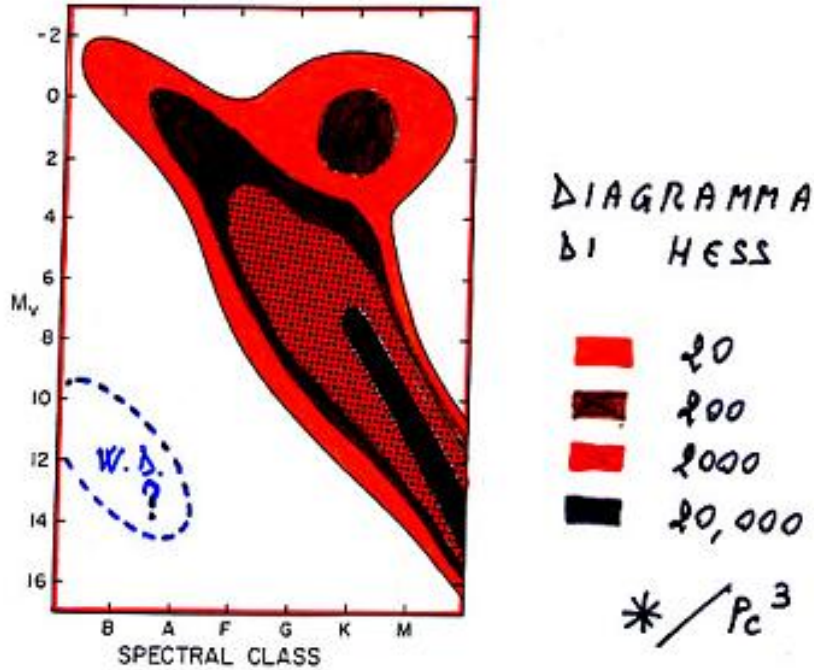
*App. Mag.  
limited*



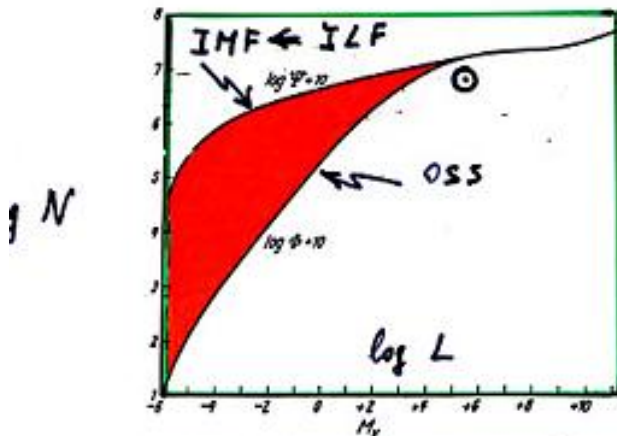
*Distance  
limited*

# Il diagramma di Hess

Figure 5.2. Schematic Hess diagram for stars in our neighborhood. Numbers of stars per cubic parsec are shown by contours which refer to 20, 200, 2000, and 20,000 stars. The main sequence runs along the ridge. Probably the peak is reached at about the bottom right corner of the diagram, with about 40,000 stars per cubic parsec. Statistics for fainter stars do not permit us to say how fast the slope falls off from there. The contours for white dwarfs are not shown; these stars populate a moderately high ridge, roughly parallel to the main ridge and separated from it by a deep valley.



Statistica stellare. Funzione di luminosità

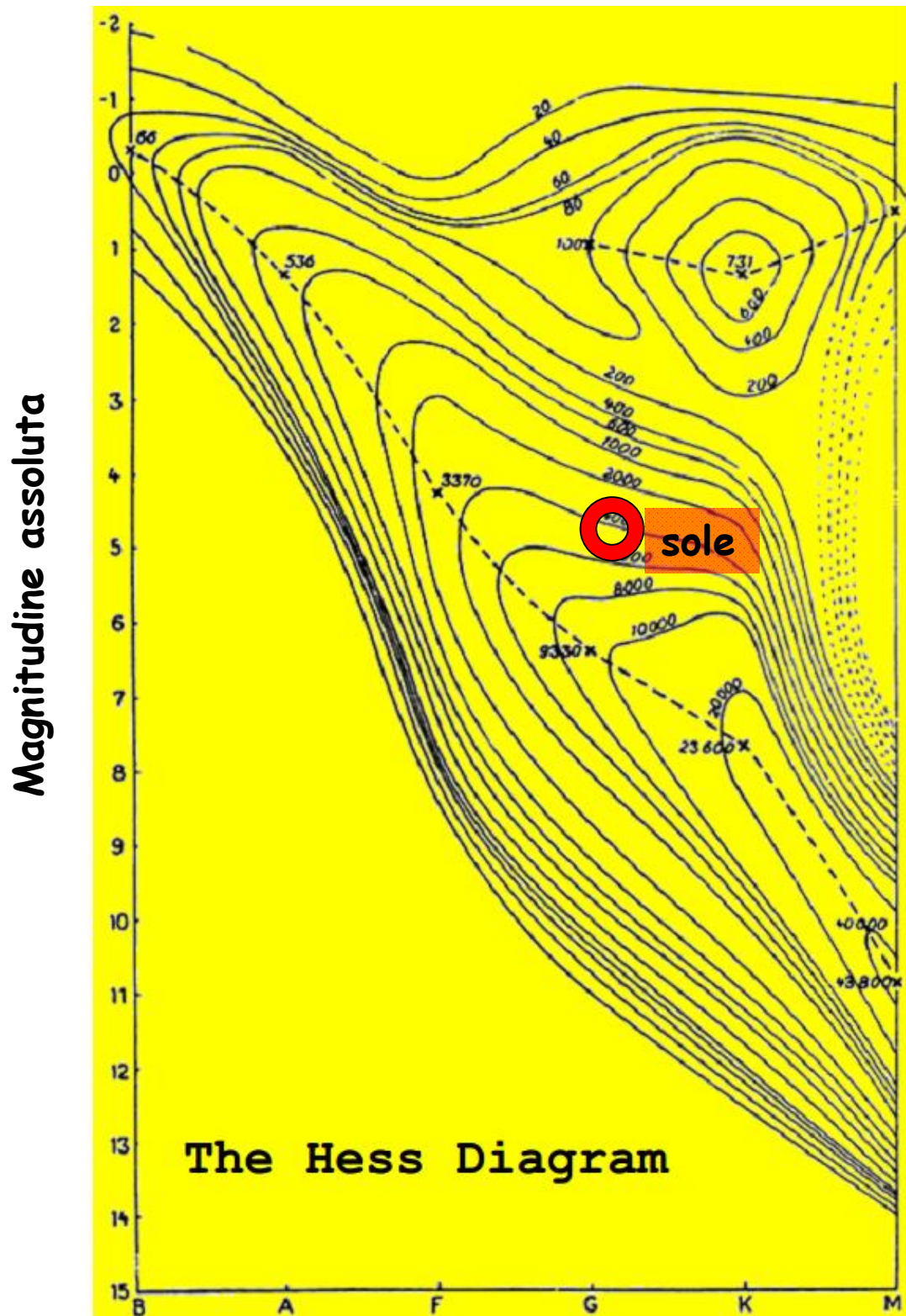


KAPTEYN  
& VAN RHIJN '20

SALPETER (1953)

Fig. 26.8: Funzione di luminosità  $\phi(M_v)$  e funzione iniziale di luminosità  $\psi(M_v)$ , per stelle della sequenza principale nei dintorni del sole. La  $\phi$  e la  $\psi$  danno rispettivamente il numero osservato di stelle per  $\text{pc}^3$  comprese fra  $M_v - 1/4$  ed  $M_v + 1/4$ , e di quelle formatesi a partire dalla formazione della Galassia.

## Il diagramma di Hess (2)



# La IMF

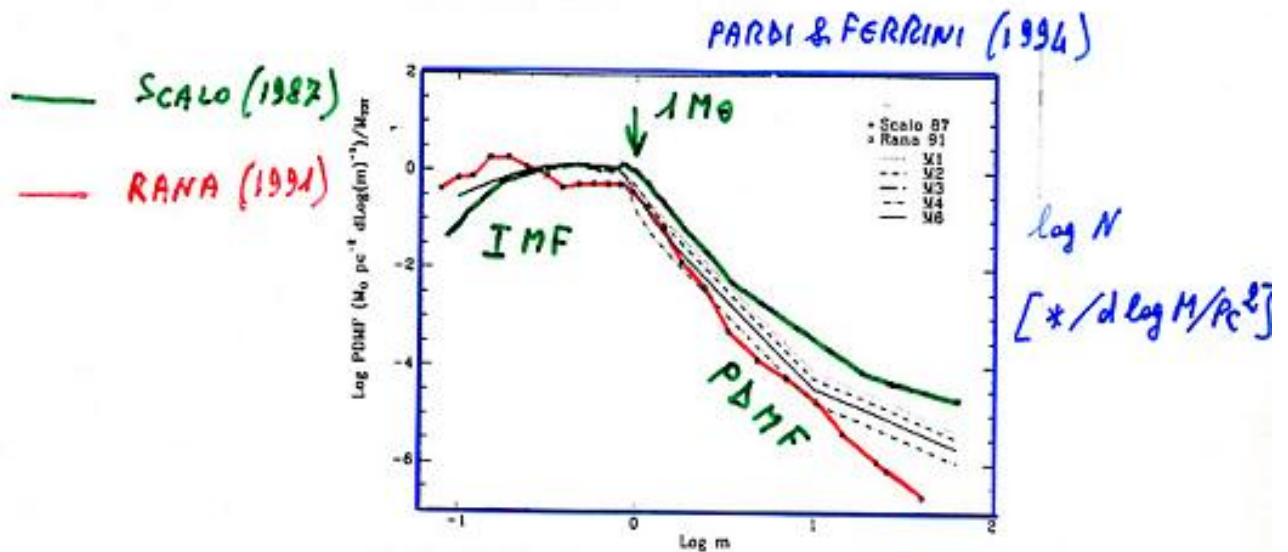
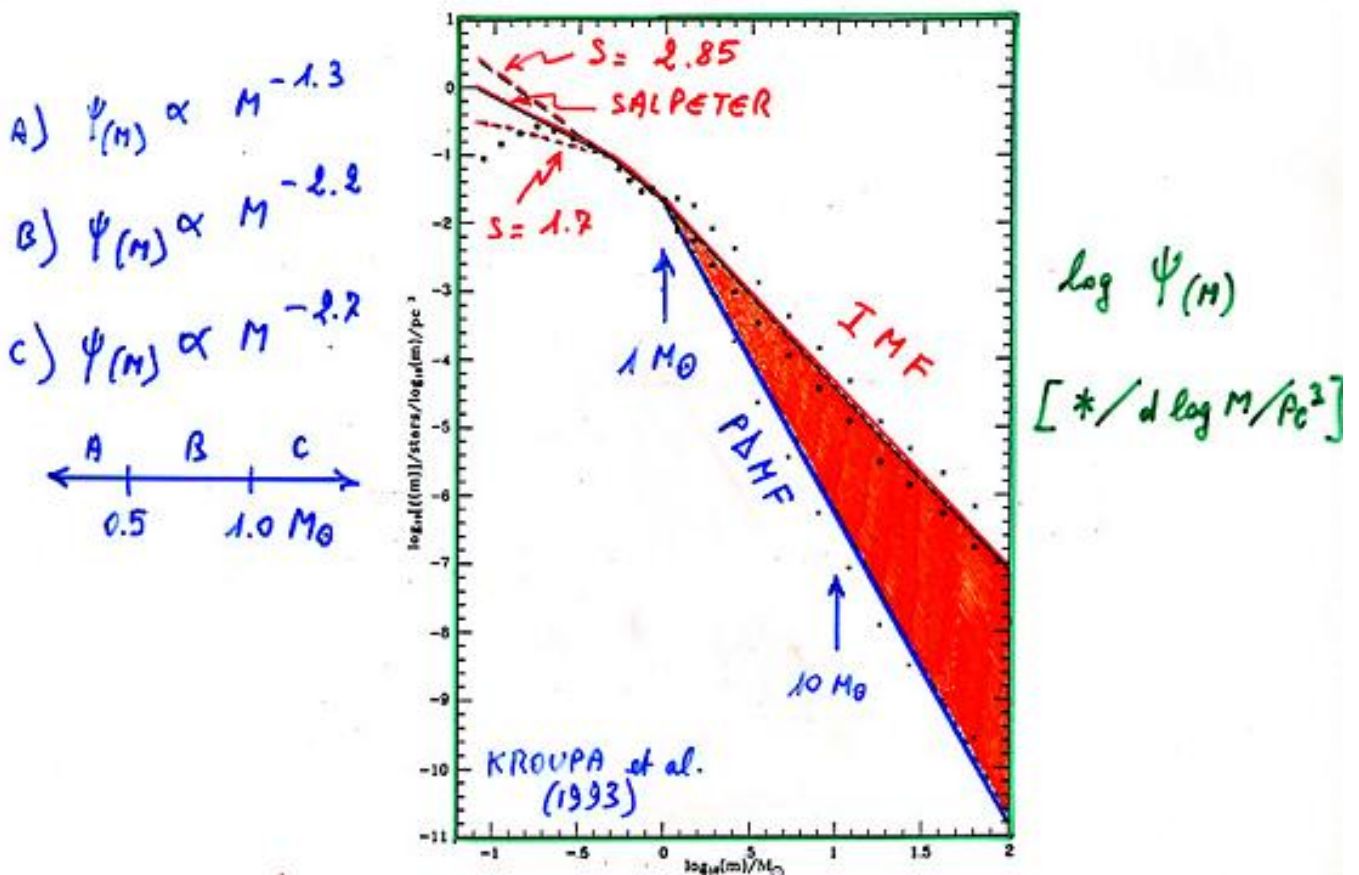
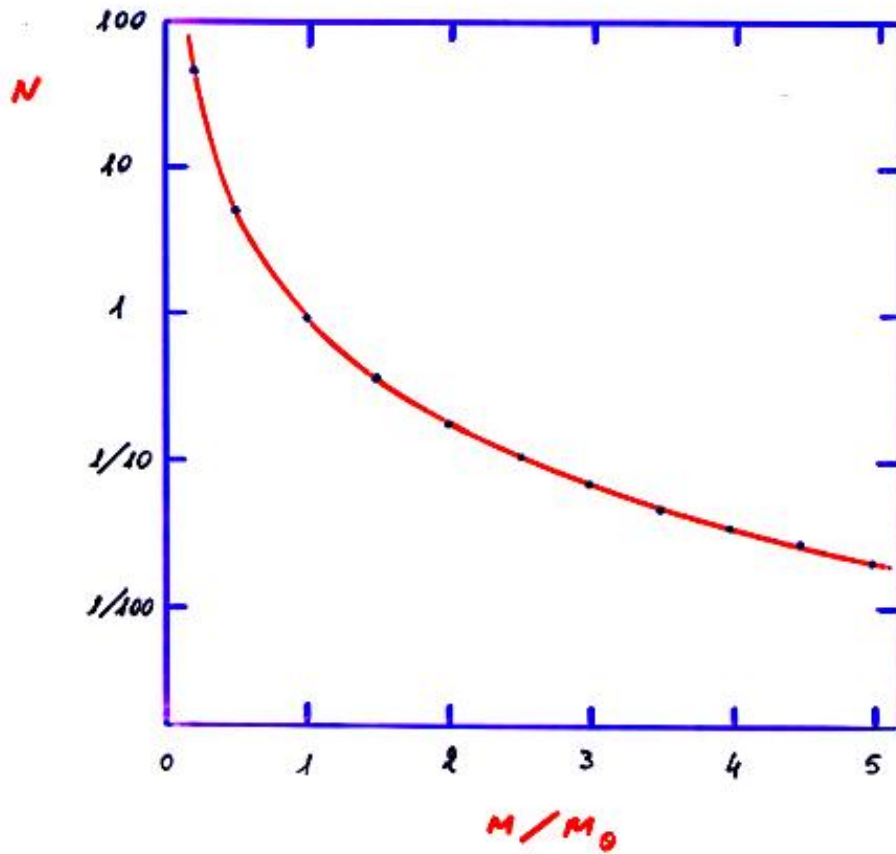


FIG. 12.—PDFs predicted by the model in cases M1–M4 and M6 superposed on data of Scalzo (1987 [triangles]) and Rana (1991 [squares]).



# La IMF (2)



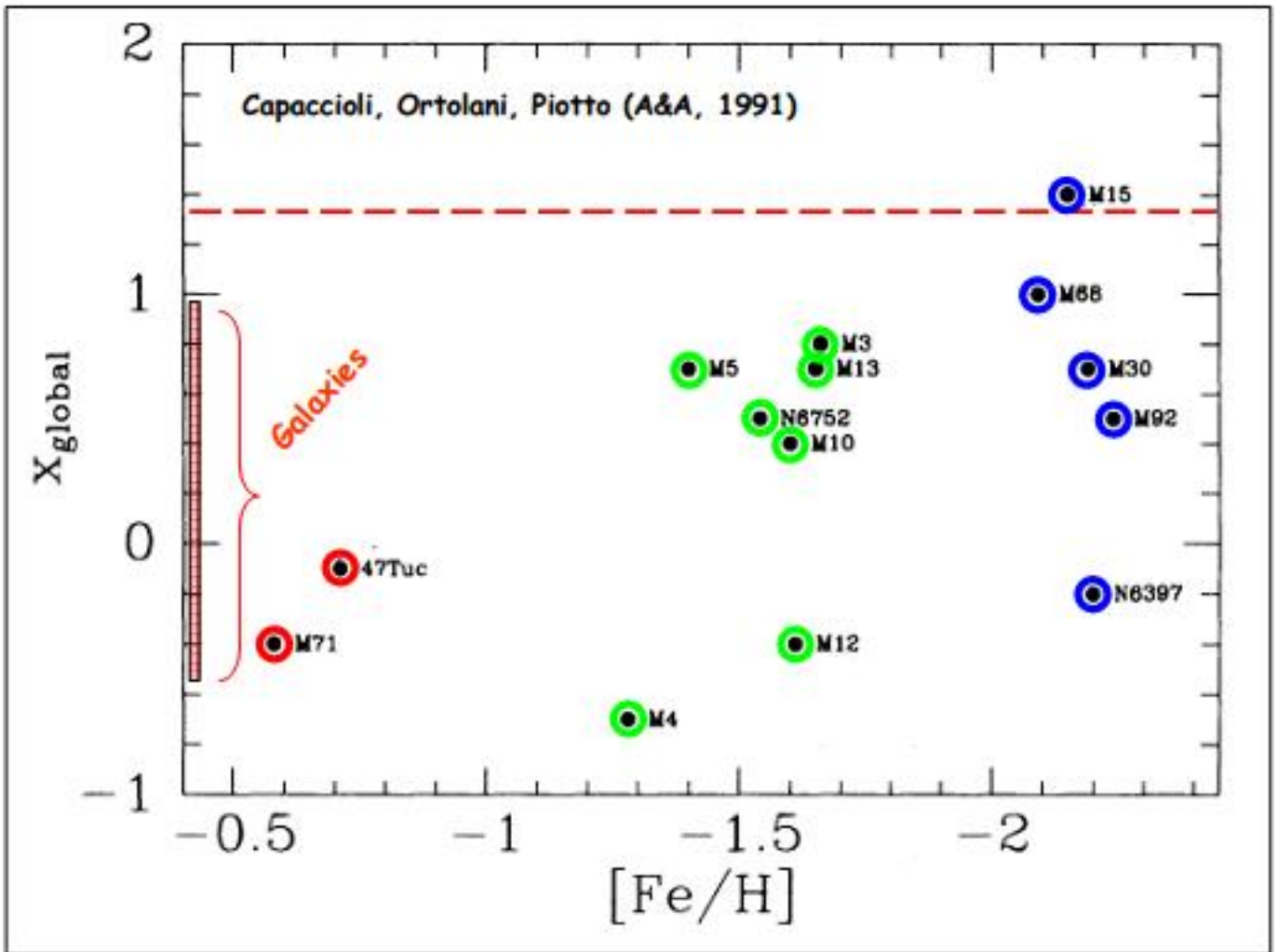
$M$	$L$	$N$
0.1	0.0001	220
0.5	0.06	5
1	1	1
2	16	1/5
5	625	1/40
10	10'000	1/220
50	610 <sup>6</sup>	1/10'000



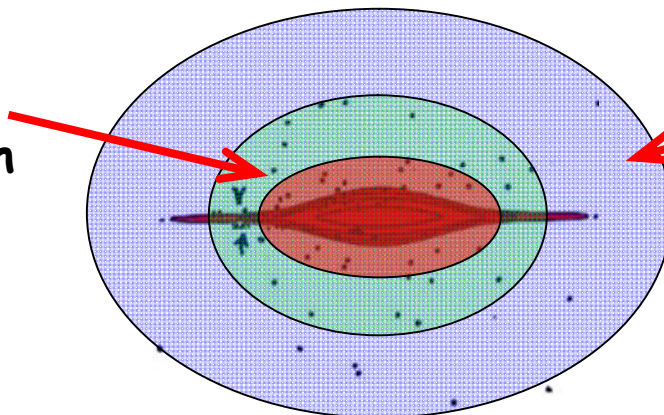
# La IMF negli ammassi globulari galattici

Metal rich

Metal poor



Ammassi metal-rich



Ammassi metal-poor

**Articoli consigliati (vedi Webpage):**

<http://www.bo.astro.it/~eps/lezioni/lezioni.html>

- Galaxy Colors (Buzzoni)
- LF (Schechter)
- Sandage (Disco MW)
- Sandage & Fouts (Bottlinger)
- Bottlinger
- SFR (Kennicutt)
- SFR (Ryder & Dopita)
- SFR (Schmidt)
- IMF (Miller & Scalo)
- IMF (Kroupa)
- IMF (Kalirai 2013)
- IMF (Weidemann)
- Energetica e Metallicità'
- Chemical evolution of spiral galaxies (Buzzoni)

# Teoria delle Popolazioni Stellari Semplici (SSPs)

Renzini & Buzzoni (1986)

Definition of SSP:

1) A generation of COEVAL stars ( $SFR = \delta_0$ )  
(so that we can define an AGE of the population)

2) Fixed metallicity (unique  $Z$ )

Star partition:

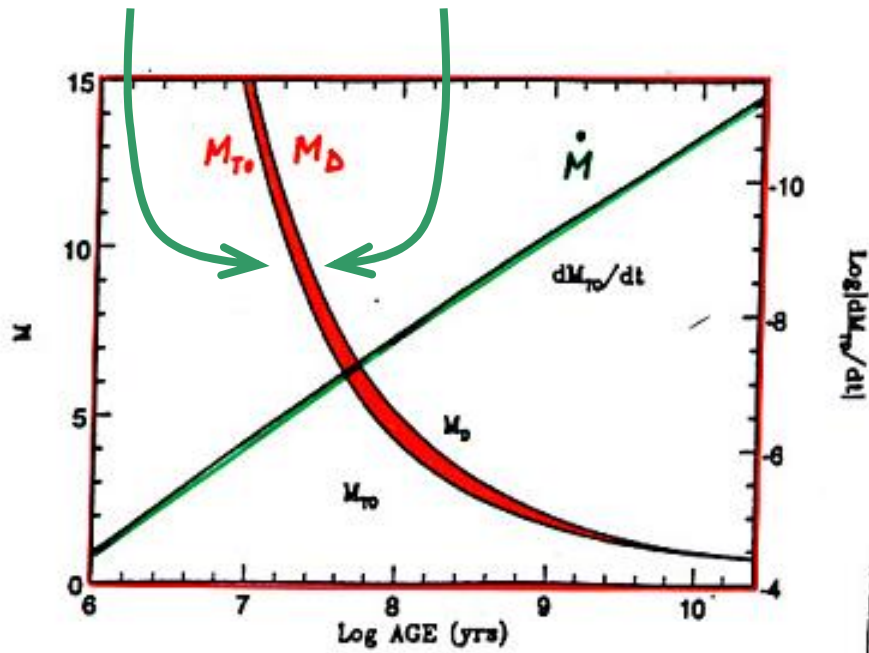
$$MS: \quad N_{(H)} = A M^{-S} \quad (IMF)$$

Post-MS:

$$\Delta M = M_{\text{DYING}} - M_{TO} \approx - \left. \frac{dM}{dt} \right|_{\tau_{PMS}} \approx M_{TO} \frac{\tau_{PMS}}{T}$$

$$N_{PMS} = A M_{TO}^{-S} \Delta M = A M_{TO}^{-S} \dot{M}_{TO} \tau_{PMS}$$

Massa al Turn Off      Massa finale (Nane Bianche)



Renzini & Buzzoni (1986)

Flusso evolutivo specifico

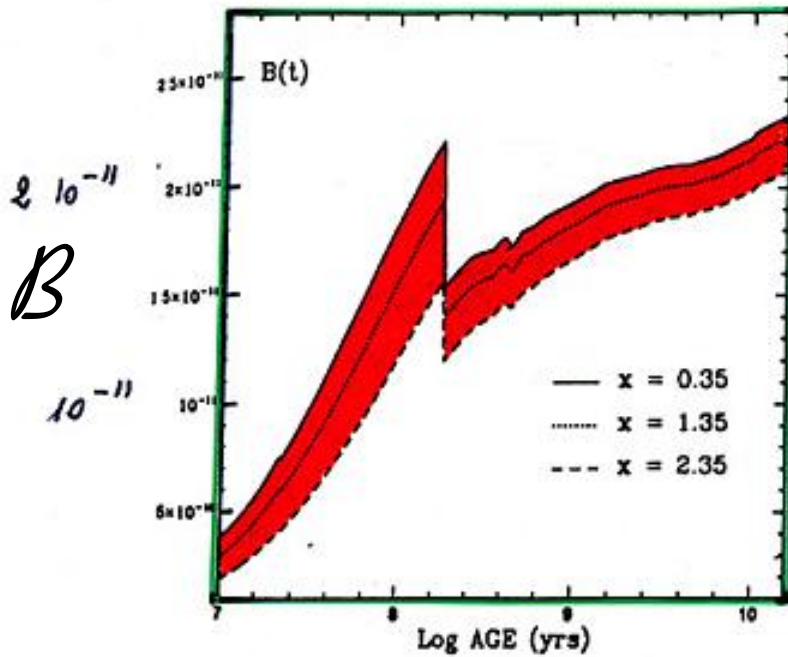


Fig. 1.3: The specific evolutionary flux  $B(t)$  as a function of age for three IMF slopes  $(1 + x)$ .

$$B = (b/L_{tot})$$

$$N_{\text{PMS}} = \underbrace{A M_{\text{TO}}^{-s} \dot{M}}_l \tau_{\text{PMS}}$$

$$l = \beta L_{\text{TOT}}$$

$$N_{\text{PMS}} = \beta L_{\text{TOT}} \tau_{\text{PMS}} = 1.7 \cdot 10^{11} \left( \frac{L}{L_{\odot}} \right) \left( \frac{\tau}{\text{yr}} \right)$$

↓  
specific Evolutionary  
Flux

## LUMINOSITY

$$L_{\text{MS}} = A \int_0^{M_{\text{TO}}} l_* M^{-s} dM$$

$$\begin{cases} l_* \propto M^3 \\ t_* \propto M^{-2} \end{cases}$$

$$L_{\text{MS}} \approx \frac{A}{4-s} M_{\text{TO}}^{4-s} \quad (s < 4)$$

$$L_{\text{MS}} \propto t^{-\frac{4-s}{2}} \sim t^{-0.85}$$

$$L_{\text{PMS}} = \int_{\text{PMS}} l_* dN = A M_{\text{TO}}^{-s} \dot{M}_{\text{TO}} \int_{\text{PMS}} l_* d\tau$$

fuel  $\sim$  const.

$$L_{\text{PMS}} \propto t^{-\frac{3-s}{2}} \sim t^{-0.35}$$

$$\frac{L_{PHS}}{L_{MS}} \propto \frac{t^{-\frac{3-s}{2}}}{t^{-\frac{4-s}{2}}} \propto \sqrt{t}$$

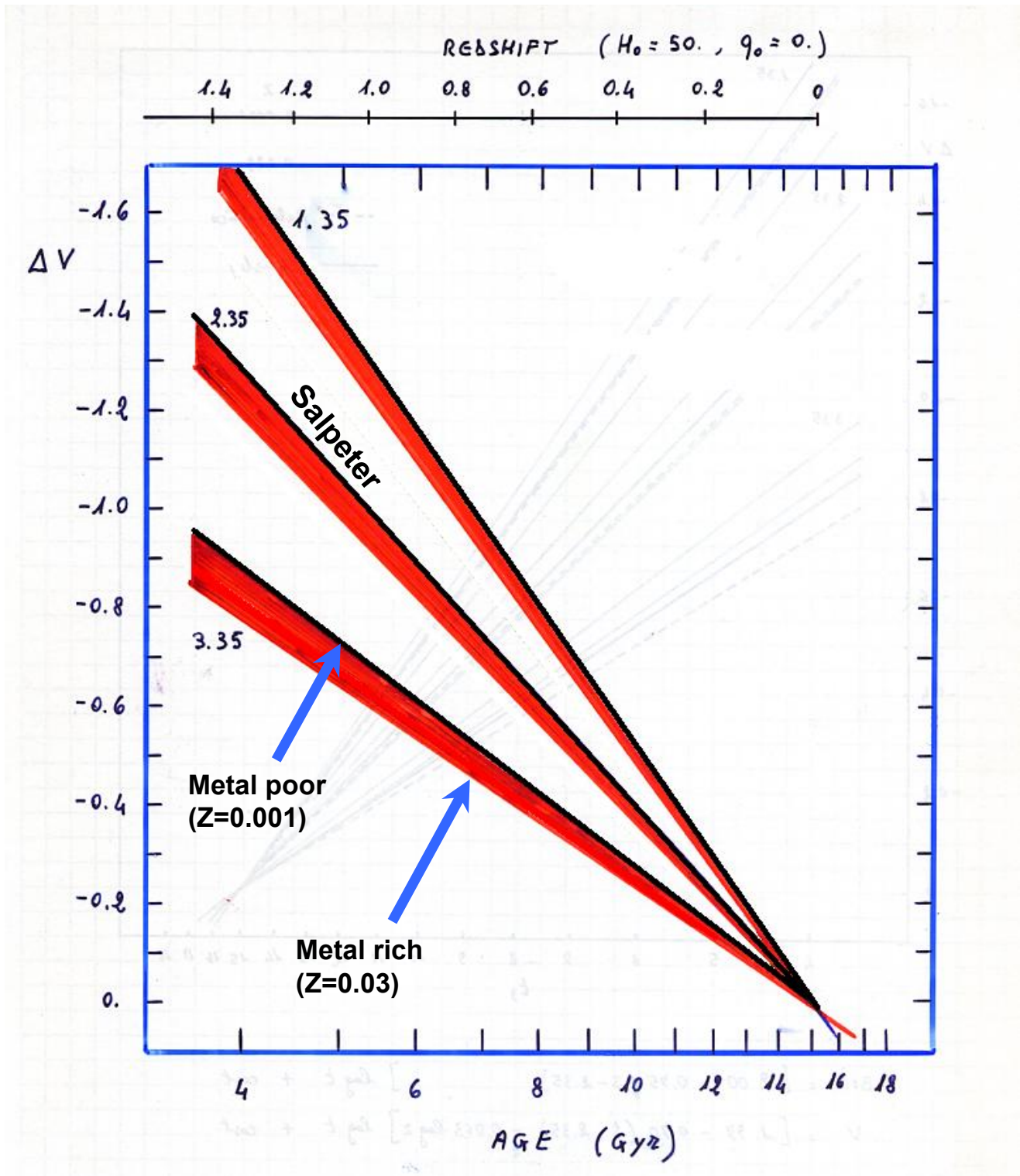
Conclusion: MS always dominates with decreasing time

Corollary: Total SSP luminosity is a DECREASING function of time

Model evolutionary rate at different bands

$$\begin{array}{l} L_{BOL} \propto t^{-0.75} \\ L_B \propto t^{-0.95} \\ L_V \propto t^{-0.86} \\ L_I \propto t^{-0.75} \\ L_K \propto t^{-0.71} \end{array}$$

$$\begin{array}{l} Z = Z_{\odot} \\ S = 2.35 \end{array}$$



$$t \propto \frac{1}{M^2} \frac{\tilde{k}}{\mu^4}$$

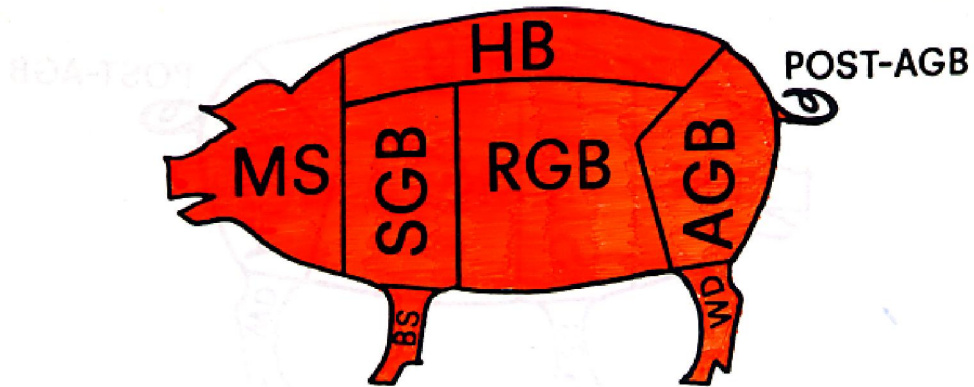
$$L_* \propto M^3 \frac{\mu^4}{\tilde{k}}$$

$$\rightarrow \frac{dt}{t} = -\frac{2}{3} \frac{dL_*}{L_*} + \frac{1}{3} \frac{d\tilde{k}}{\tilde{k}} - \frac{4}{3} \frac{d\mu}{\mu}$$

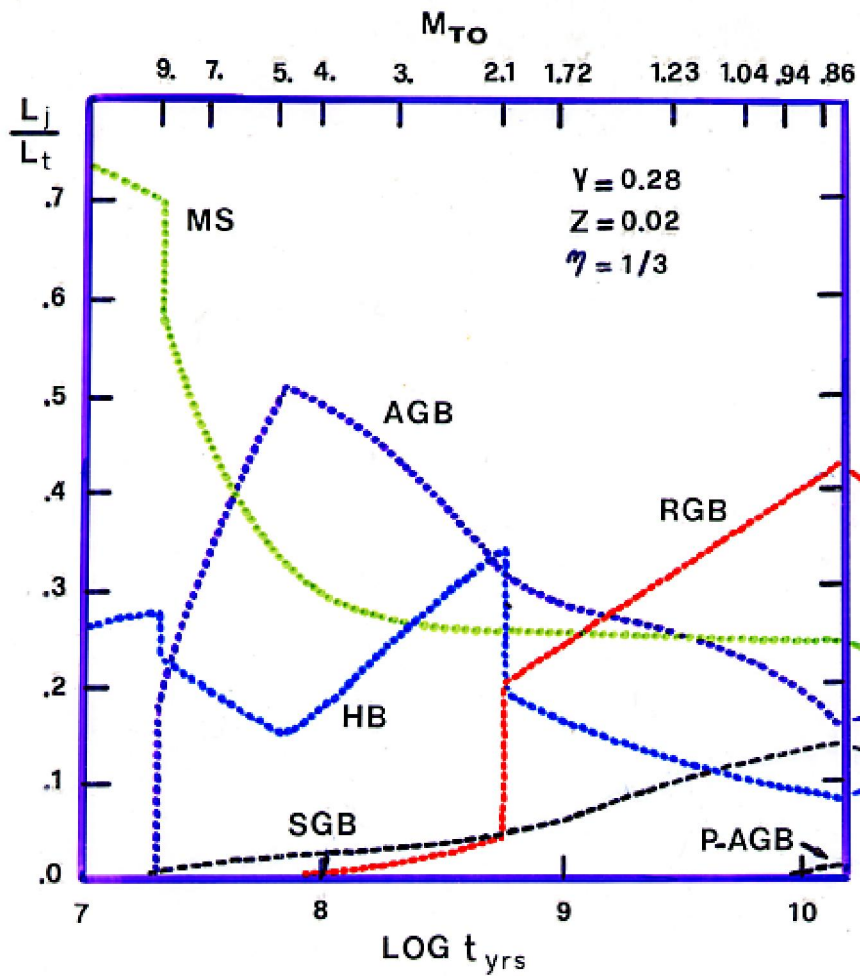
Quindi, la stessa variazione di luminosita'  $dL/L$ , avviene su tempi piu' lunghi ( $dt/t$ ) se  $k \uparrow$  (ovvero se  $Z \uparrow$ )

# SSP

## Contributi bolometrici



*All the cuts of a stellar population.*



Renzini & Buzzoni (1986)



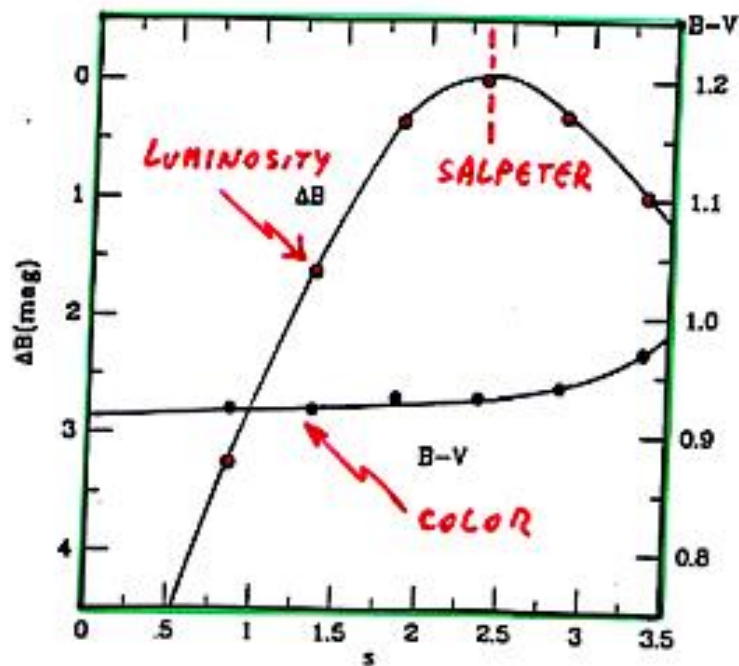
**Articoli consigliati (vedi Webpage):**

<http://www.bo.astro.it/~eps/lezioni/lezioni.html>

- SSPs (Tinsley)
- SSPs (Renzini & Buzzoni)
- Galaxy Colors (Buzzoni)
- IMF (Miller & Scalo)
- IMF (Kroupa)
- IMF (Kalirai 2013)
- IMF (Weidemann)

# IMF e Luminosità totale

Una IMF alla Salpeter permette alla SSP di rilasciare la max luminosità per unità di massa



Buzzoni  
(1995)

$$M_{TOT} = A \int M M^{-s} = \frac{A}{2-s} [M_v^{2-s} - M_l^{2-s}]$$

$s > 2$  DWARF-DOMINATED SSP

$s < 2$  GIANT-DOMINATED SSP

Una IMF alla Salpeter permette alla SSP di rilasciare la max luminosita' per unita' di massa:  
**DIMOSTRAZIONE**

$$L_{tot} \propto A \dot{M} M_{TO}^{-s} \quad \text{Solo "A" e } M_{TO}^{-s} \text{ dipendono da "s"}$$

$$M_{TOT} = A \int M_*^{-s} M_* dM_* = \frac{A}{2-s} \left[ M_*^{2-s} \right]_{low}^{up}$$

Assumiamo  $s > 2$  e vediamo se esiste soluzioni all'interno di questo dominio

$$\forall s > 2 \quad A = \frac{M_{TOT} (2-s)}{M_{low}^{2-s}}$$

$$L_{tot} \propto \frac{M_{TOT} (2-s)}{M_{low}^2} \left( \frac{M_{TO}}{M_{low}} \right)^{-s}$$

(non dipende da "s")

$$\left( \frac{L}{M} \right) \propto \frac{1}{M_{low}^2} (2-s) \left( \frac{M_{TO}}{M_{low}} \right)^{-s}$$

$$\frac{\partial (L/M)}{\partial s} = 0 \implies -1 \left( \frac{M_{TO}}{M_{low}} \right)^{-s} = (2-s) \ln \left( \frac{M_{TO}}{M_{low}} \right) \left( \frac{M_{TO}}{M_{low}} \right)^{-s}$$

$$2 - s_{MAX} = \frac{1}{\ln \left( \frac{M_{low}}{M_{TO}} \right)}$$

$$s_{MAX} = 2 - \frac{1}{\ln \left( \frac{M_{low}}{M_{TO}} \right)}$$

$$M_{low} \sim 0.1 M_{\odot}$$

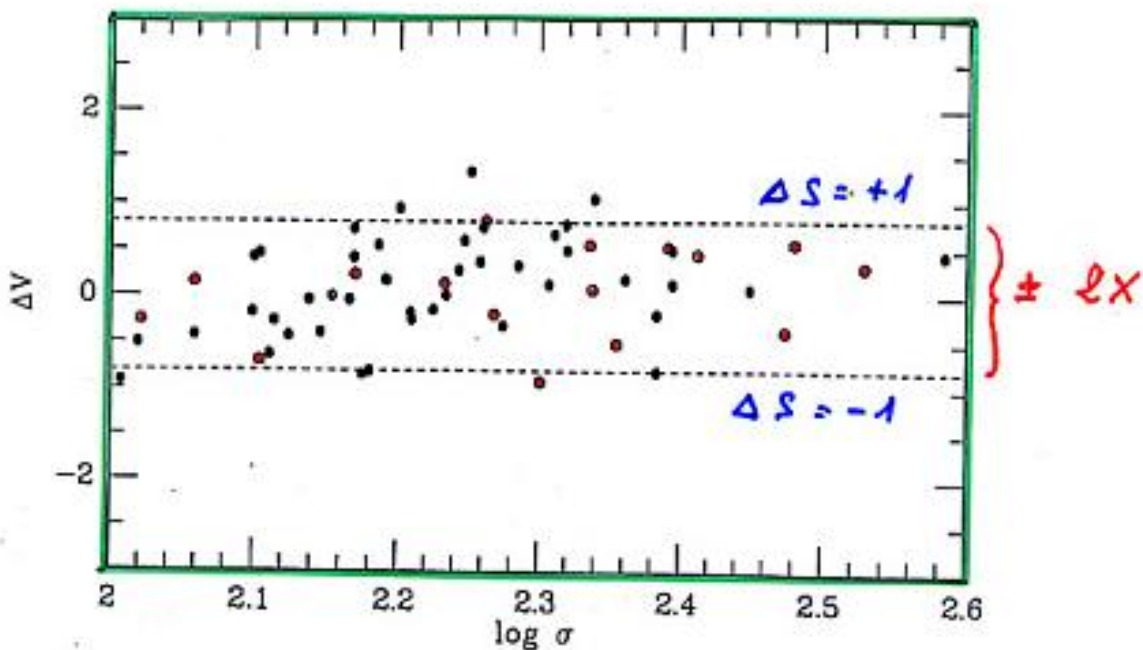
$$\forall M_{TO} \rightarrow 0.01 \lesssim \frac{M_{low}}{M_{TO}} \lesssim 0.1$$

$$2.2 \lesssim s_{MAX} \lesssim 2.4$$

# Dispersione della IMF fra le galassie ellittiche

- = 16 galx VIRGO
- = 43 galx COMA

Bower, Lucy & Ellis (1992)



same  $\sigma \Rightarrow$  same Mass  $\Rightarrow$  same  $[Fe/H]$

IF (AGE = CONST)

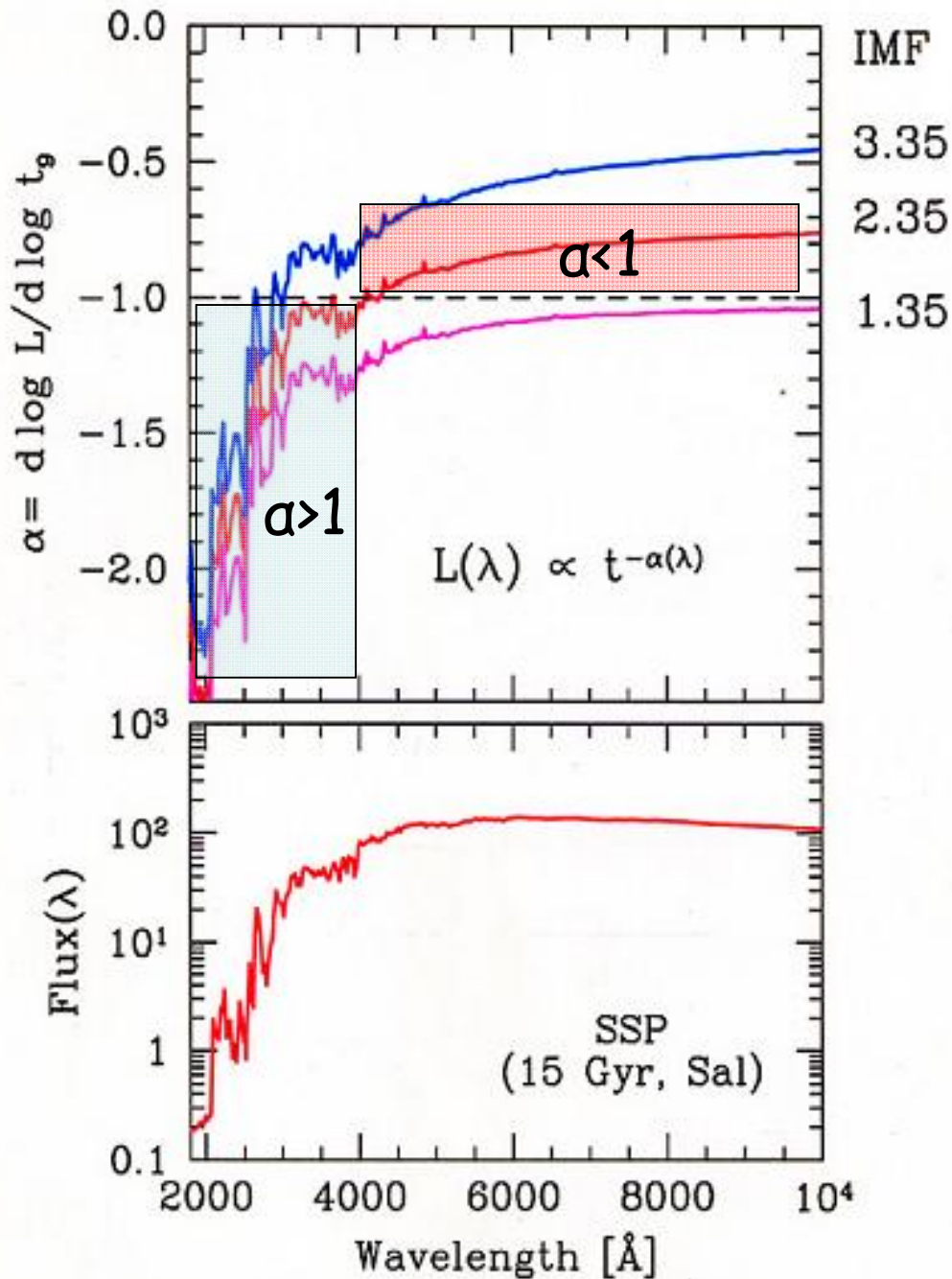
THEN  $\Rightarrow \Delta V_{mag} \Leftrightarrow \Delta S$

**Articoli consigliati (vedi Webpage):**

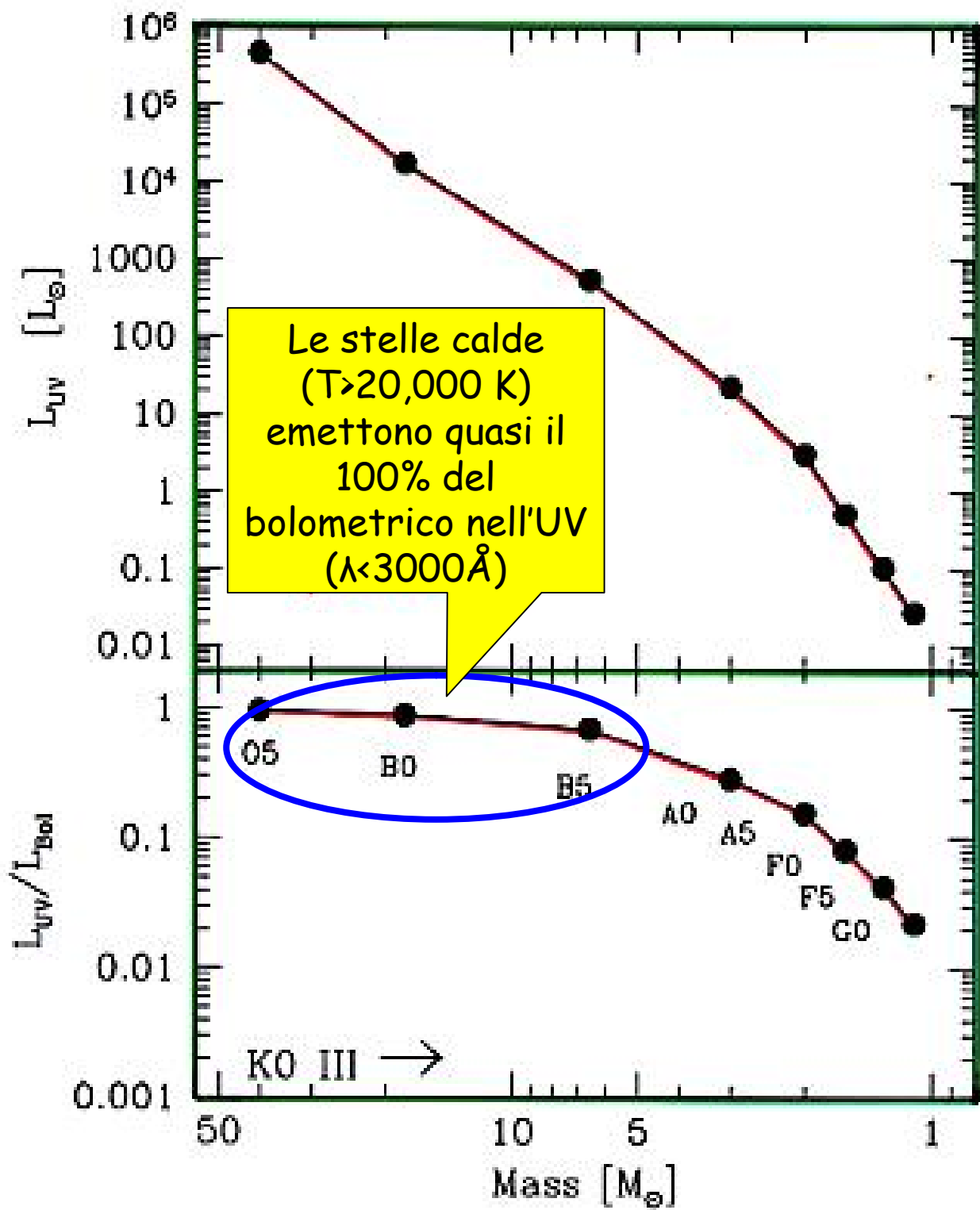
<http://www.bo.astro.it/~eps/lezioni/lezioni.html>

- IMF (Miller & Scalo)
- IMF (Kroupa)
- IMF (Kalirai 2013)
- IMF (Weidemann)

## Evoluzione fotometrica delle SSP: dal bolometrico al monocromatico



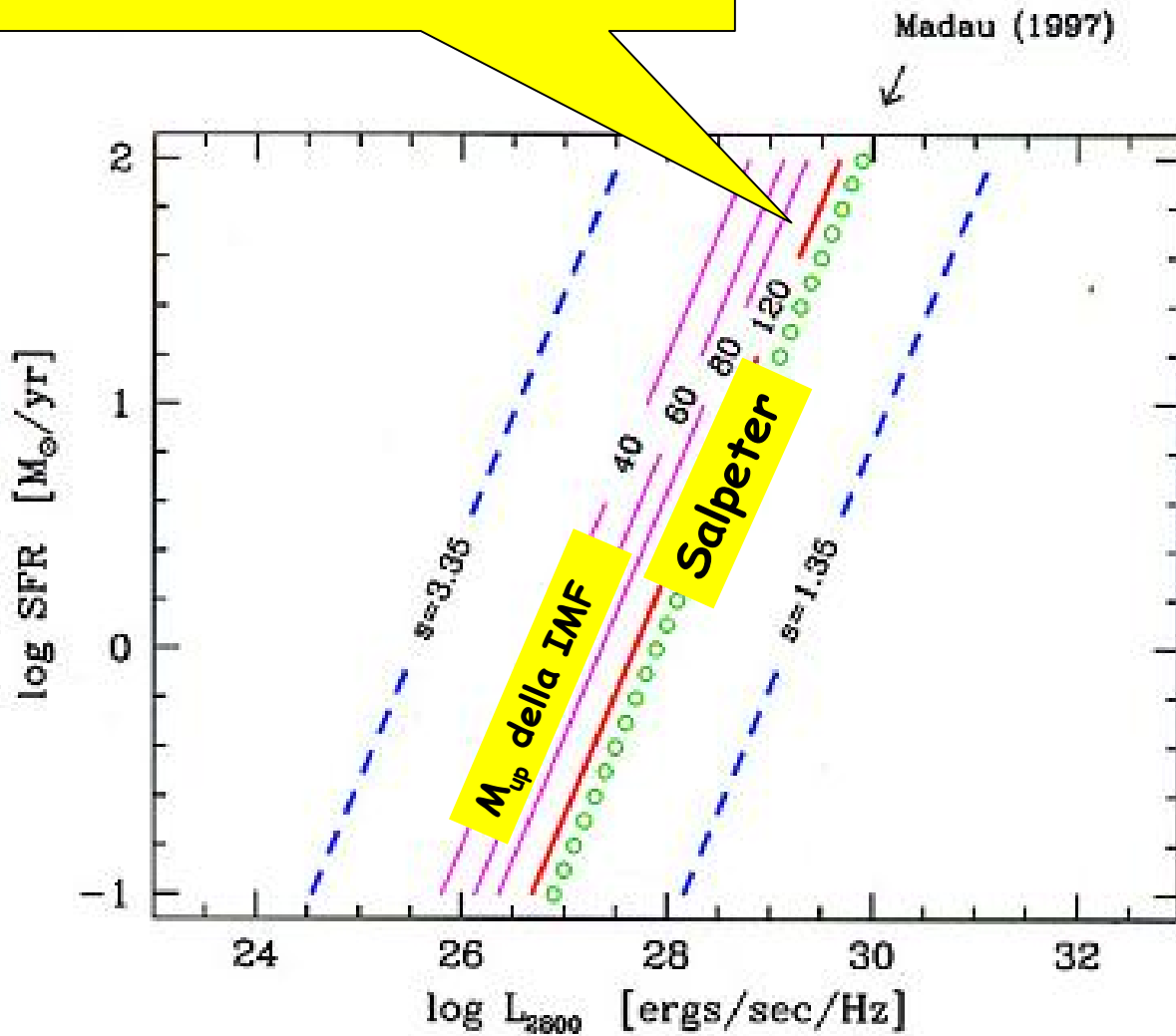
L'evoluzione fotometrica delle SSPs nell'UV avviene piu' veloce di  $t^{-1}$  !! Dunque, in una CSP, l'UV traccia la SFR recente.



Buzzoni (2002)

$L_{UV} \rightarrow SFR$

Deve esserci corrispondenza lineare fra  $L_{UV}$  e SFR

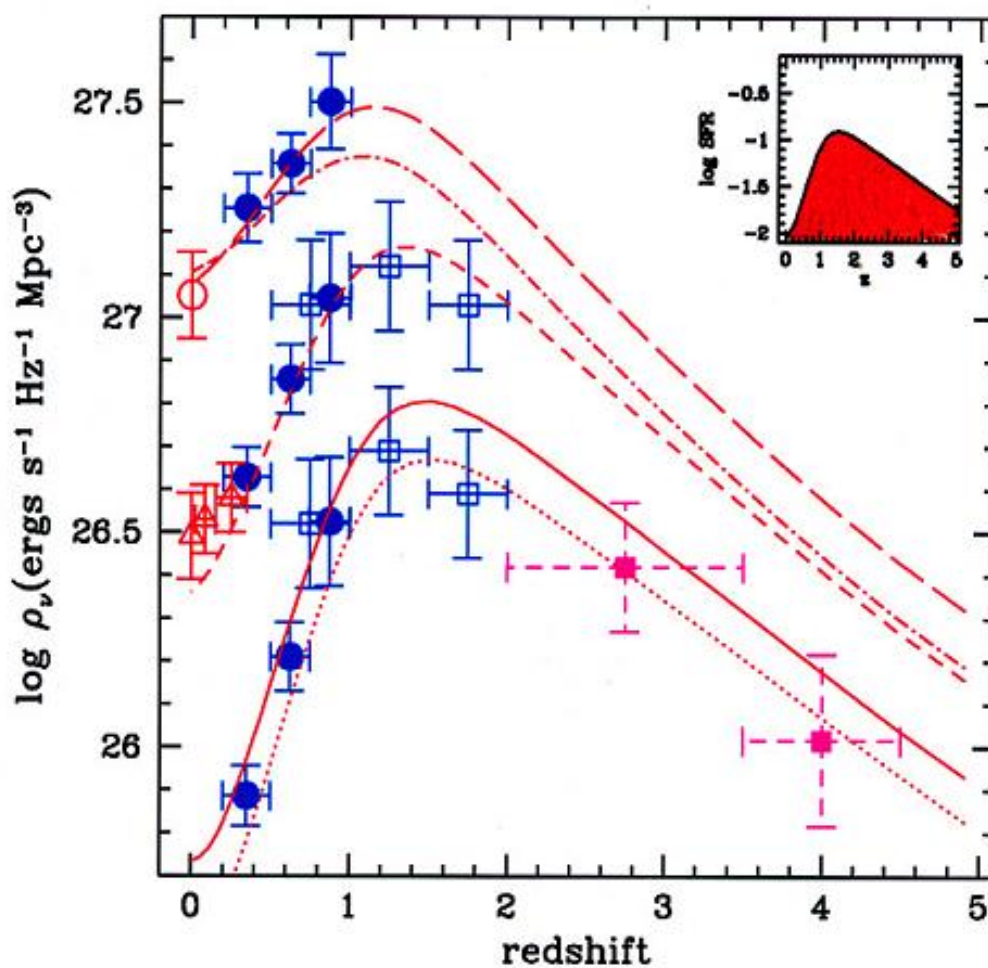


(Buzzoni 2002)



# Il "Madau Plot" e la Storia della Formazione Stellare Cosmica

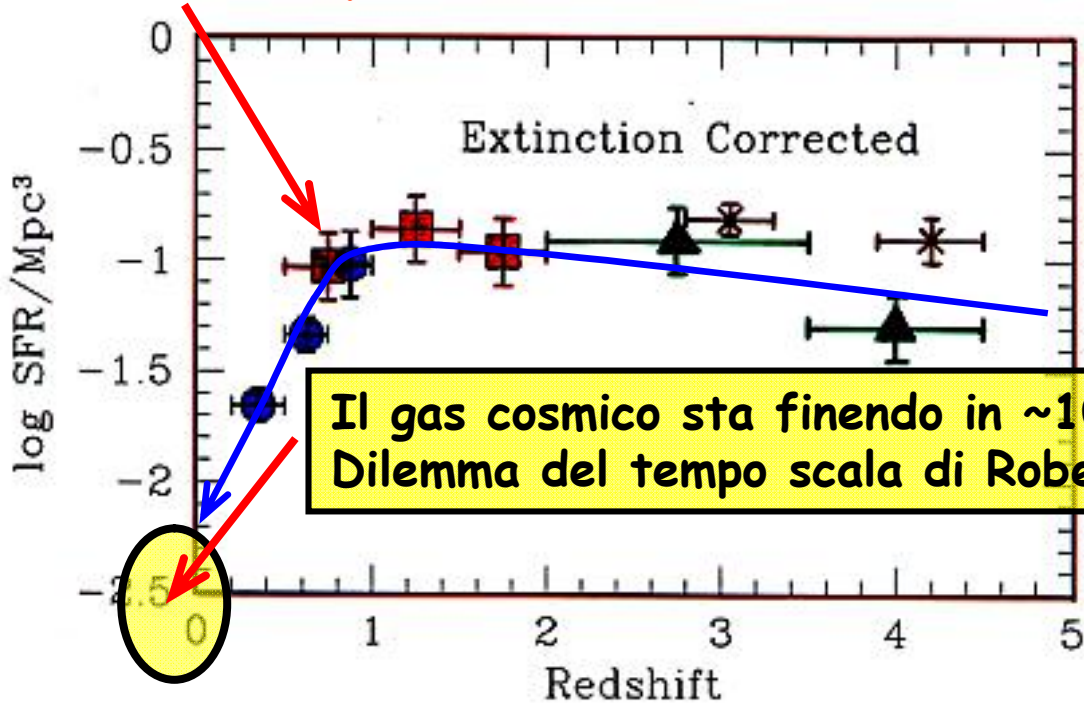
(Madau 1997)



# Evoluzione del Madau plot

(inclusando incompletezza, assorbimento polveri etc.)

Cosa e' successo qui?



- = LILLY et al. (1996)
- = CONNOLLY et al. (1997)
- ▲ = MADAU et al. (1997)
- x = STEIDEL et al. (1999)

$$(H_0, q_0) = (50, \frac{1}{2})$$

Tempo di Roberts:  $t_R \sim \frac{f_{gas} M_{gal}}{SFR_{now}}$  ma (vedi dopo)  $b = \frac{SFR_{now}}{M_{gal}} t_{gal}$

Combinandole:  $\frac{t_R}{t_{gal}} = \frac{f_{gas}}{b} \sim \frac{\sim 0.1}{\sim 1}$  Quindi  $t_R \sim 1-2$  Gyr max

**Articoli consigliati (vedi Webpage):**

<http://www.bo.astro.it/~eps/lezioni/lezioni.html>

- SSPs (Tinsley)
- SSPs (Renzini & Buzzoni)
- Galaxy Colors (Buzzoni)
- Dropout galaxies (Madau)
- Madau Plot
- SFR (Kennicutt)
- SFR (Ryder & Dopita)
- SFR (Schmidt)
- IMF (Kalirai 2013)
- Balmer break (Hamilton)
- Energetica e Metallicità
- Grandi Surveys Extragalattiche

# Teoria delle Popolazioni Stellari Composite (CSPs)

Buzzoni (2005)

Definition:

$$[CSP] = \int [SSP] \otimes SFR$$

A relevant case:  $SFR = \text{const}$

$$L_{CSP} = \int_0^T L_{SSP} dt$$

$\downarrow$   
 $t^{-\alpha}$       ( $\alpha < 1$ )

$L_{CSP} \Big _T = \frac{T^{1-\alpha}}{1-\alpha}$	$L_{CSP} \propto t^{0.15}$
---	----------------------------

Conclusion: Total luminosity in a CSP is an INCREASING function of time

Color evolution:

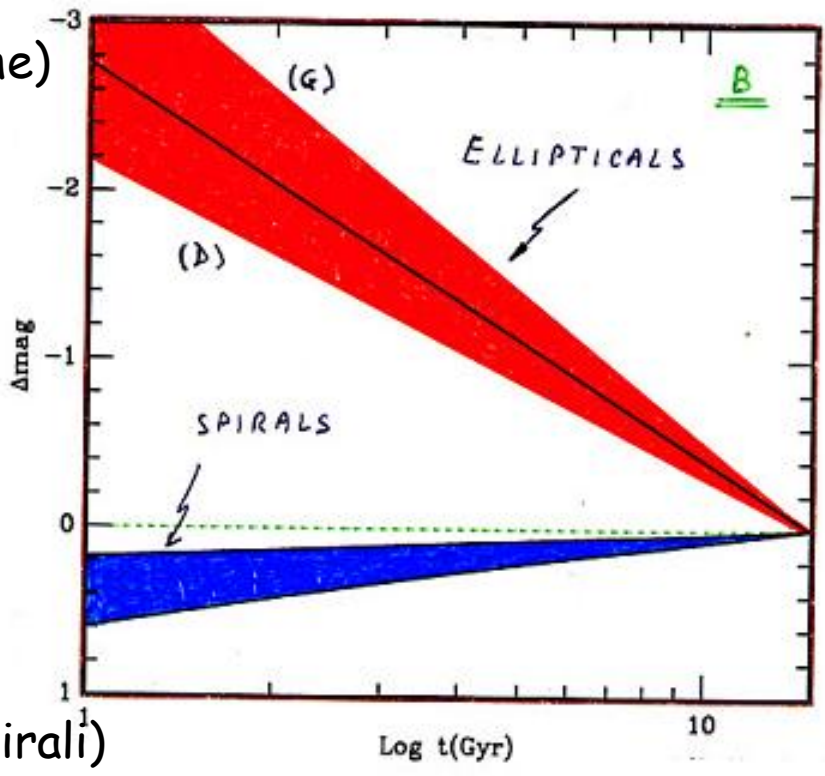
SSP	CSP
$\begin{cases} L_B \propto t^{-\alpha_B} \\ L_V \propto t^{-\alpha_V} \end{cases}$	$\begin{cases} L_B \propto t^{1-\alpha_B} \\ L_V \propto t^{1-\alpha_V} \end{cases}$

**SAME LAW!**

$$\frac{L_B}{L_V} \propto t^{-(\alpha_B - \alpha_V)}$$

# LUMINOSITY EVOLUTION

SSPs  
(≈ Ellittiche)



CSPs  
(≈ Dischi Spirali)

Ellipticals	$L_t \propto t^{-\alpha} \sim t^{-0.8}$
Spirals (disk)	$L_t \propto t^{1-\alpha} \sim t^{+0.2}$

# Star Formation Rate (Leggi di Schmidt)

$$SFR = - \frac{d f_{gas}}{d t}$$

$$PDMF(M, t) = \int_0^{\tau \leq T} SFR \times IMF(M) dt$$

↓  
OBSERVED

$0 \leq \tau \leq T$

ASSUMED  $SFR \propto f_{gas}^m$   $m=2$  SCHMIDT LAW

$m=1$   $SFR = k f = -\dot{f}$   $SFR = k e^{-k t}$

$m=2$   $SFR = k f^2 = -\dot{f}$   $SFR = \frac{k}{(1+k t)^2}$

$k = \frac{1}{\tau}$  (star formation timescale)

$\lim k \rightarrow \infty$   $\tau \rightarrow 0 \Rightarrow SSP$   
 $SFR \rightarrow \delta(0)$

# Star Formation Rate (Leggi di Schmidt)

Soluzioni:

$$m = 1$$

$$\left\{ \begin{array}{l} \text{SFR} = \dot{f}_* = -\dot{f}_{\text{gas}} \\ \dot{f}_* = k f_{\text{gas}} \end{array} \right\} \rightarrow k f_{\text{gas}} = -\frac{df_{\text{gas}}}{dt}$$

$$\frac{df_{\text{gas}}}{f_{\text{gas}}} = -k dt \quad \text{integrata: } f_{\text{gas}}(t) = f_{\text{gas}}(0) e^{-kt}$$

possiamo assumere  $k = \frac{1}{\tau}$  ← tempo scala

Quindi, alla fine ho:

$$\left\{ \begin{array}{l} f_{\text{gas}} = e^{-kt} \\ \text{SFR} = k e^{-kt} \end{array} \right. \quad b = \frac{\text{SFR}_0}{\langle \text{SFR} \rangle} = \frac{k e^{-kt}}{\frac{k}{t} \int_0^t e^{-kz} dz} = \frac{kt}{e^{+kt} - 1}$$

$0 \leq b \leq 1$

$$m = 2 \quad (\text{Legge di Schmidt canonica})$$

$$\left\{ \begin{array}{l} \text{SFR} = -\dot{f}_{\text{gas}} \\ \text{SFR} = k f_{\text{gas}}^2 \end{array} \right\} \rightarrow k f_{\text{gas}}^2 = -\frac{df_{\text{gas}}}{dt}$$

$$\frac{df_{\text{gas}}}{f_{\text{gas}}^2} = -k dt \quad \text{integrata: } \frac{1}{f_{\text{gas}}(0)} - \frac{1}{f_{\text{gas}}(t)} = -kt$$

$$\left\{ \begin{array}{l} f_{\text{gas}} = \frac{1}{1+kt} \\ \text{SFR} = \frac{k}{(1+kt)^2} \end{array} \right. \quad b = \frac{k}{(1+kt)^2} \frac{t}{\int \frac{k}{(1+kt)^2}} = \frac{1}{1+kt}$$

$0 \leq b \leq 1$

# Star Formation Rate (Power Law)

Soluzioni:

Assumo che l'efficienza del meccanismo di formazione stellare sia un parametro intrinseco della galassia, che solo dipende dalla sua morfologia.

Ne consegue che:

$$\begin{cases} \text{SFR} = k t^{-\beta} \\ \text{SFR} = -\dot{f}_{\text{gas}} \end{cases} \rightarrow k t^{-\beta} = -\frac{df_{\text{gas}}}{dt}$$

$k$  ha le dimensioni di  $\tau^{+(\beta-1)}$

$$df_{\text{gas}} = -k t^{-\beta} dt \rightarrow 1 - f_{\text{g}}(t) = \frac{k}{1-\beta} t^{1-\beta}$$

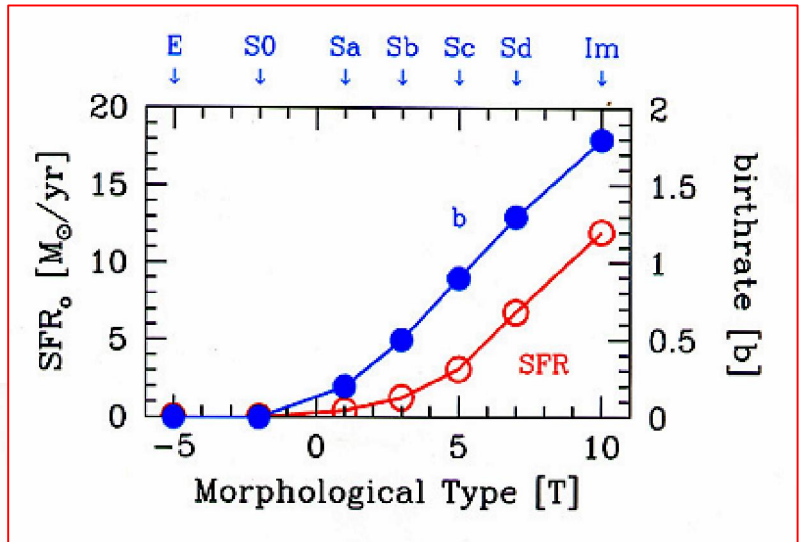
$$\left\{ \begin{array}{l} f_{\text{g}}(t) = 1 - \frac{k t^{1-\beta}}{1-\beta} \\ \text{SFR}(t) = k t^{-\beta} \end{array} \right\} \quad b = \frac{k t^{-\beta}}{\frac{k}{t(1-\beta)}} = (1-\beta) \quad \forall t$$

Quindi il Birtlrate è indipendente dal tempo -  
il gas si esaurisce in un tempo finito:

$$t_{\text{MAX}} = \left( \frac{1-\beta}{k} \right)^{\frac{1}{1-\beta}}$$



# SFR & Birthrate



Buzzoni (2002)

Birthrate

$$b = \frac{SFR_0}{\langle SFR \rangle}$$

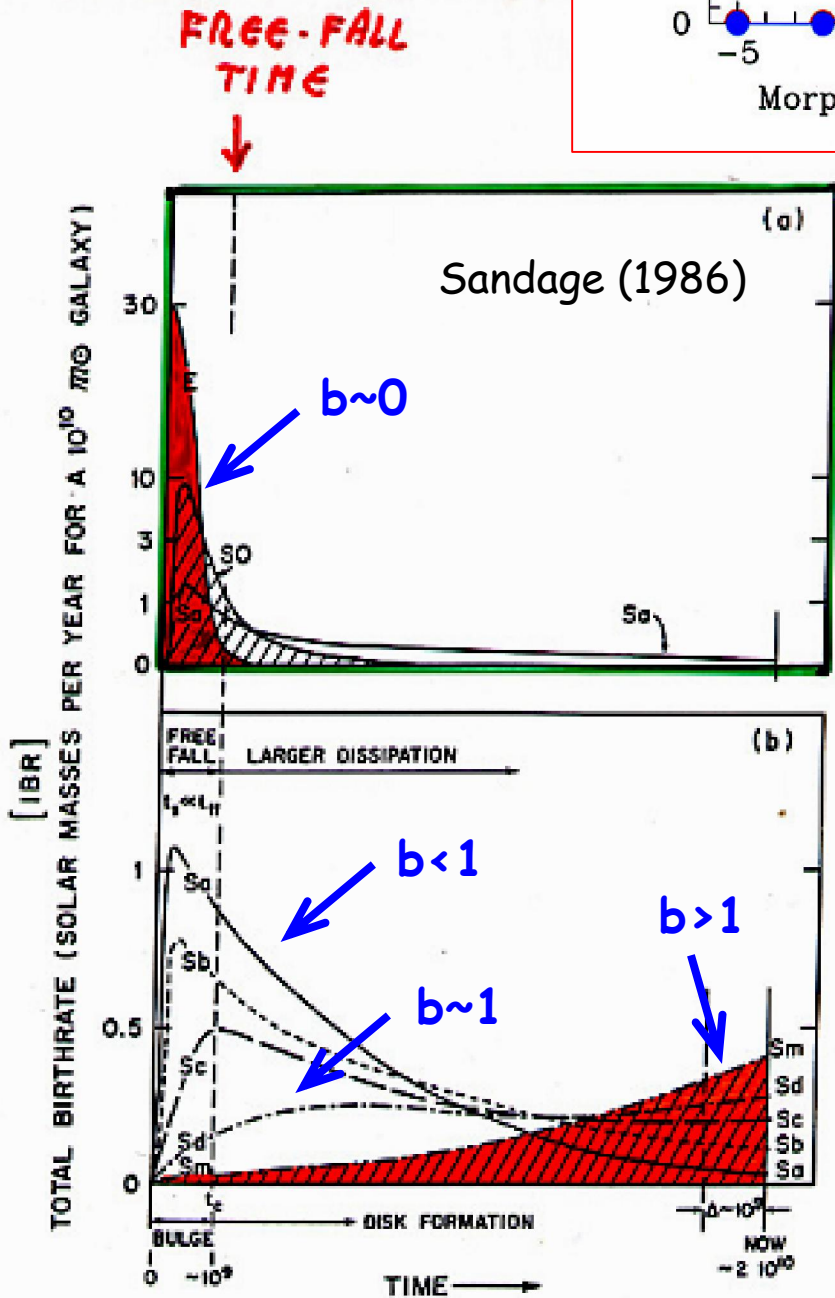
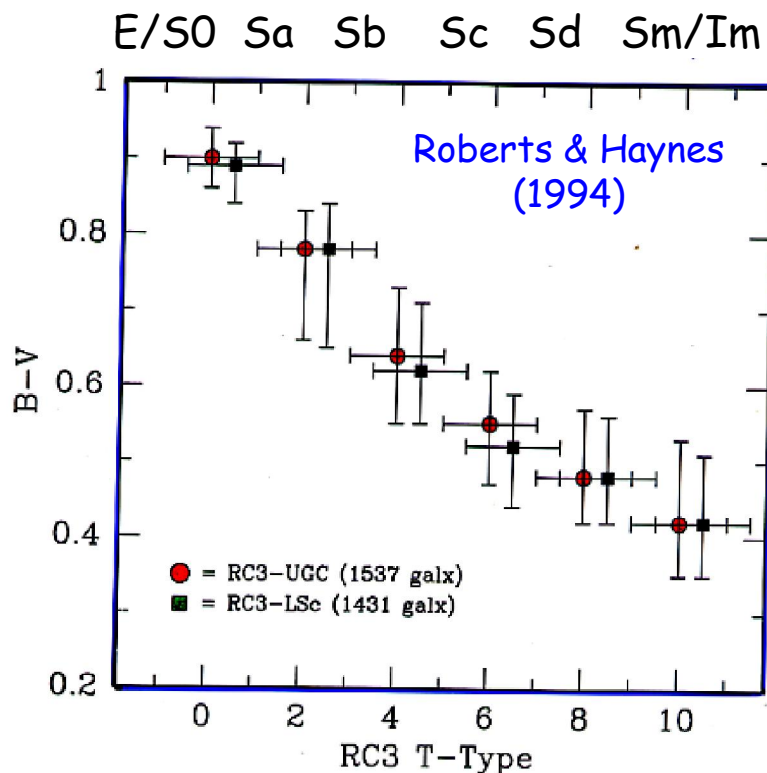


Fig. 10. Same as Fig. 9 with later Hubble types shown in the lower panel. The integral under the Sm curve is shaded for illustration. The curves are only schematic showing the trends that have been established by Gallagher et al. (1984)

# Eta' media delle popolazioni e colore integrato delle galassie



Nel caso di una SFR a legge di potenza:

$$SFR = k t^{-\beta}$$

$$L(t) = k' \int \tau^{-\alpha} (t-\tau)^{-\beta} d\tau = k' \frac{\Gamma(1-\alpha)\Gamma(1-\beta)}{\Gamma(2-\alpha-\beta)} t^{1-\alpha-\beta}$$

$$b = \frac{SFR(t)}{\langle SFR \rangle} = \frac{k t^{-\beta} (1-\beta) t}{k t^{(1-\beta)}} = (1-\beta) \quad \forall t$$

Eta' media delle SSP componenti (pesate con la luminosita')

$$\langle t \rangle = \frac{k' \int \tau \tau^{-\alpha} (t-\tau)^{-\beta} d\tau}{k' \int \tau^{-\alpha} (t-\tau)^{-\beta} d\tau} = \frac{\int \tau L(\tau)}{L(t)}$$

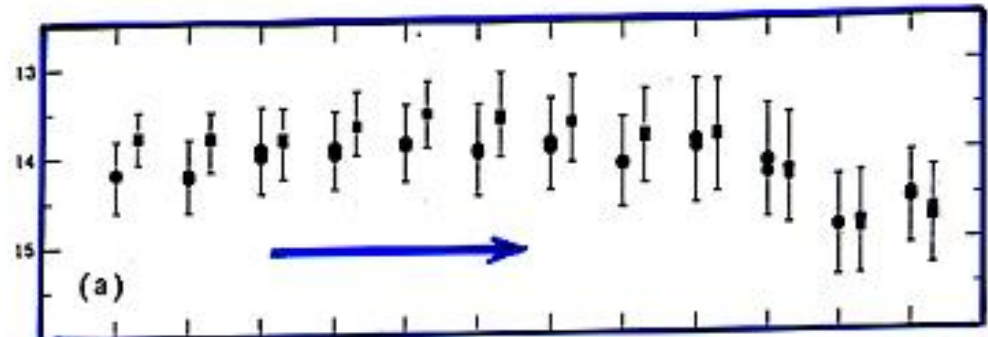
Ricordando che  $\Gamma(1+m) = m! \Gamma(m)$

$$\langle t \rangle = \frac{\Gamma[1+(1-\alpha)] \Gamma(1-\beta)}{\Gamma[2+(1-\alpha)-\beta]} \frac{\Gamma(2-\alpha-\beta)}{\Gamma(1-\alpha)\Gamma(1-\beta)} \frac{t^{2-\alpha-\beta}}{t^{1-\alpha-\beta}}$$

$$\langle t \rangle = \frac{1-\alpha}{2-\alpha-\beta} t$$

$$\frac{\langle t \rangle}{t} \ll 1 \quad \text{se} \quad b \gg 0$$

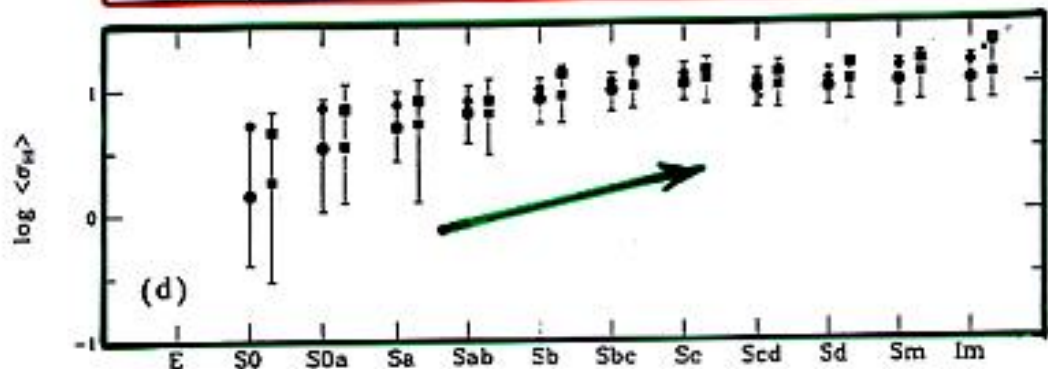
SURFACE  
BRIGHTNESS  
 $\Sigma_B$



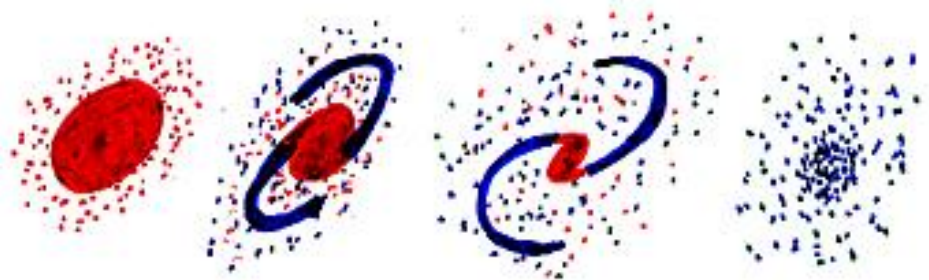
SURFACE  
DENSITY  
 $\sigma_T$



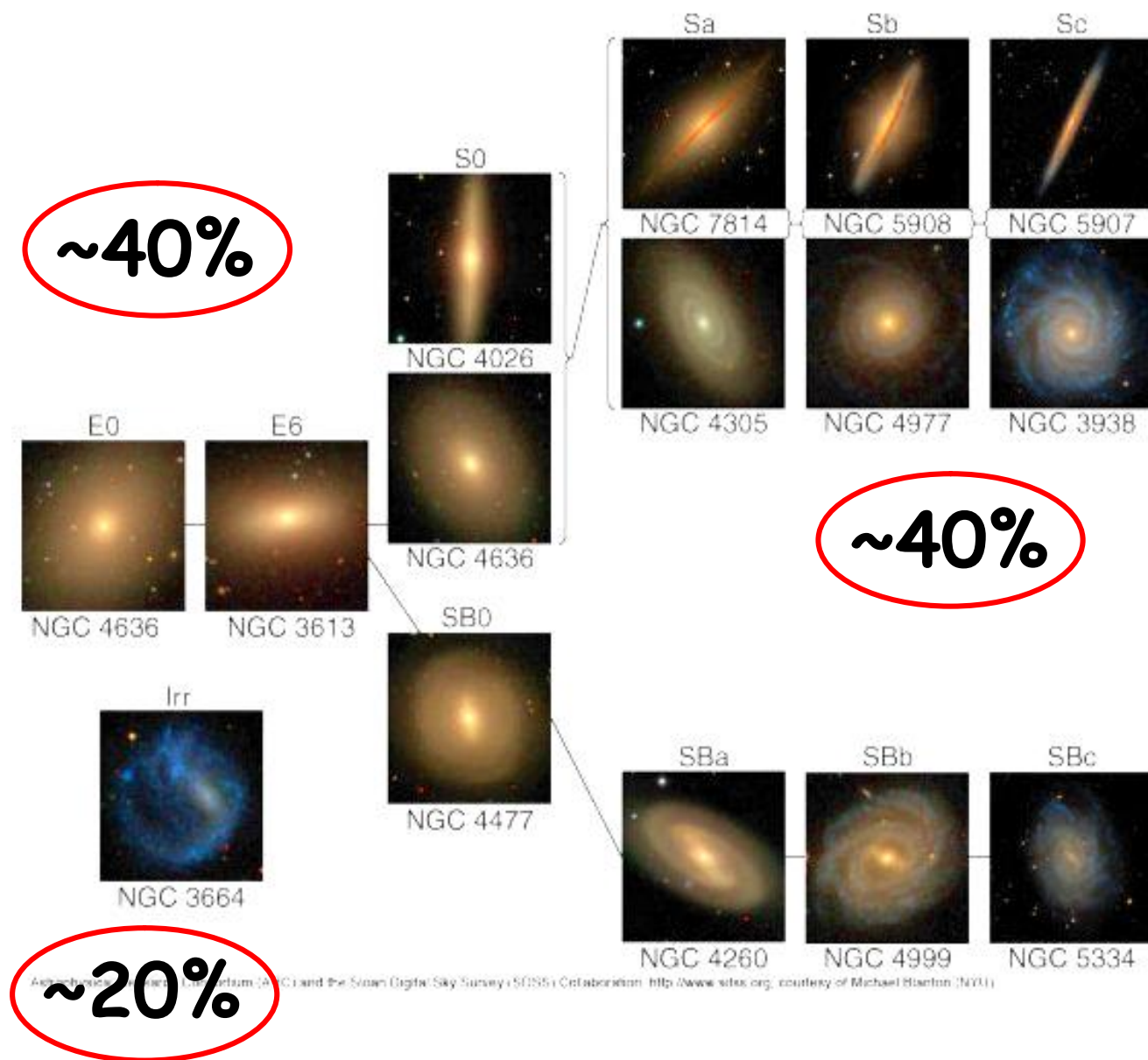
GAS  
(HI)



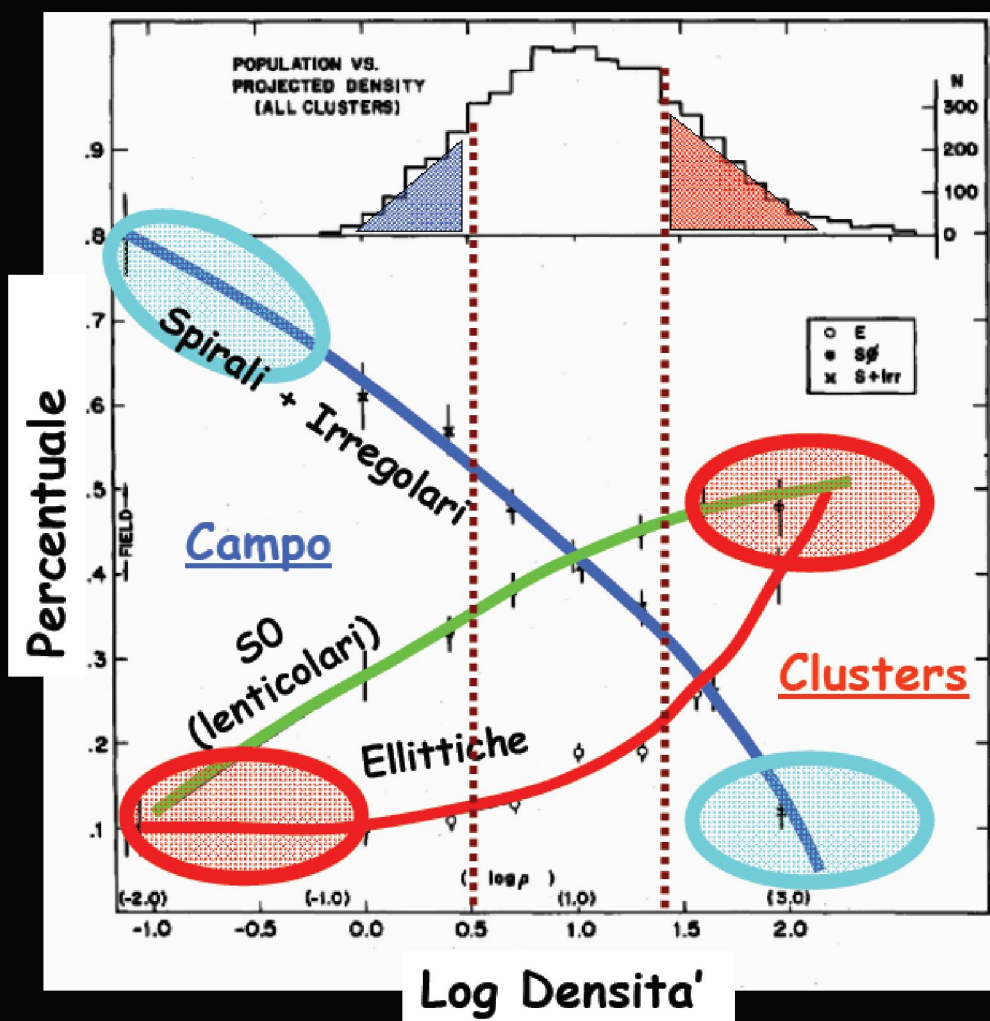
E S0 Sa Sb Sc Sd I



# Classificazione Morfologica di Hubble

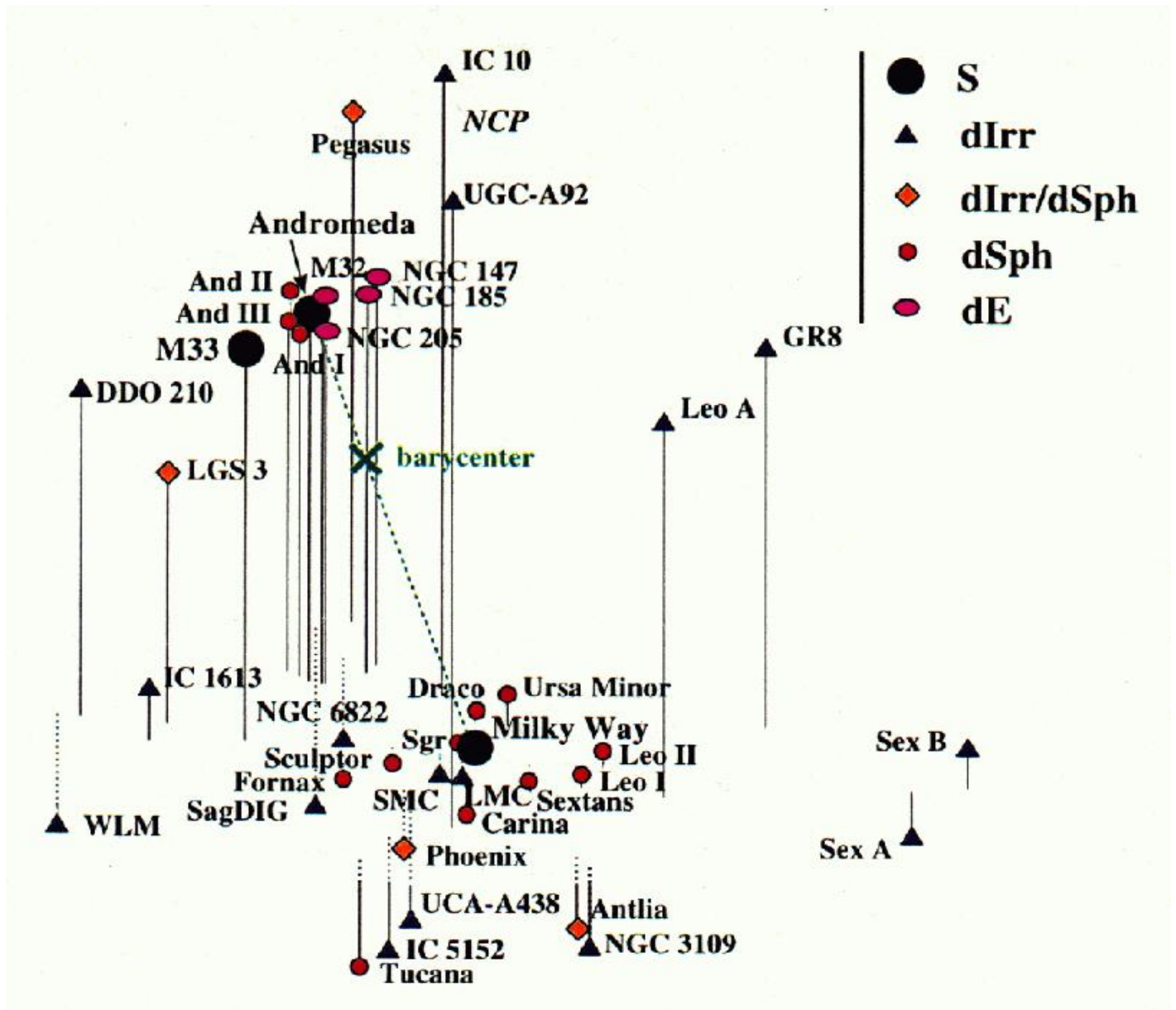


# Distribuzione galattica e tipo morfologico (Segregazione morfologica)



Dressler (1980)

# Il Gruppo Locale



[http://it.wikipedia.org/wiki/Gruppo\\_Locale](http://it.wikipedia.org/wiki/Gruppo_Locale)

# Galassie Ellittiche

**NGC 5044**  
(~120 Milioni a.l.)

**NGC 1316**

**Galassie  
ellittiche**

**M104  
El Sombrero**



**NGC 1300  
(69 Milioni a.l.in Eridano)**

**Galassie  
a spirale**





# Galassie Irregolari

NGC 55 (~LMC)  
6 Milioni a.l.



# Sferoidali nane

La sferoidale nana in  
Fornax (Gruppo Locale)



# Gli Ammassi di Galassie

NGC  
4473

NGC  
4458

NGC  
4435

NGC  
4461

M  
86

M  
84

NGC  
4438

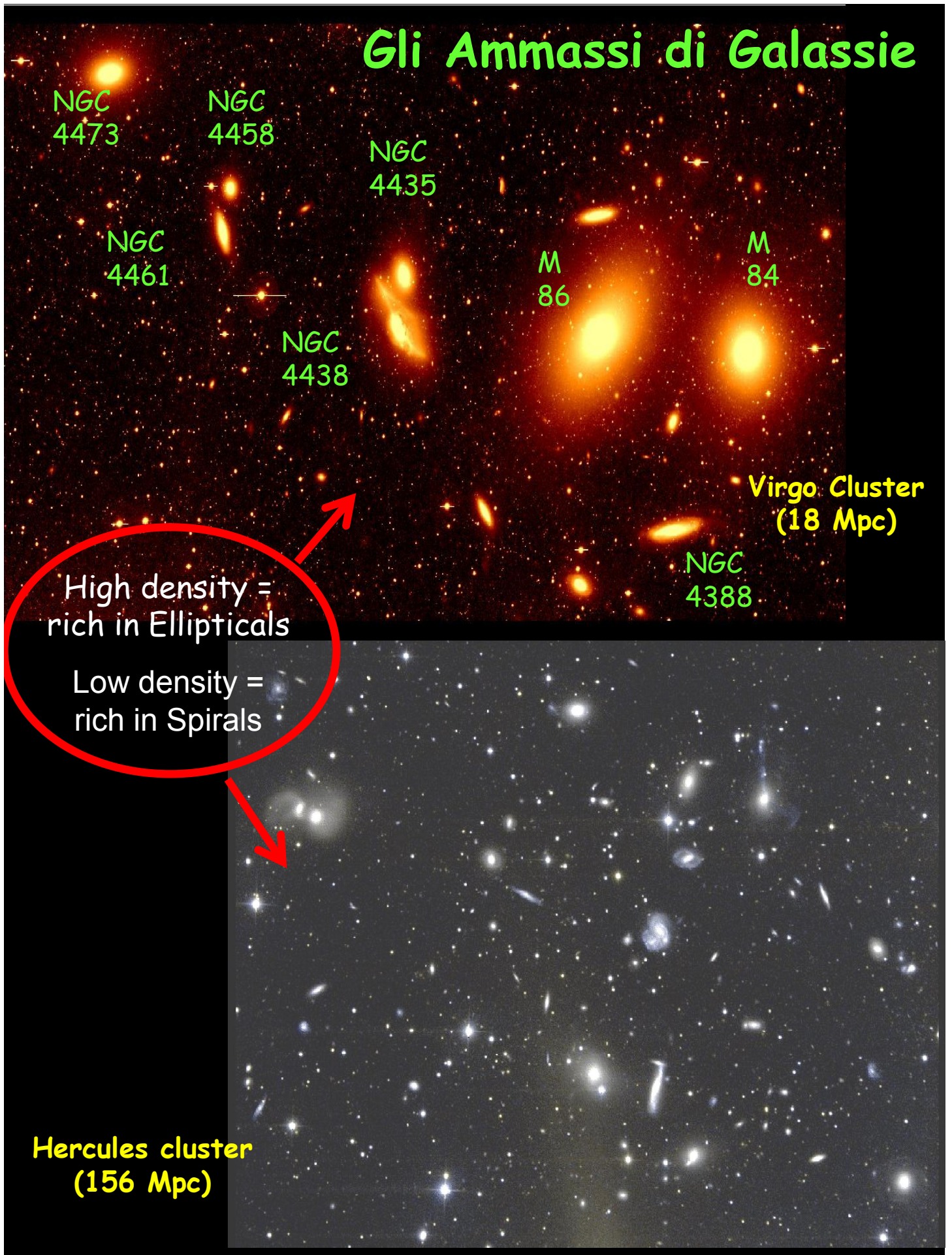
Virgo Cluster  
(18 Mpc)

NGC  
4388

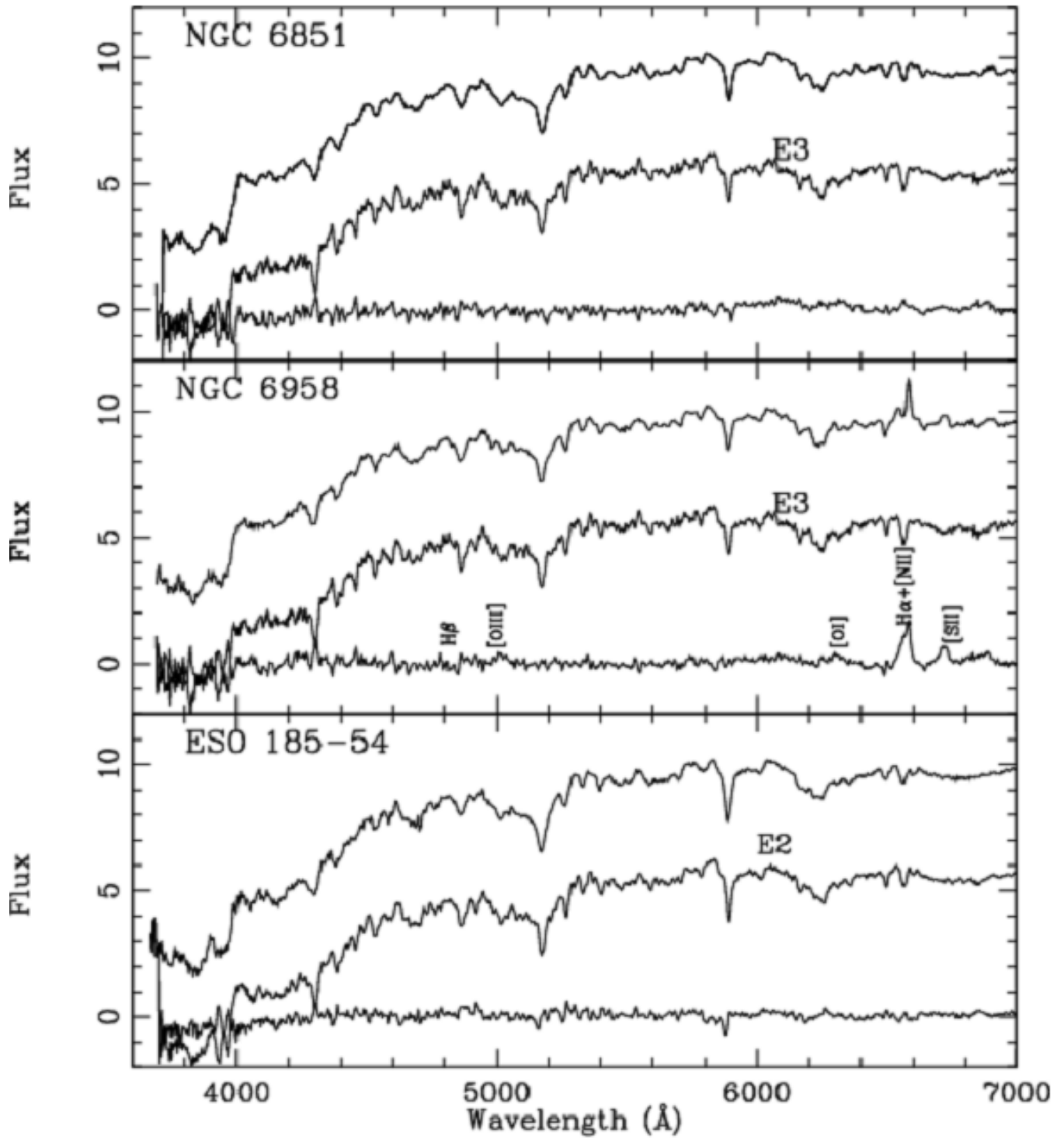
High density =  
rich in Ellipticals

Low density =  
rich in Spirals

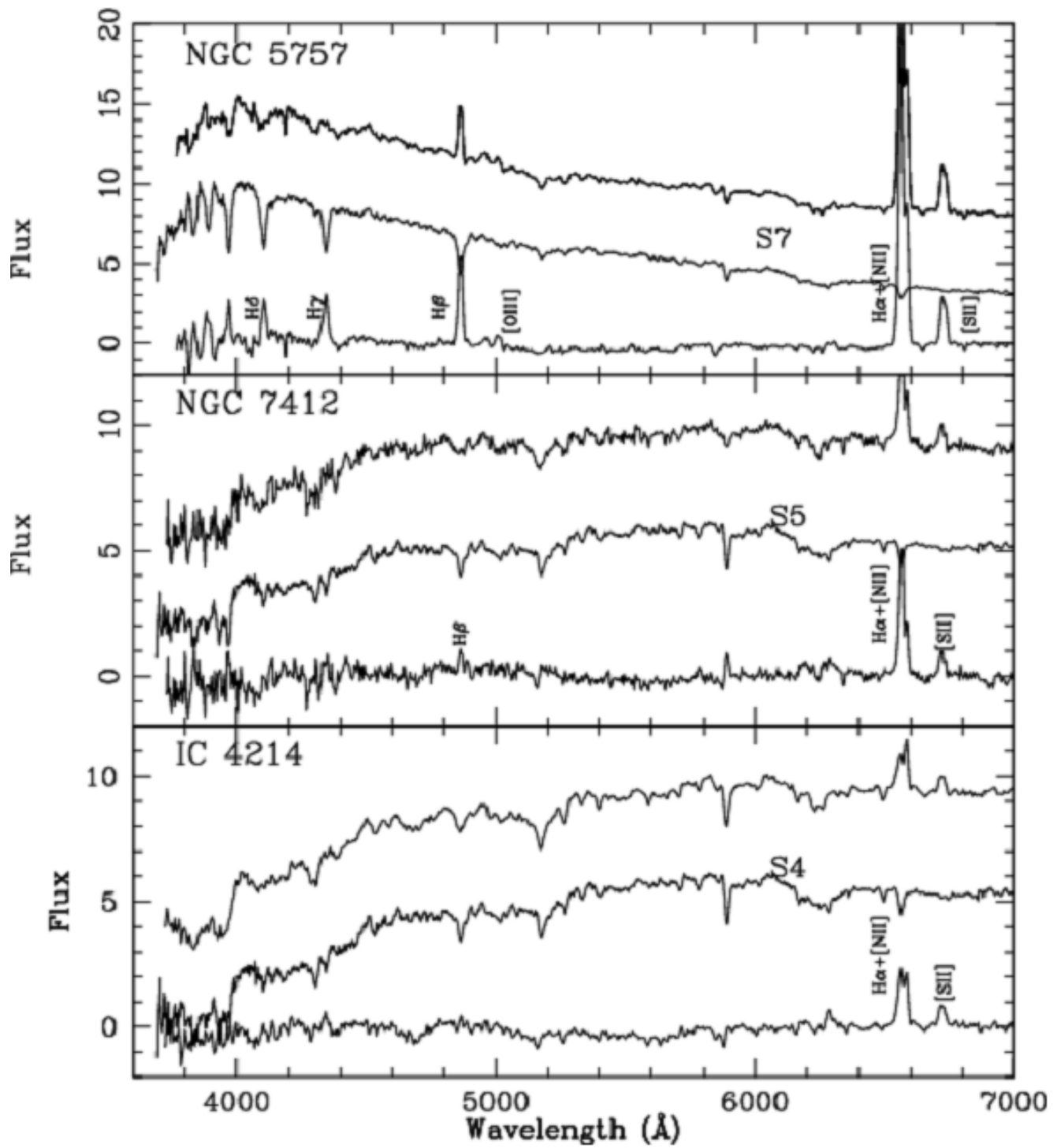
Hercules cluster  
(156 Mpc)



# Lo spettro delle Ellittiche



# Lo spettro delle Spirali

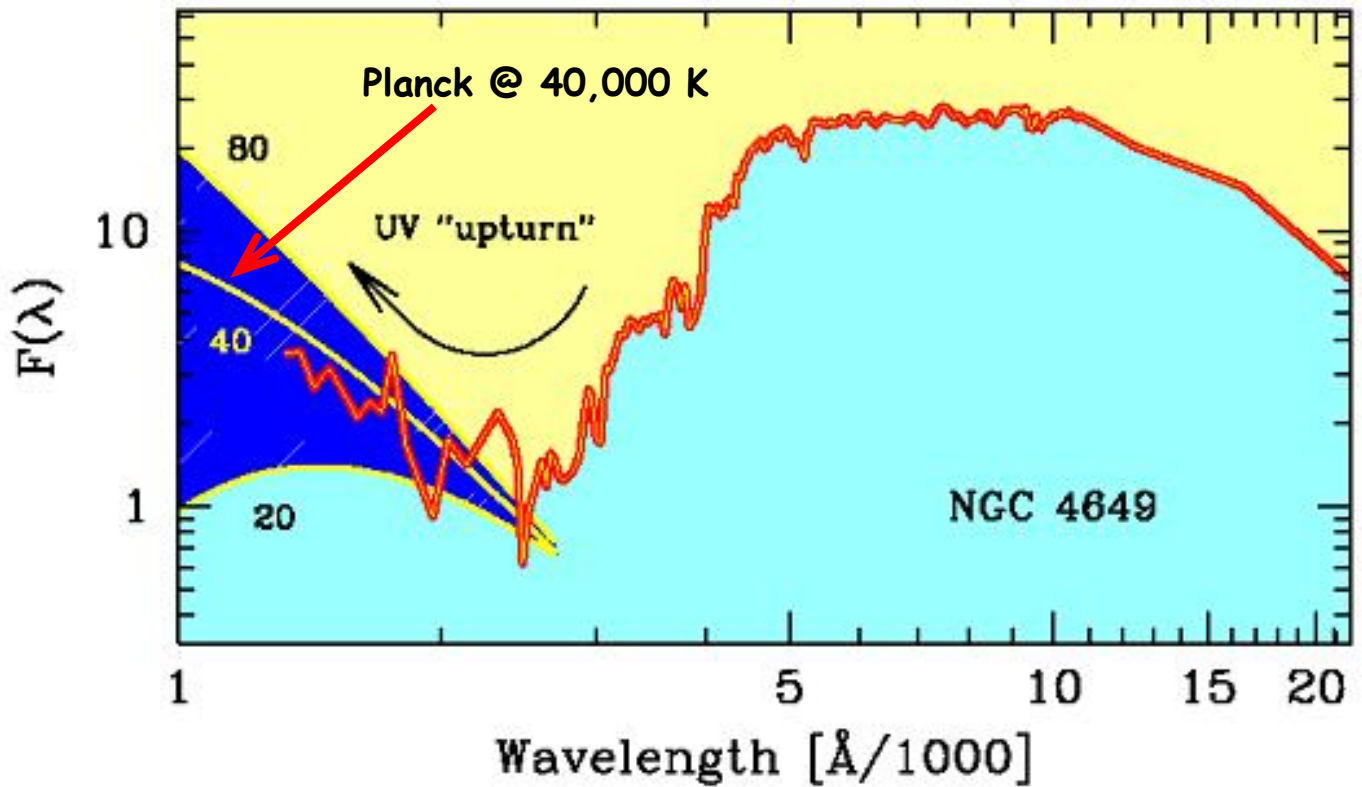


**Articoli consigliati (vedi Webpage):**

<http://www.bo.astro.it/~eps/lezioni/lezioni.html>

- SSPs (Tinsley)
- SSPs (Renzini & Buzzoni)
- Galaxy Colors (Buzzoni)
- LF (Schechter)
- Galaxy Spectral Atlas (Kennicutt1)
- Galaxy Spectral Atlas (Kennicutt2)
- SFR (Kennicutt)
- SFR (Ryder & Dopita)
- SFR (Schmidt)
- Balmer break (Hamilton)
- Lick indices (Worthey)
- UV indices (Fanelli)
- Chemical evolution of spiral galaxies (Buzzoni)

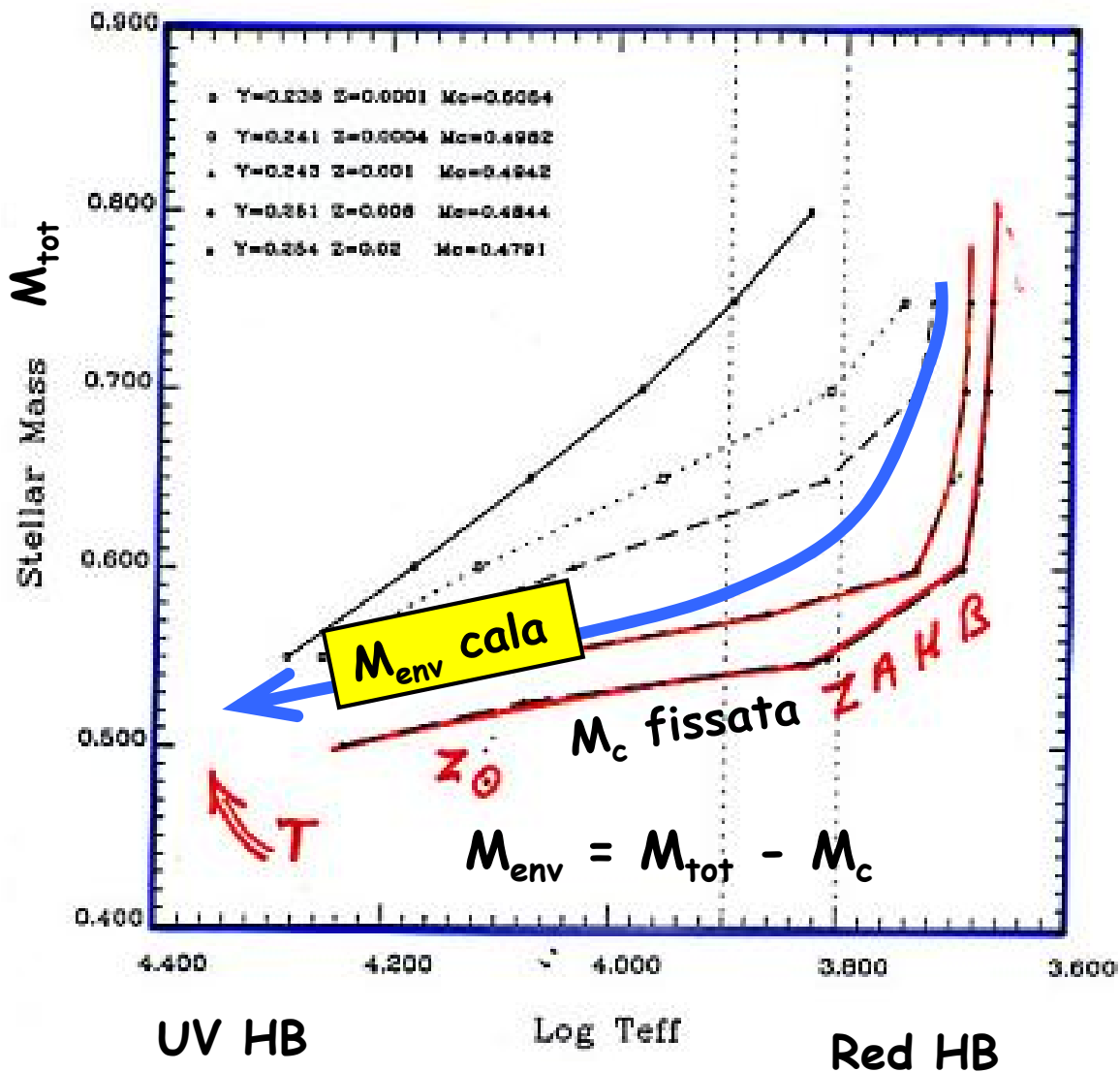
# L'emissione UV nelle SSPs: l'UV Upturn nelle galassie ellittiche



$\left[ \frac{\text{Integrale Planck}}{\text{Bolometric}} \right] =$	20,000	40,000	80,000 K
	<b>1.4%</b>	<b>2.1%</b>	<b>6.0%</b>

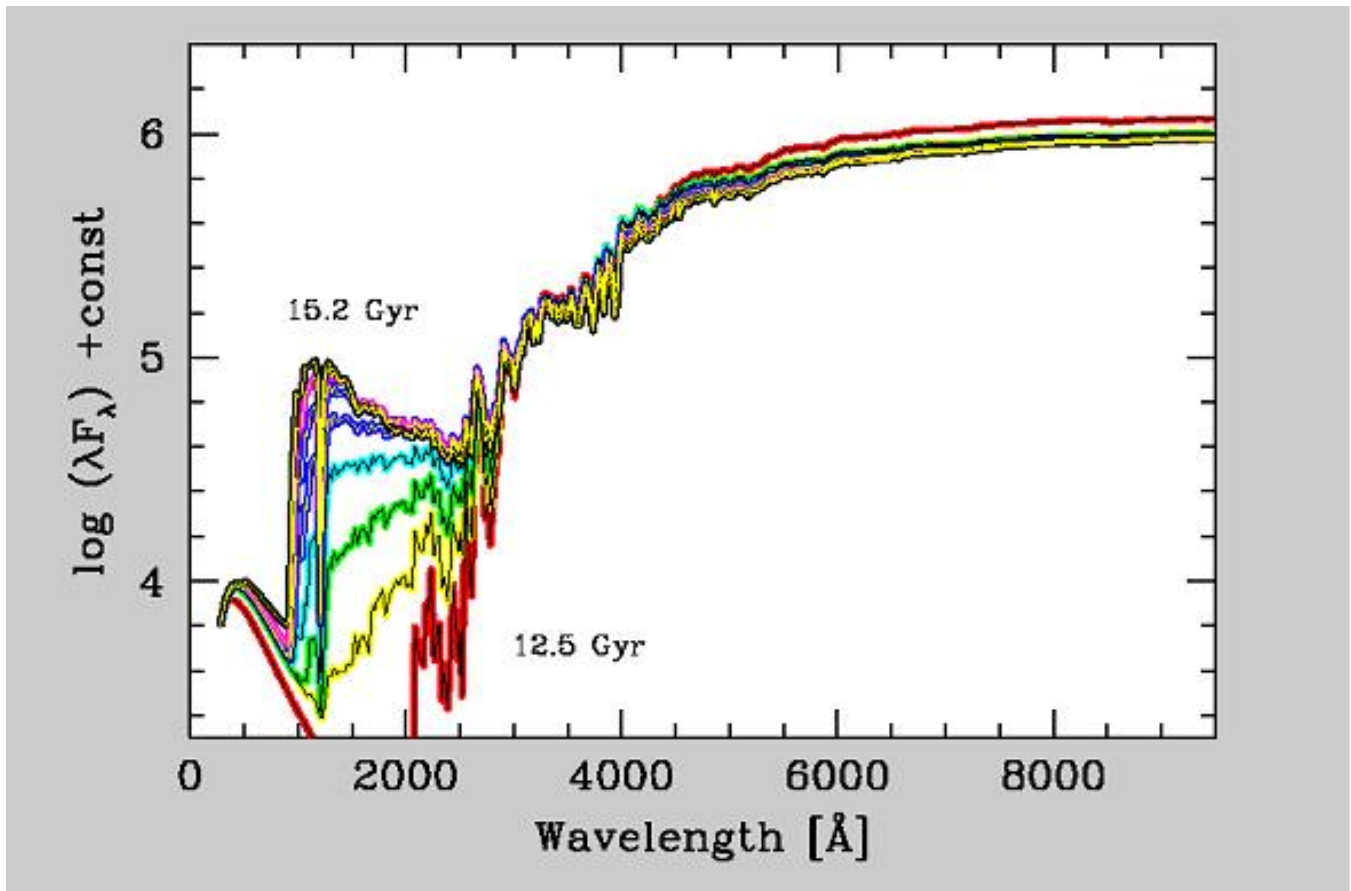
# Il meccanismo della Massa di core in HB

Castellani (1991)



- $M_{env}$  cala se
- 1) Aumenta  $M_c$  ( $= Y \uparrow$  perche'  $Z \uparrow$ )
  - 2) Aumenta la "mass loss" ( $= Z \uparrow$  ??)

# Evoluzione spettrale dell'UV upturn



A parità di efficienza del meccanismo che modula  $M_{env}$ , se aumenta  $M_{TO}$  possiamo aspettarci che aumenti anche  $M_{HB}$ . Siccome la  $T_{HB}$  è molto sensibile a  $M_{HB}$ , se  $t \uparrow$  allora  $M_{TO} \uparrow$  e  $M_{HB} \uparrow$ . Quindi  $M_{env} \uparrow$  e  $T \downarrow$ . Quindi il Braccio Orizzontale tende velocemente al rosso e l'UV upturn scompare:

$$\frac{dt}{t} \approx -2 \frac{dM_{TO}}{M_{TO}} \approx -2 \frac{dM_{HB}}{M_{HB}}. \text{ Se } \frac{dM_{HB}}{M_{HB}} \approx 0.1 \Rightarrow \frac{dt}{t} \approx 0.2$$

Quindi, andando indietro di circa 2-3 Gyr ( $z \sim 0.2-0.3$ ) l'effetto dovrebbe scomparire.



M. CASTELLANI et al. (1994)

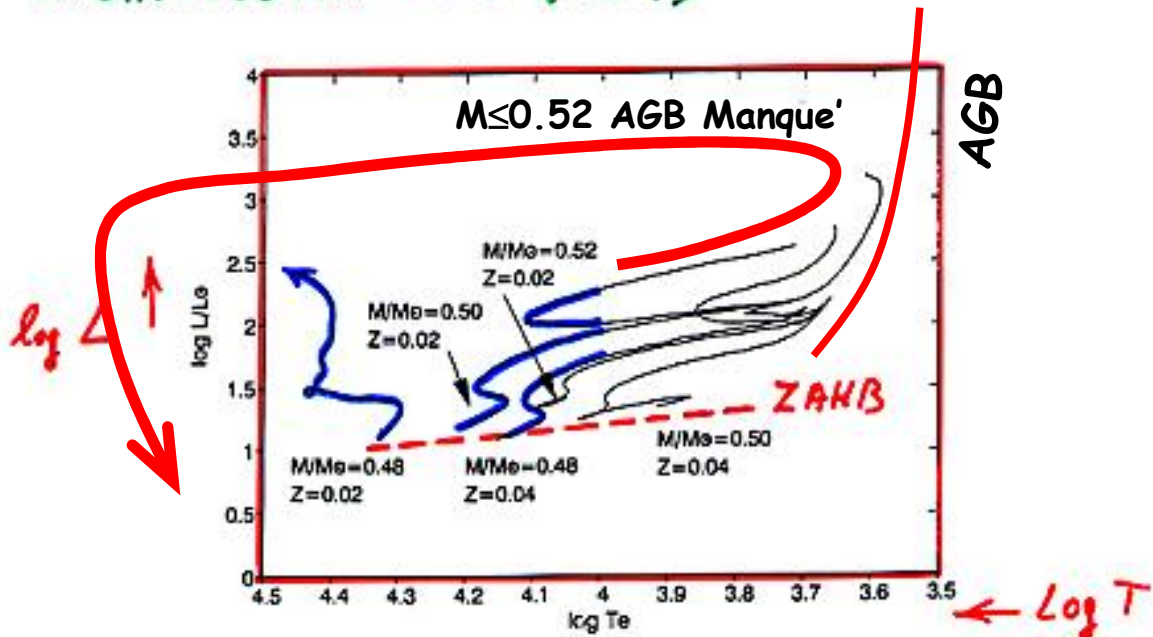


FIG. 1.—The H-R diagram of the models evolved at constant mass covering the central He-burning phase and (in some models) the initial He shell-burning phases.

V. CASTELLANI & TORNAMBÈ (1992)

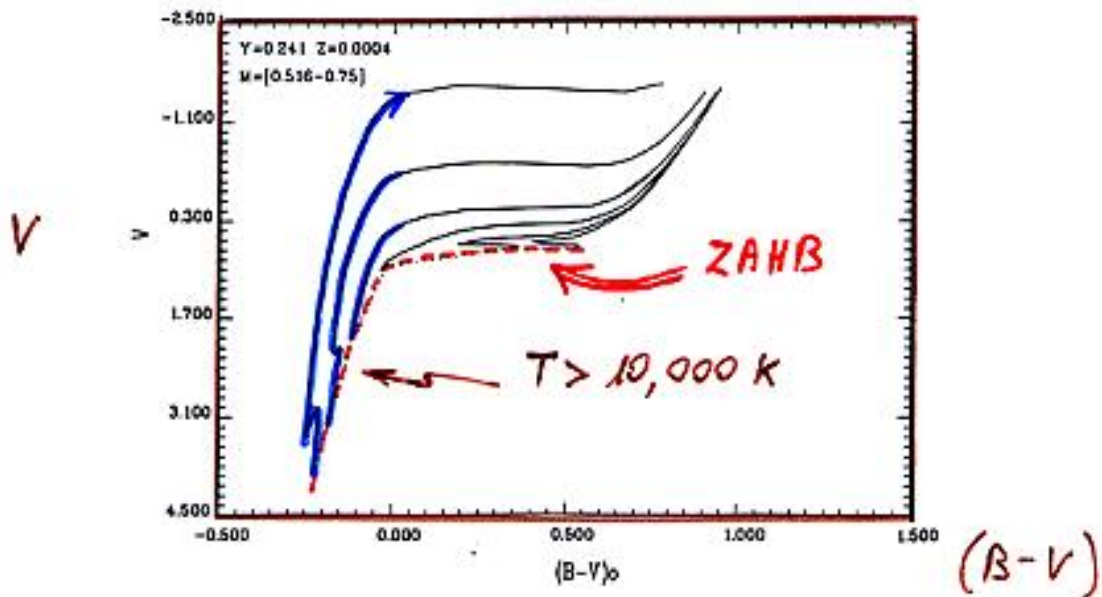


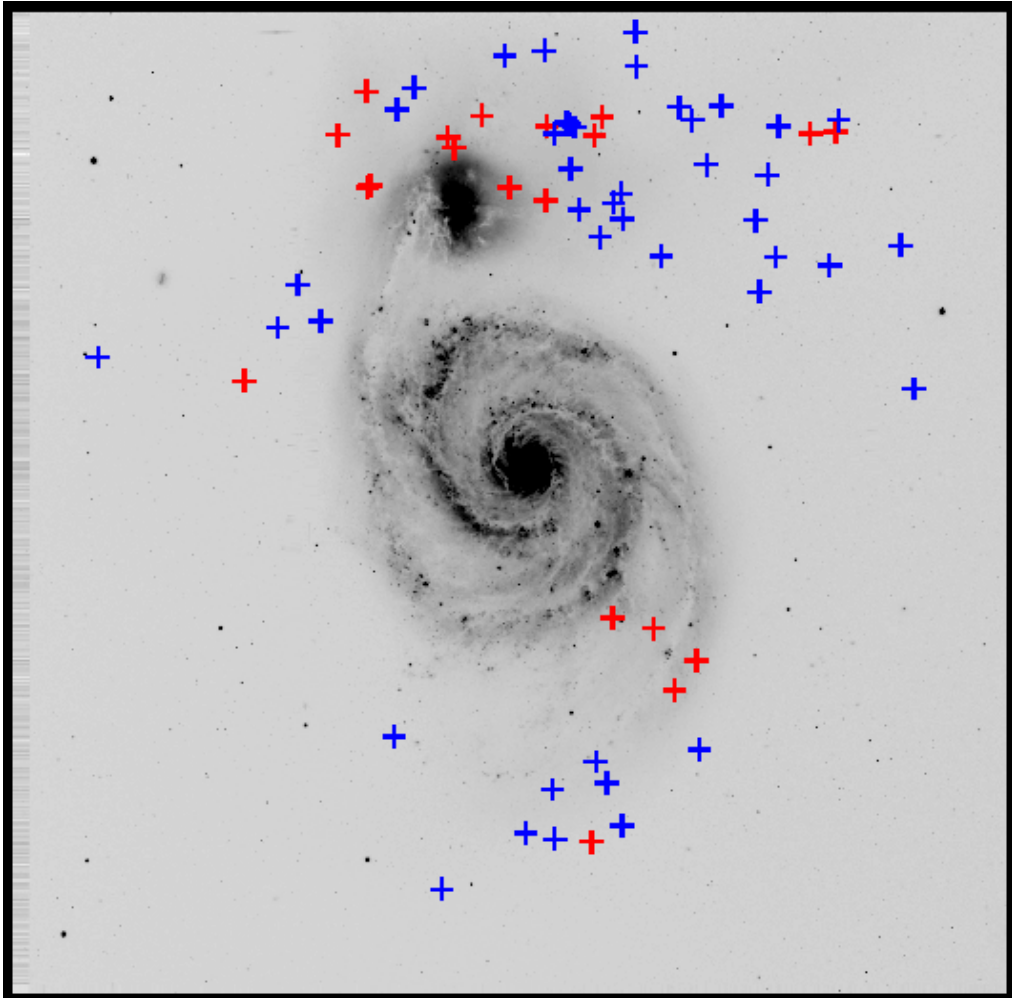
Fig. 5. The evolutionary paths in the  $V$ ,  $B - V$  plane of HB models with  $Z = 0.0004$  and for selected values of the stellar mass in the labeled range of masses

**Articoli consigliati (vedi Webpage):**

<http://www.bo.astro.it/~eps/lezioni/lezioni.html>

- SSPs (Tinsley)
- SSPs (Renzini & Buzzoni)
- Galaxy Spectral Atlas (Kennicutt1)
- Galaxy Spectral Atlas (Kennicutt2)
- UV Upturn (Brown)
- UV Upturn (Dorman)
- UV Upturn (OConnell)
- UV Upturn (Yi)
- Balmer break (Hamilton)
- Lick indices (Worthey)
- UV indices (Fanelli)

# Le Nebulose Planetarie



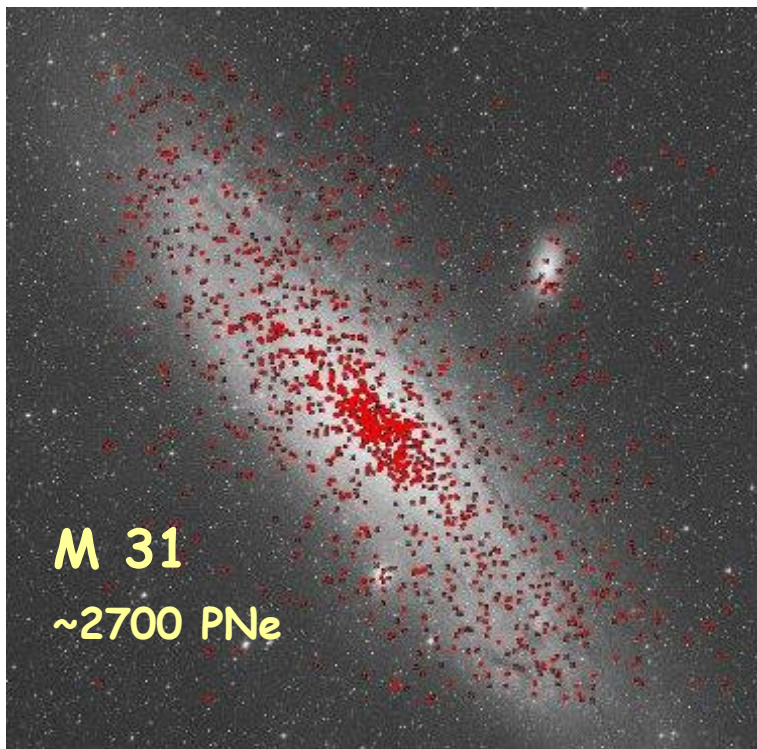
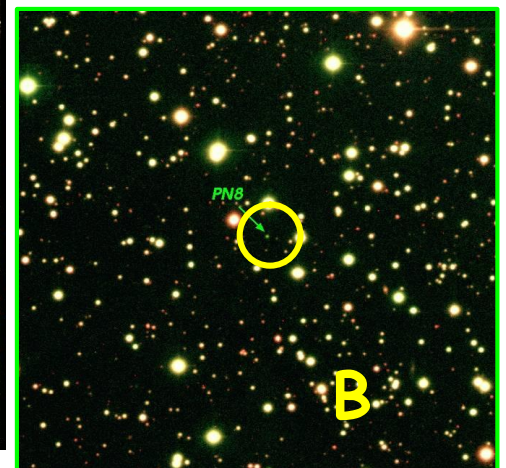
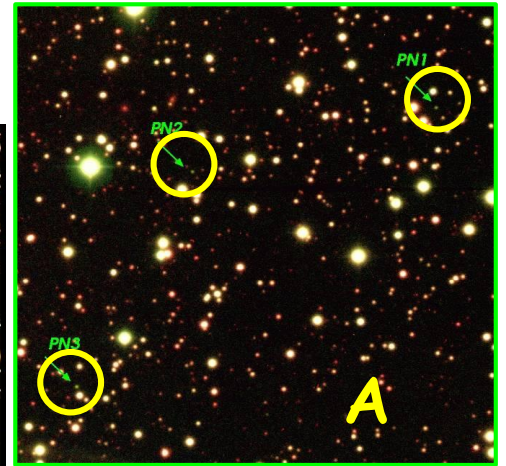
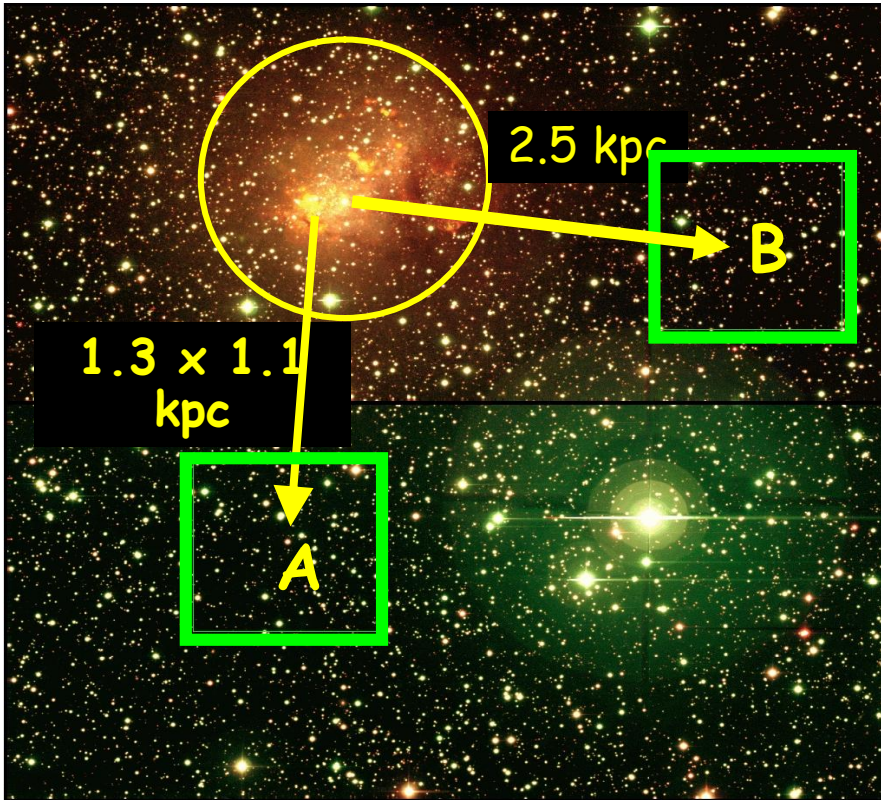
Feldmeier, Ciardullo & Jacoby (1997)

Planetary Nebulae follow **Luminosity** not surface brightness!

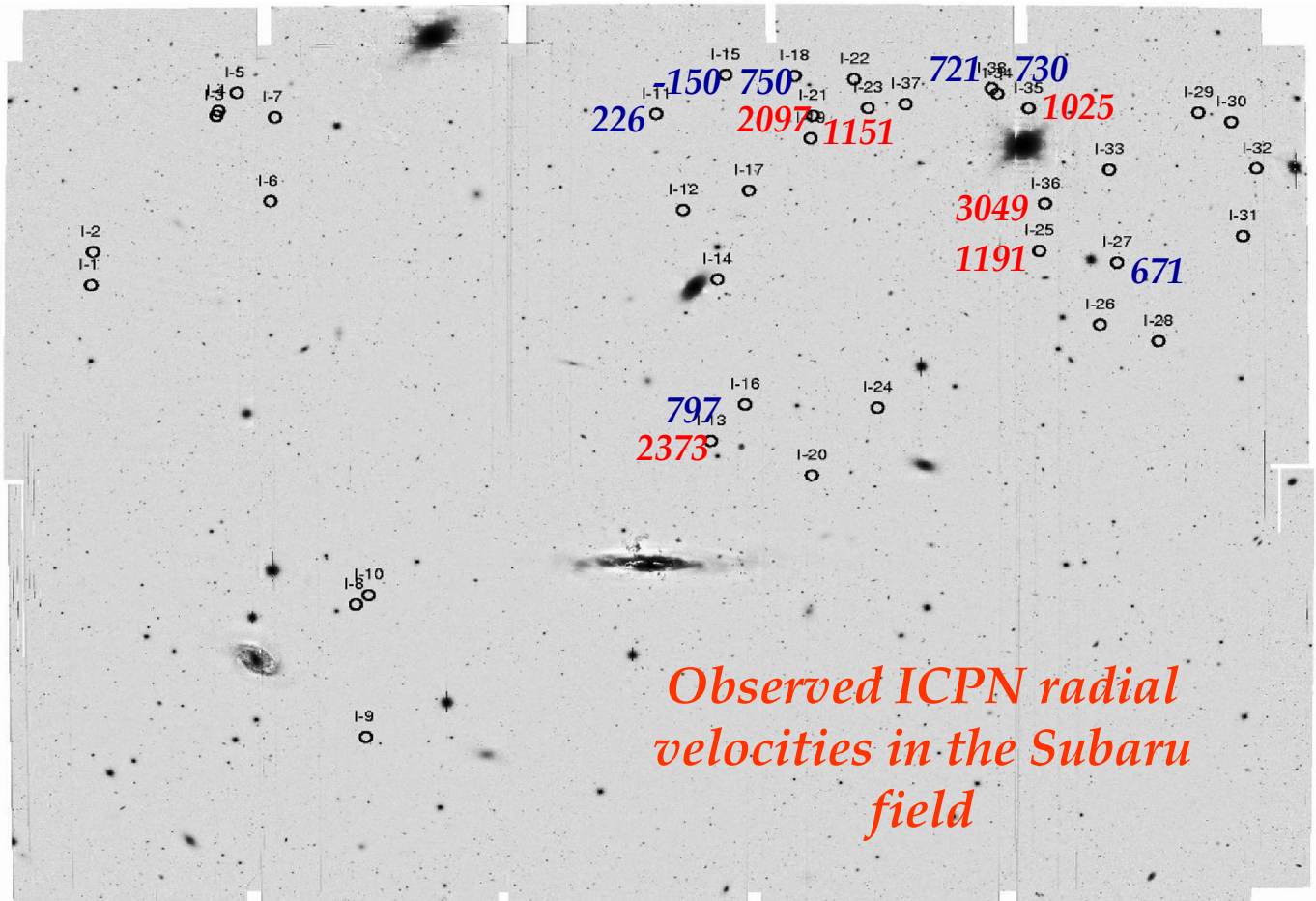
Stars can exist at great distances from luminous galaxies

# Il censimento delle PNe nelle galassie del Gruppo Locale

Magrini et al. 2003 A&A 407 51



# Planetarie intra-galattiche nell'Ammasso della Vergine



*Observed ICPN radial velocities in the Subaru field*

(Arnaboldi et al. 2002)

$$N_{PN} = BL_{tot} \tau_{PN} \longrightarrow \alpha = \frac{N_{PN}}{L_{tot}} = B \tau_{PN}$$

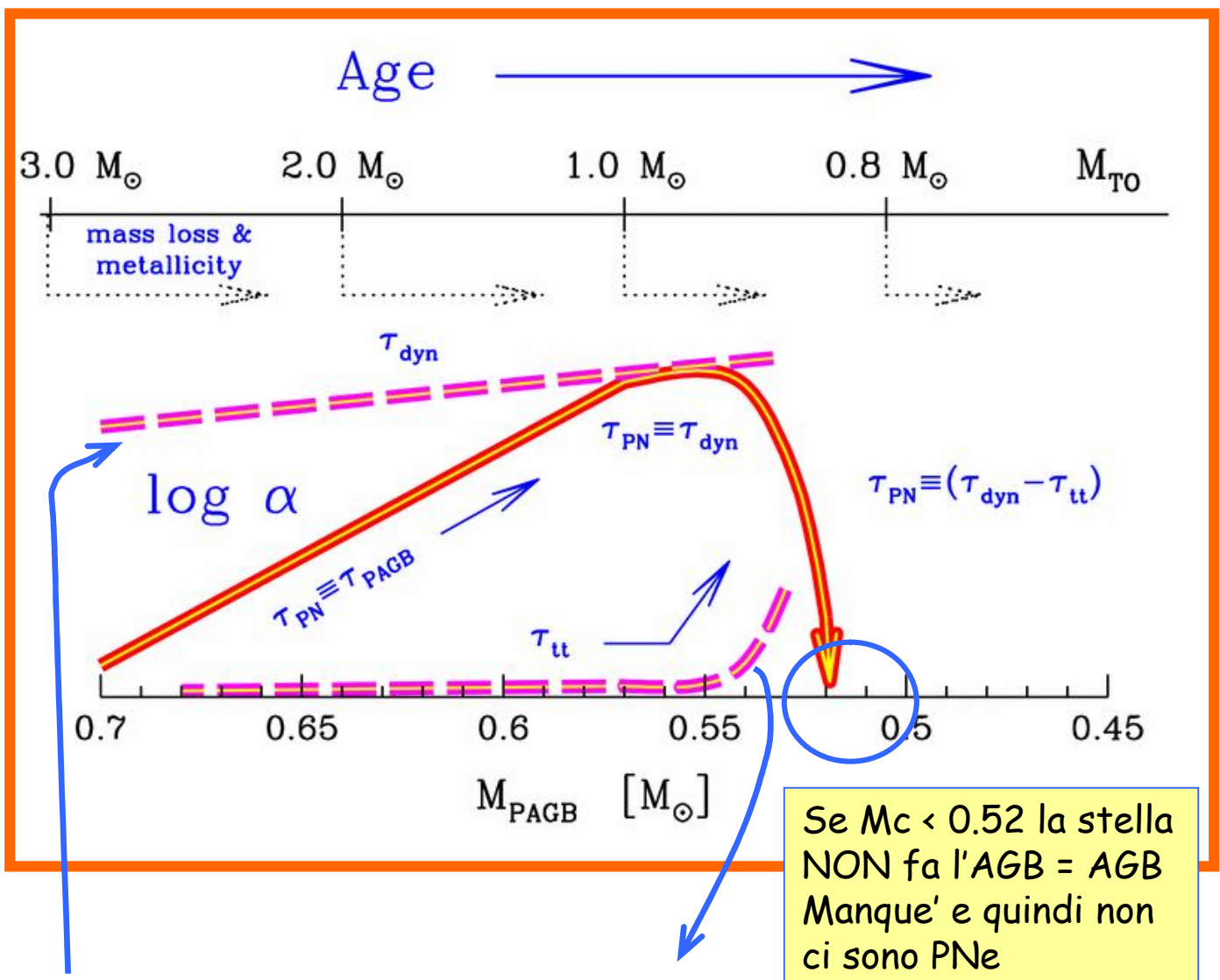
quindi  $\alpha = \frac{N_{PN}}{L_{tot}} \approx 2 \times 10^{-11} \times 3 \times 10^4 = 6 \times 10^{-7}$

Ovvero, 1 PN campiona:  $L_{tot} \approx \frac{1}{\alpha} \approx 1.7 \times 10^6 L_{sun}$



# Tempi scala di visibilita' delle PNe

Buzzoni, Arnaboldi & Corradi (2006)

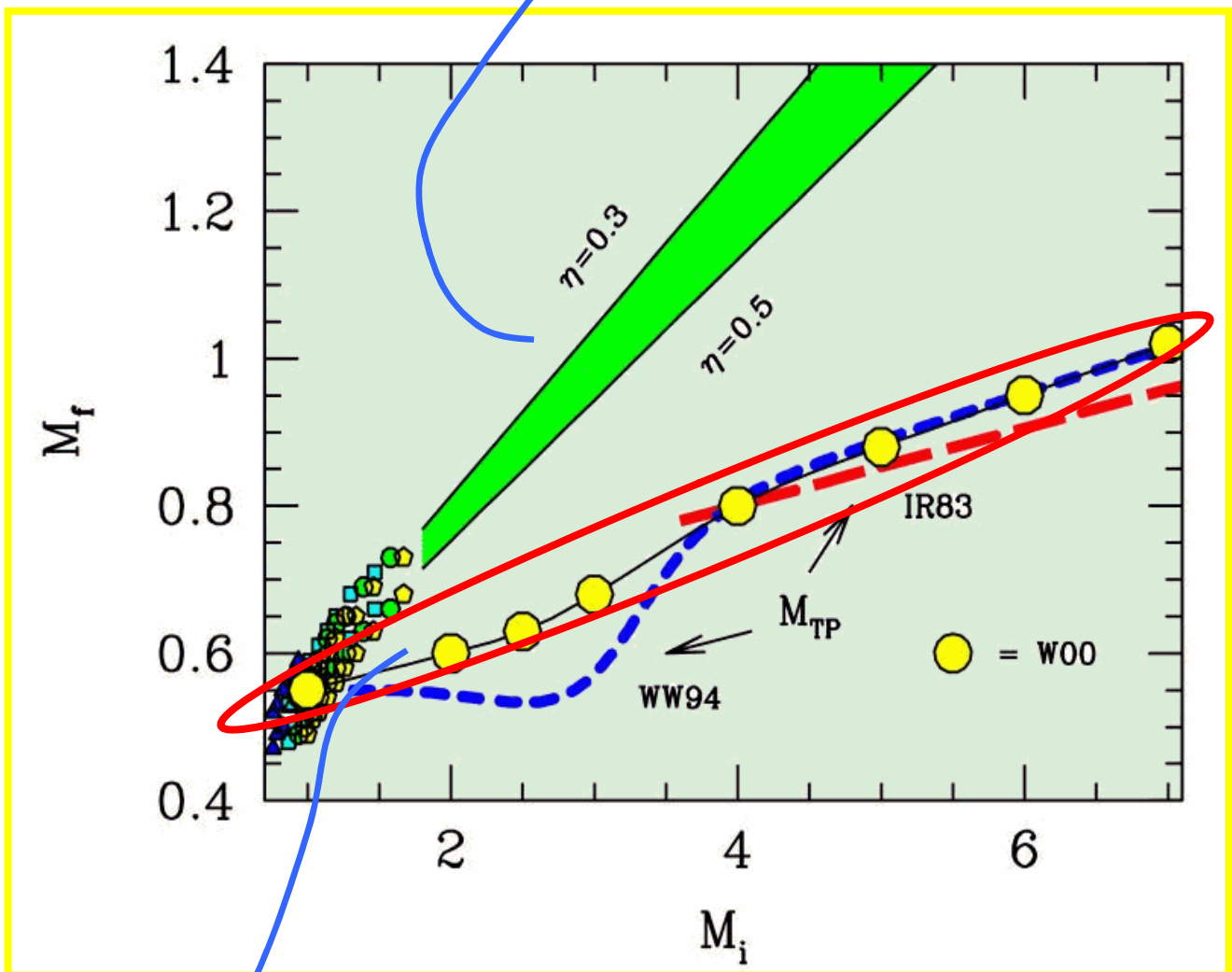


Tempo dinamico  
(evaporazione involuppo)  
 $V \sim 10$  km/sec

Tempo di transizione  
da AGB freddo a  
 $T \sim 50,000$  K

# Massa iniziale e finale delle stelle

Formula di Reimers (1975)



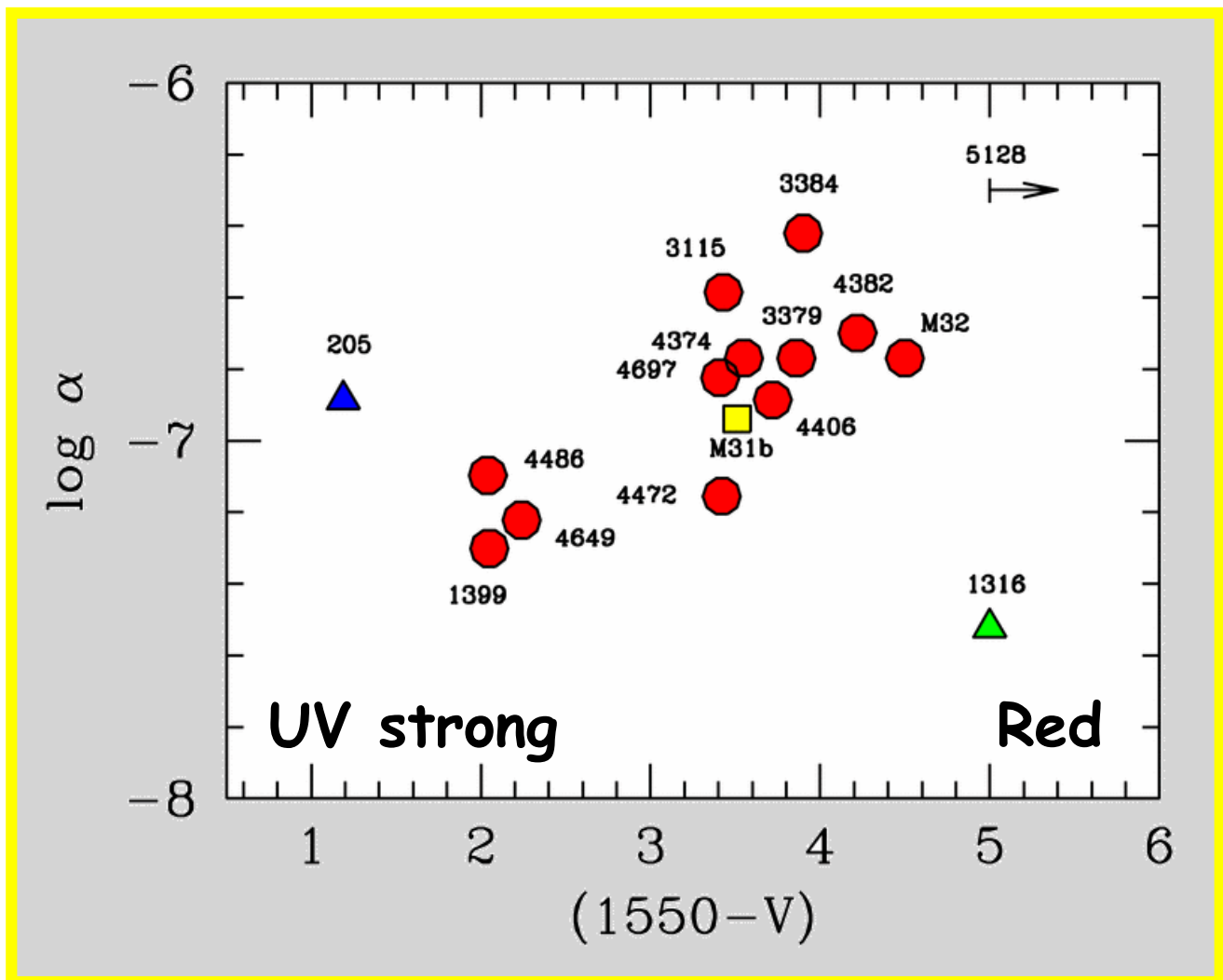
Buzzoni, Arnaboldi & Corradi (2006)

Osservazione empirica di Weidemann (2000) dagli ammassi aperti Galattici, dove  $M_i = M_{TO}$ , e  $M_f = M_{WD}$

Si vede che le PNe devono avere sempre una massa  $\ll 1M_{sun}$



# PNe e UV upturn nelle galassie ellittiche



Buzzoni, Arnaboldi & Corradi (2006)

Un forte UV da stelle HB implica molte stelle AGB manque' e quindi  $\alpha \downarrow$

**Articoli consigliati (vedi Webpage):**

<http://www.bo.astro.it/~eps/lezioni/lezioni.html>

- SSPs (Renzini & Buzzoni)
- Nebulose Planetarie (Arnaboldi)
- Nebulose Planetarie (Feldmeier)
- Nebulose Planetarie (Buzzoni)
- IMF (Weidemann)

# Entropia Fotometrica

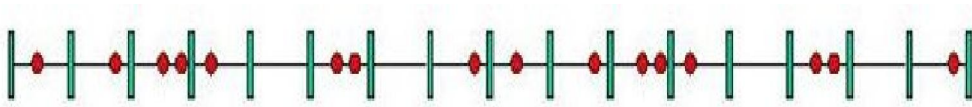
## What a Photometric Entropy theory is for?

Entropy is a measure of the intrinsic "variance" of a stellar aggregate along the different spectral range of observation.

- **Surface-brightness Fluctuations**
- **Crowding**
- **Diagnostics from Narrow-band Spectroscopy**

# Some Fundamentals

$$p(x) = \frac{e^{-\lambda} \lambda^x}{x!} \quad \text{for } \lambda > 0 \text{ and } x = 0, 1, 2, \dots$$



1, 2, 3, .....

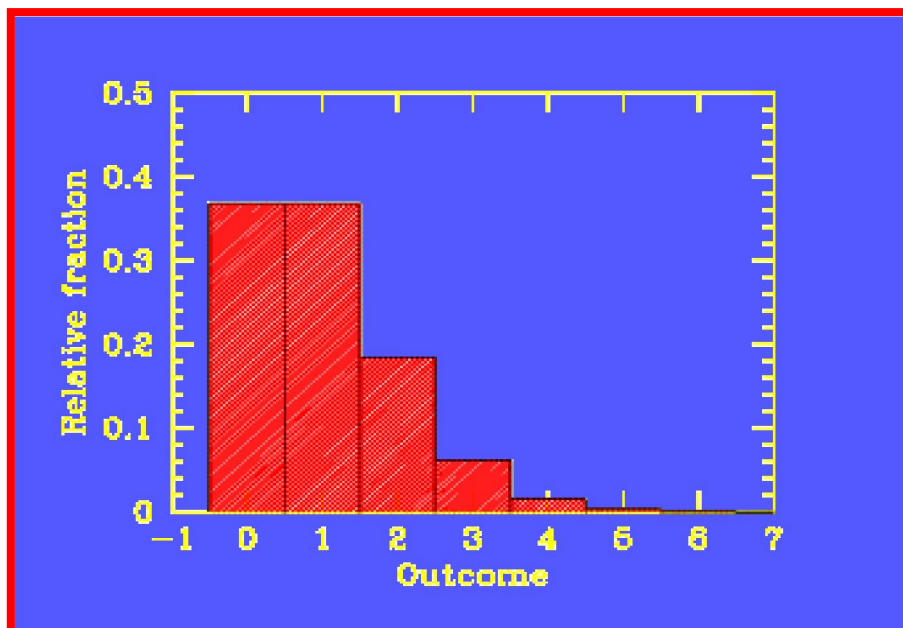
.....  $N_{\text{tot}}$

→  $N = 1 \pm 1$  for each cell     $L_{\text{tot}} = \sum \ell_* = N_{\text{tot}} \ell_*$

$$\sigma(N_{\text{tot}}) = \sqrt{\sum 1} = \sqrt{N_{\text{tot}}}$$

$$\sigma(L_{\text{tot}}) = \sqrt{\sum \ell_*^2} = \ell_* \sqrt{N_{\text{tot}}}$$

$$\sigma(L_{\text{tot}})/L_{\text{tot}} = 1/\sqrt{N_{\text{tot}}}$$

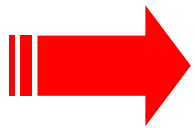


More generally, if  $\ell_*$  is NOT a constant, we can still define

$$\sigma(L_{\text{tot}})/L_{\text{tot}} = 1/\sqrt{N_{\text{eff}}}$$

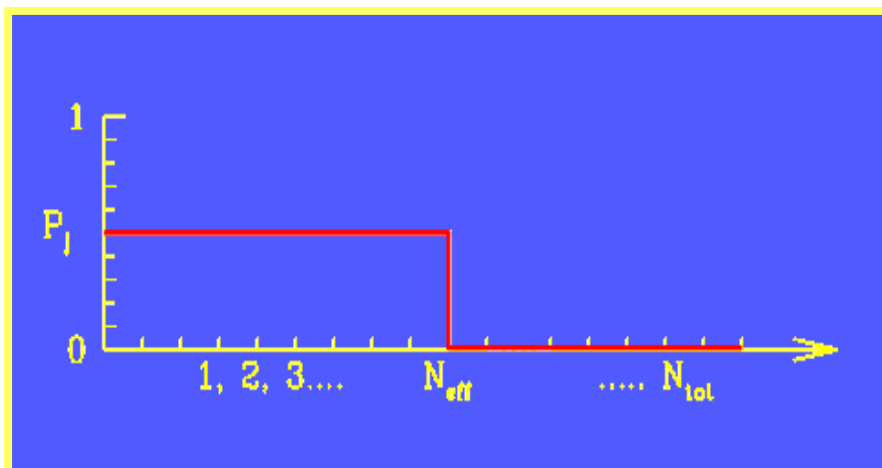
where, always,

$$N_{\text{eff}} \leq N_{\text{tot}}$$



$N_{\text{eff}}$  will depend on  $\lambda$  as  $\ell_*$  depends on  $\lambda$

$$S = \text{Log} (N_{\text{eff}}/N_{\text{tot}})$$



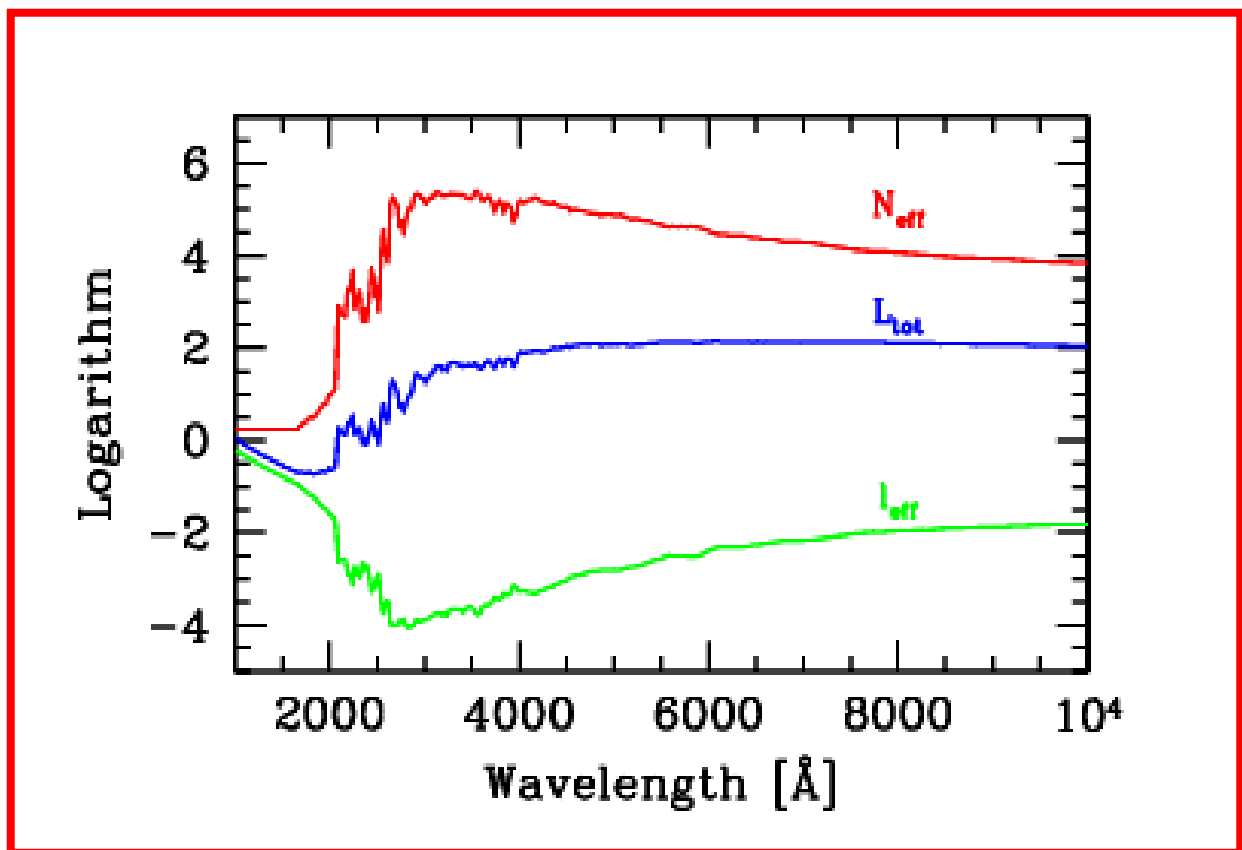
Quite importantly,

$$S = S(\lambda)$$

In order to fix  $N_{\text{eff}}$  (and Entropy) we need a photometric argument

$$\sigma^2(L_{\text{tot}}) / L_{\text{tot}} = \sum \ell_*^2 / \sum \ell_* = \ell_{\text{eff}}$$

At every  $\lambda$ , it must be:  $N_{\text{eff}} \times \ell_{\text{eff}} = L_{\text{tot}}$



Buzzoni (1993), *A&Ap*, 275, 433

Cerviño et al. (2002), *A&Ap*, 381, 51

# Teoria dettagliata

CASO A)  $N$  stelle di fissata luminosità  $l_*$

$$L_{TOT} = \sum^N l_* = N l_*$$

$$\sigma_{L_{TOT}} = \left( \sum^N \sigma_j^2 \right)^{\frac{1}{2}} \quad \forall * \quad m = 1 \pm 1 \quad (\text{Poisson})$$

$$\left( \sum^N (l_* \cdot 1)^2 \right)^{\frac{1}{2}} \rightarrow \left( N l_*^2 \right)^{\frac{1}{2}} \rightarrow l_* \sqrt{N}$$

Quindi

$$\frac{\sigma_L}{L_{TOT}} = \frac{l_* \sqrt{N}}{l_* N} = \frac{1}{\sqrt{N}}$$

CASO B)  $N$  stelle tutte diverse

$$L_{TOT} = \sum^N l_j = N \langle l \rangle \quad \text{dove } \langle l \rangle = \frac{\sum l_j}{N}$$

$$\sigma_{L_{TOT}} = \left( \sum^N l_j^2 \right)^{\frac{1}{2}} = \sqrt{N} \langle l^2 \rangle \quad \text{dove } \langle l^2 \rangle = \frac{\sum l_j^2}{N}$$

$$\frac{\sigma_{L_{TOT}}}{L_{TOT}} = \frac{\sqrt{N} \langle l^2 \rangle^{\frac{1}{2}}}{N \langle l \rangle} = \frac{K}{\sqrt{N}}$$

media quadratica

$$\text{dove } K = \left[ \frac{\langle l^2 \rangle}{\langle l \rangle^2} \right]^{\frac{1}{2}}$$

$$\frac{K}{\sqrt{N}} = \frac{1}{\sqrt{N_{eff}}} \Rightarrow \frac{N_{eff}}{N} = \frac{1}{K^2}$$

$K \geq 1$  perché  $\langle l^2 \rangle \geq \langle l \rangle^2$

Quindi è sempre  $N_{eff} \leq N$

Definiamo ENTROPIA FOTOMETRICA:

$$S = -2 \log K = \log \frac{N_{eff}}{N}$$

Analisi della varianza

$$\sigma_{L_{TOT}}^2 = \sum l_j^2$$

$$\frac{\sigma_L^2}{L_{TOT}} = \frac{N \langle l^2 \rangle}{N \langle l \rangle} \rightarrow \text{Questo rapporto ha le dimensioni di una lunghezza}$$

quindi  $l_{eff} = \frac{\langle l^2 \rangle}{\langle l \rangle} = \frac{\sum l^2}{\sum l}$

Che relazione c'è fra  $N_{eff}$  e  $l_{eff}$ ?

$$N_{eff} \cdot l_{eff} = \frac{N}{k^2} \frac{\langle l^2 \rangle}{\langle l \rangle} = \frac{N \langle l^2 \rangle \langle l \rangle}{\langle l^2 \rangle \langle l \rangle} = N \langle l \rangle$$

$\downarrow$   
 $N \frac{\sum l}{N}$

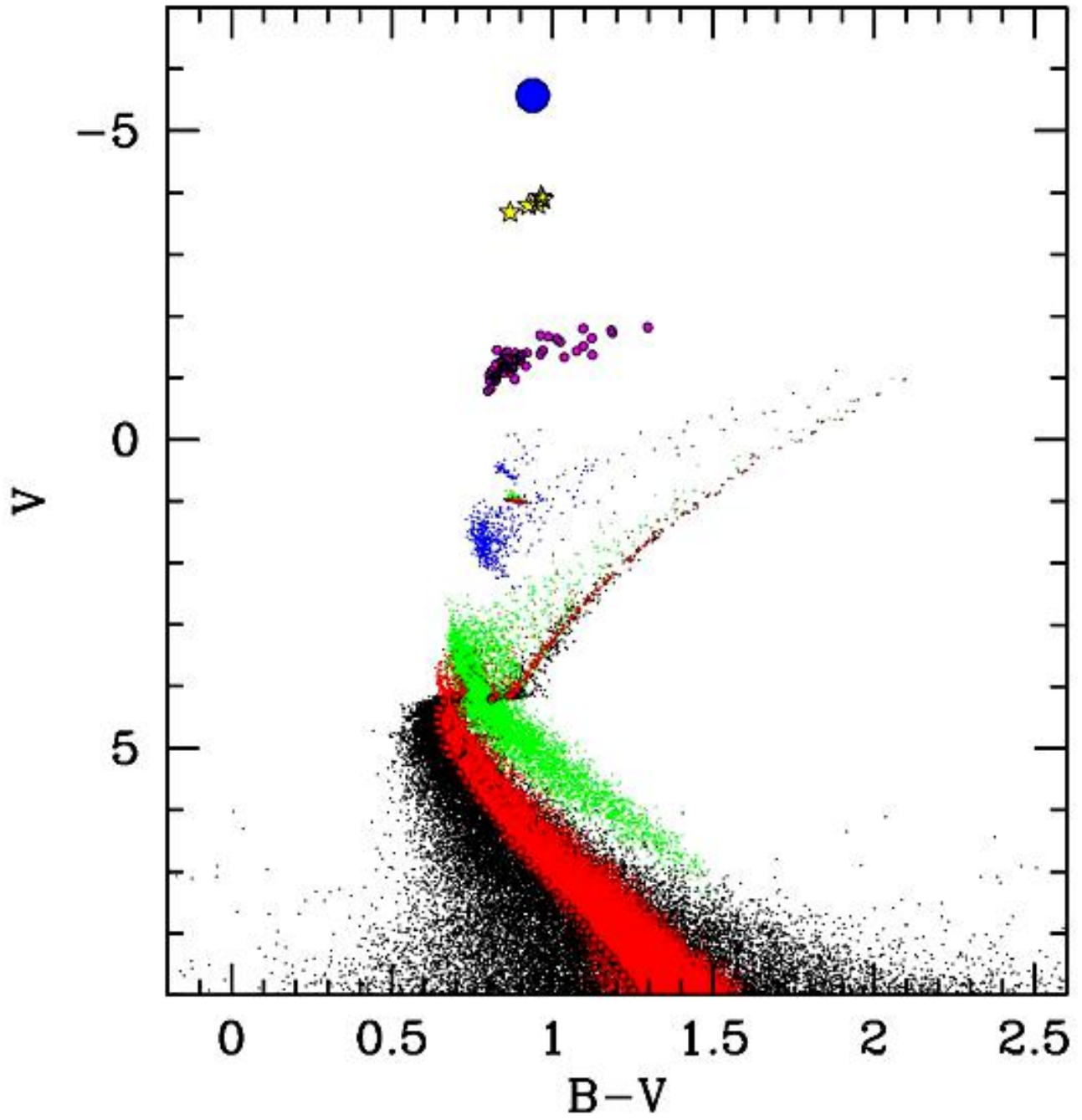
quindi  $N_{eff} \times l_{eff} = L_{TOT}$



# SSP

(Age, [Fe/H], IMF)

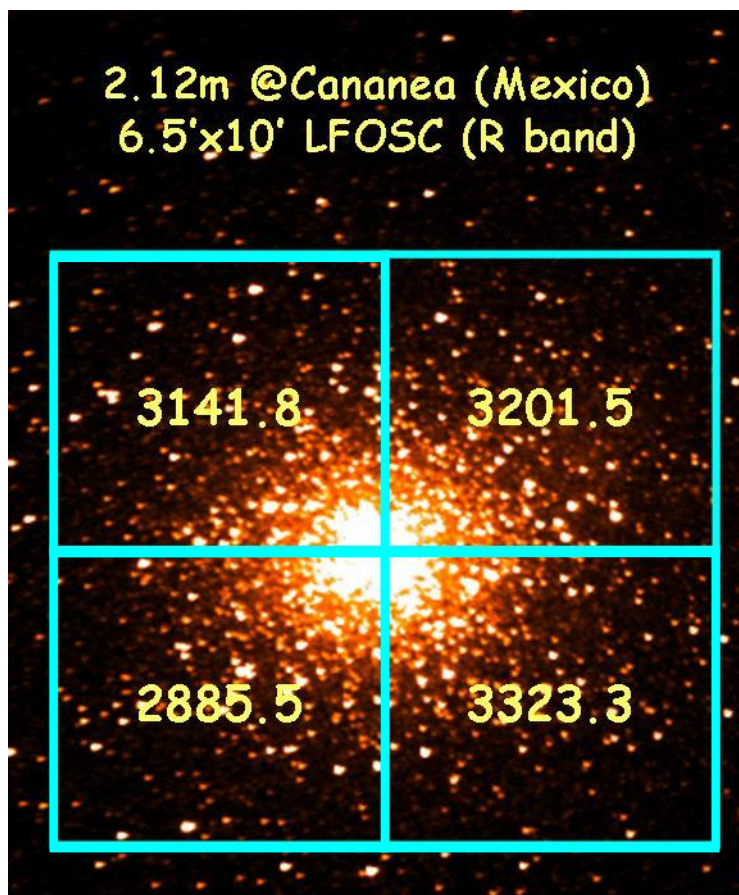
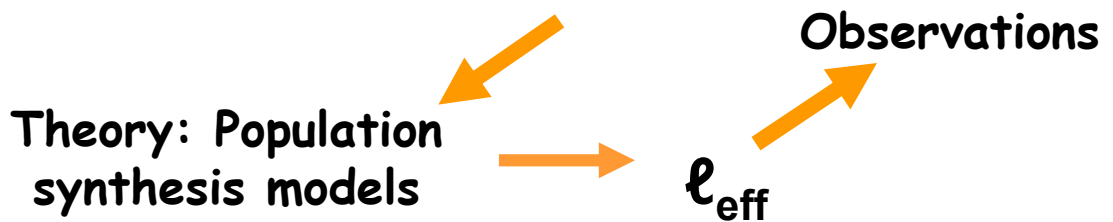
(15 Gyr, 0.0, Salpeter)



# Surface-Brightness Fluctuations: an alternative approach for the case of M53

First application of the theory to galx's: Tonry & Schneider (1988) and Tonry (1991)

$$\sigma^2(L_{\text{tot}}) / L_{\text{tot}} = \sum \ell_*^2 / \sum \ell_* = \ell_{\text{eff}}$$

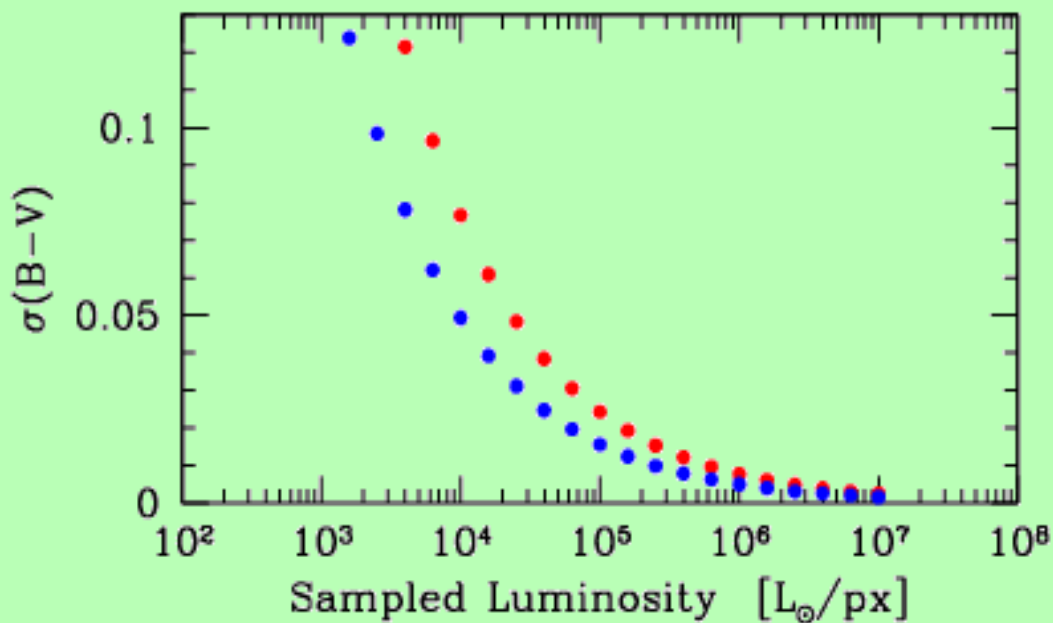


$$L_{(\text{quad})} = 3138 \pm 184$$

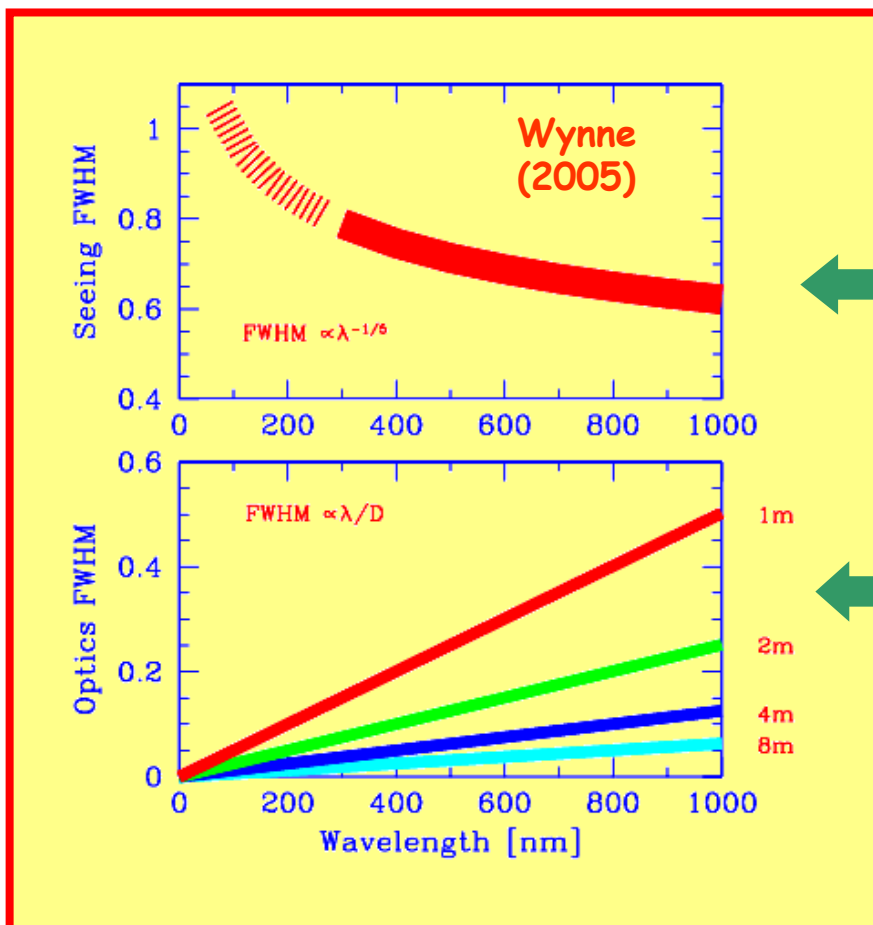
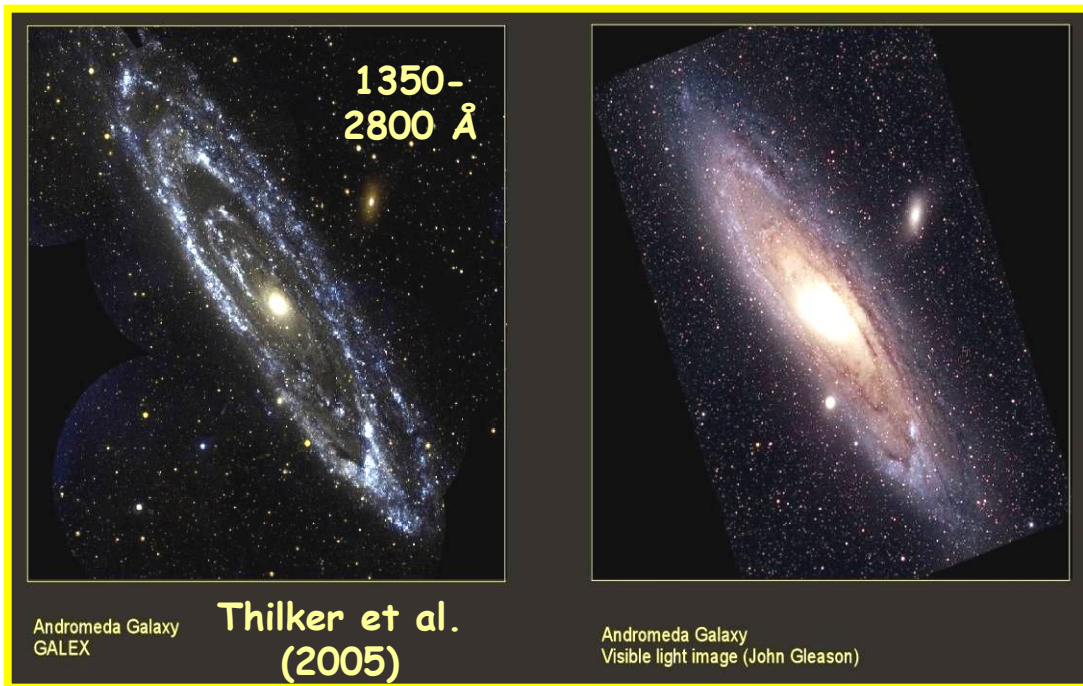
# Luminosity Sampling and Intrinsic Color Fluctuations

$$\Delta\text{mag} = \sigma(L_{\text{tot}})/L_{\text{tot}} = 1/\sqrt{N_{\text{eff}}}$$

$$\sigma(B-V) = [\sigma(B)^2 \pm \sigma(V)^2]^{1/2} = (1/N_{\text{eff}}^B \pm 1/N_{\text{eff}}^V)$$



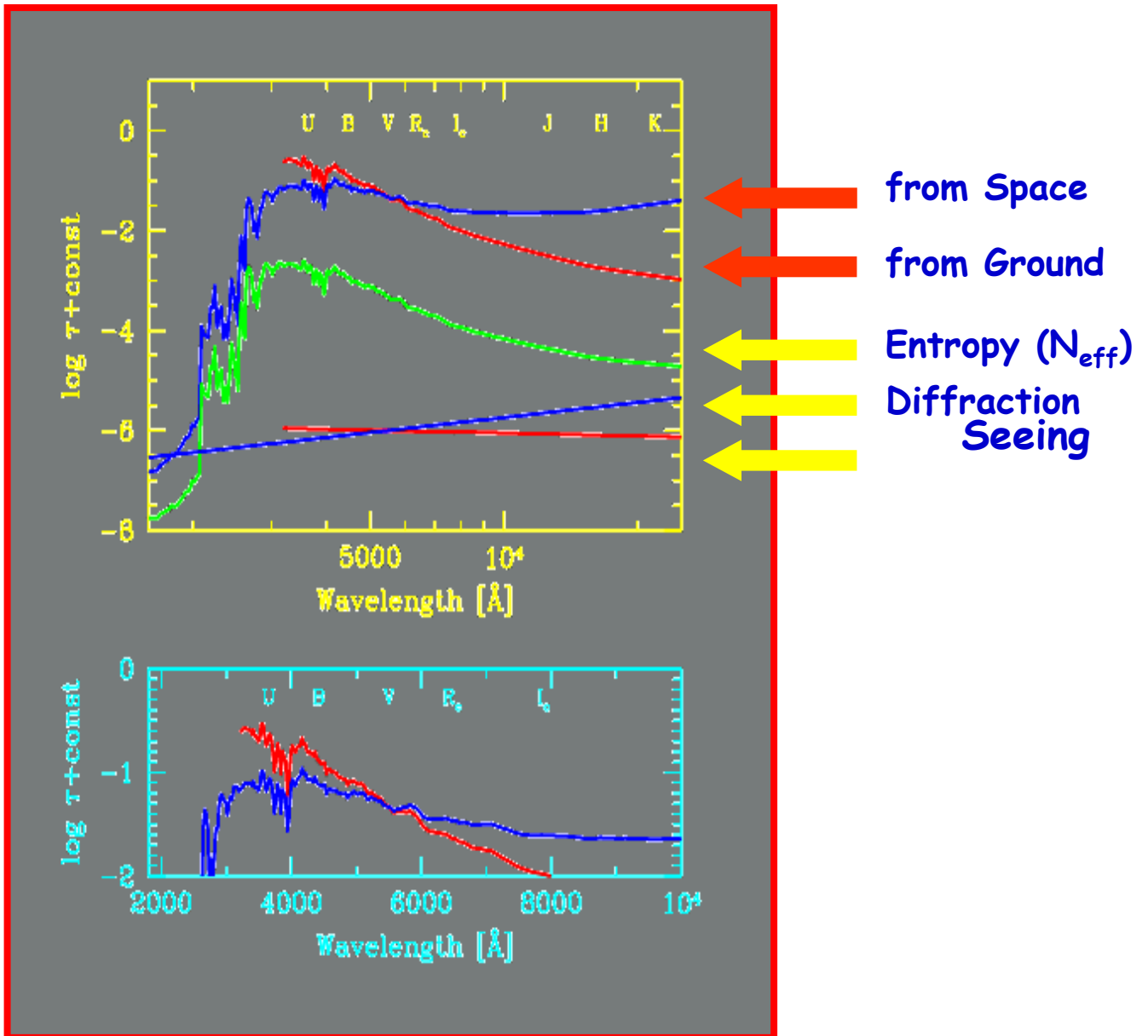
# Crowding & Optical opacity



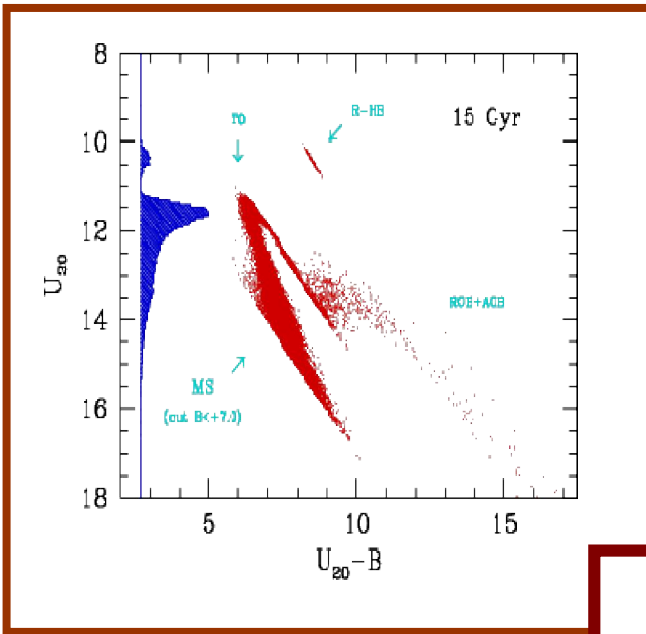
← Seeing

← Diffraction

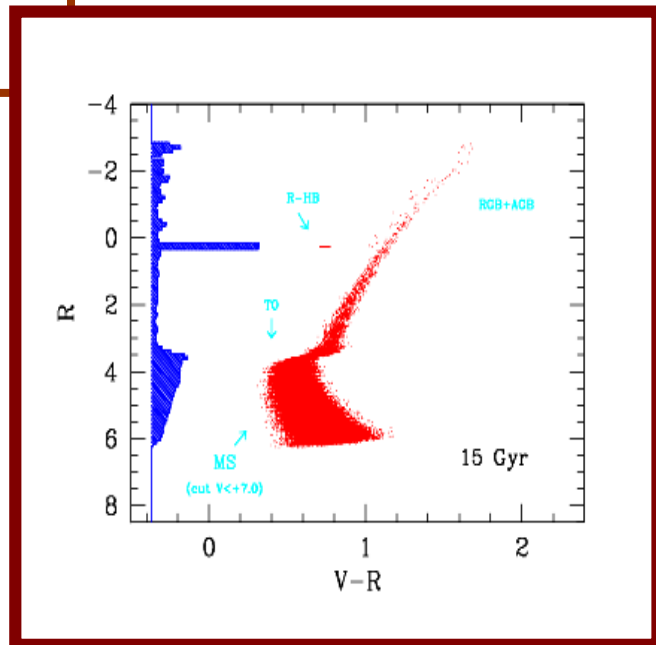
# Crowding & Opacity



# Oligarchy vs. Democracy

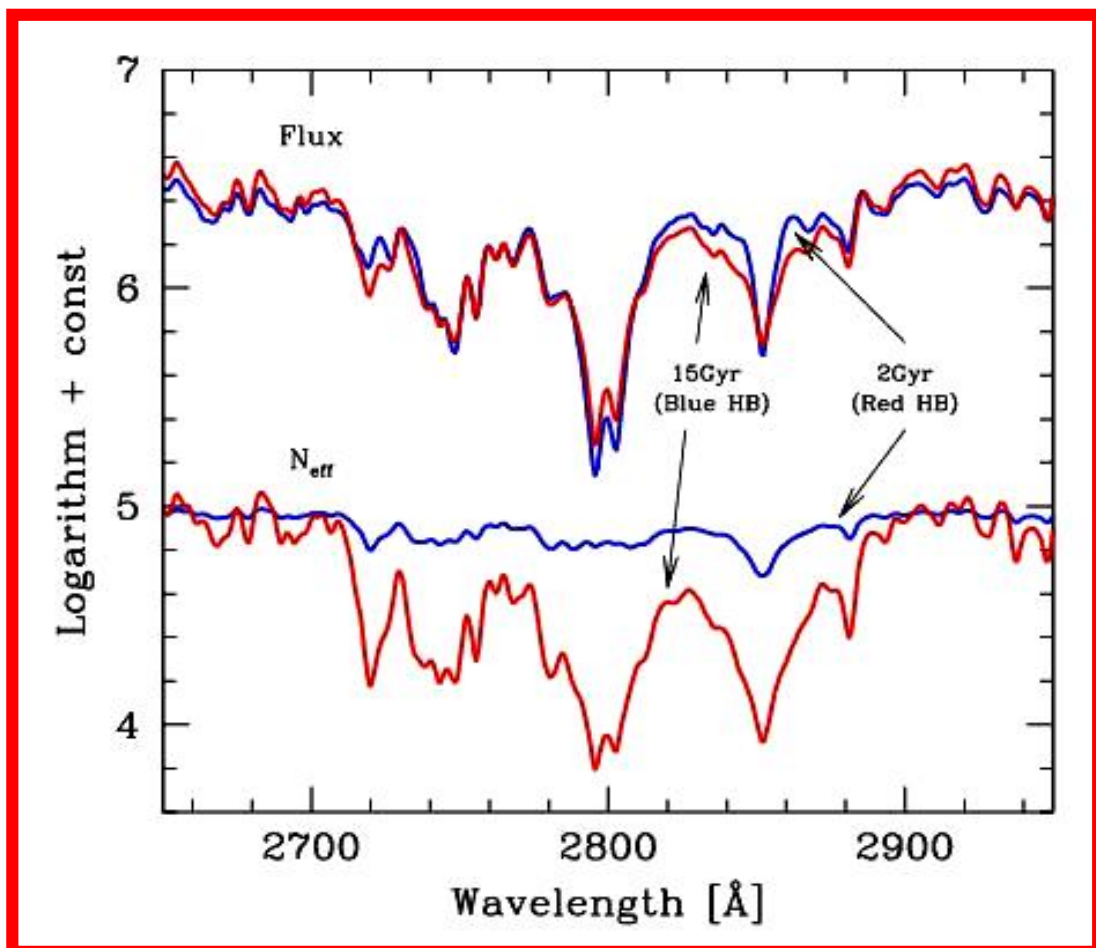
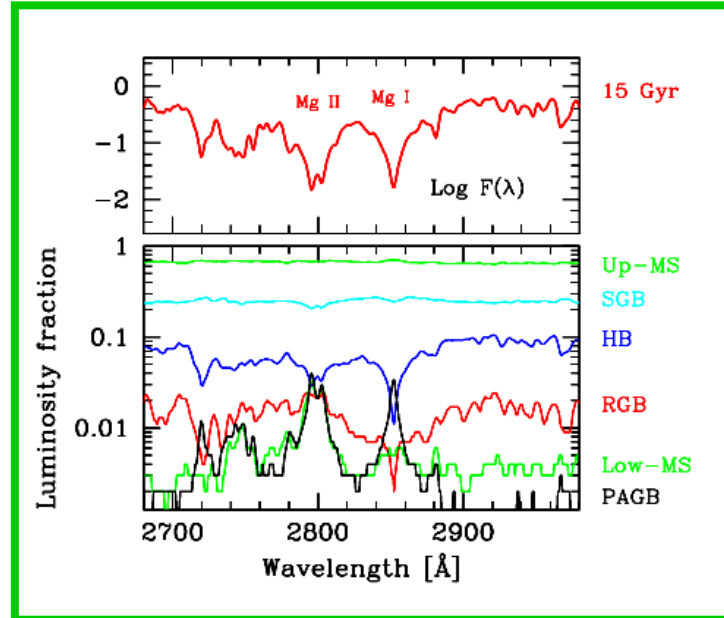


**2000 Angstroms**



**7000 Angstroms**

# Recovering the Age-Metallicity degeneracy



**Articoli consigliati (vedi Webpage):**

<http://www.bo.astro.it/~eps/lezioni/lezioni.html>

- Entropia Fotometrica (Buzzoni)
- Photometric Entropy (Cerviño & Luridiana)
- SBF (Buzzoni)
- SBF (Tonry & Schneider)



# I principi della spettroscopia (Diffrazione & Interferenza)

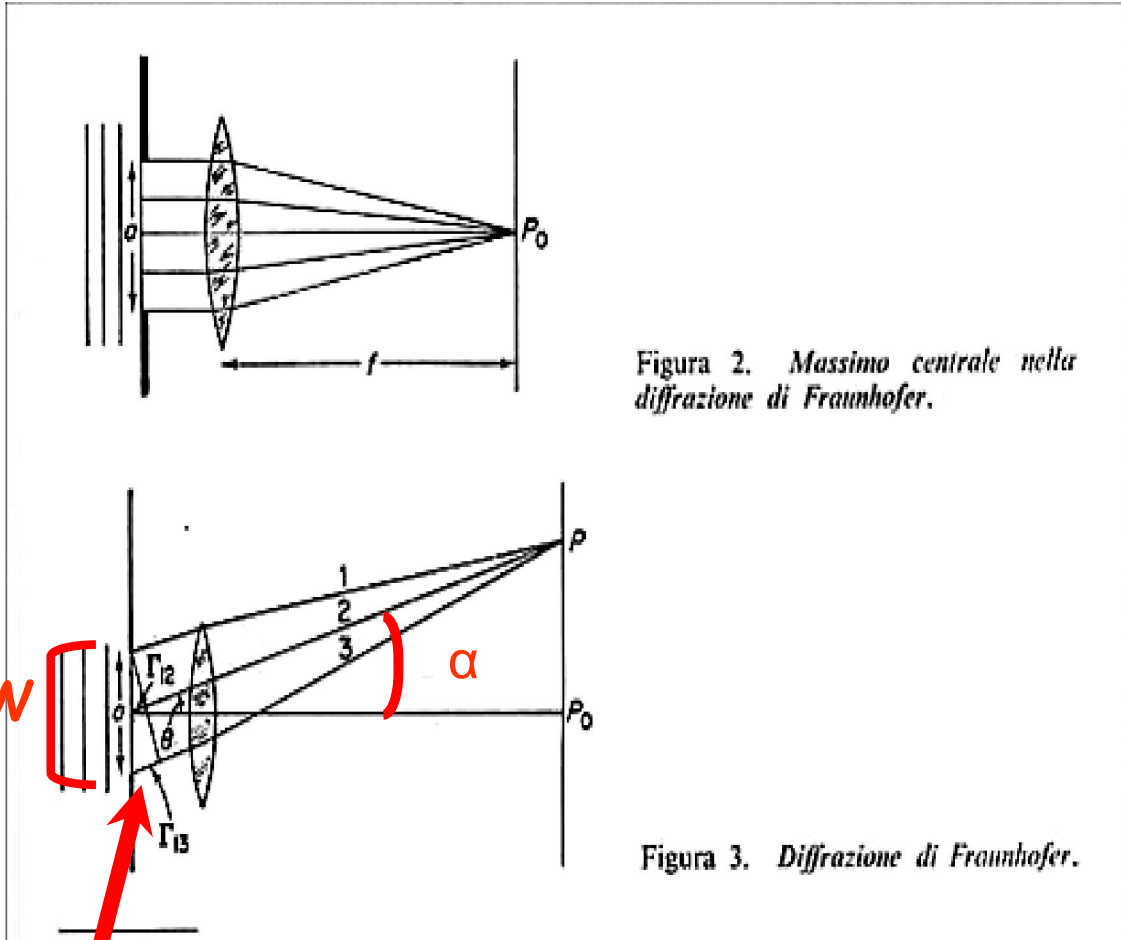


Figura 2. Massimo centrale nella diffrazione di Fraunhofer.

Figura 3. Diffrazione di Fraunhofer.

$$\frac{W}{2} \sin \alpha = \frac{m}{2} \lambda$$



$$\alpha \cong m \frac{\lambda}{W}$$

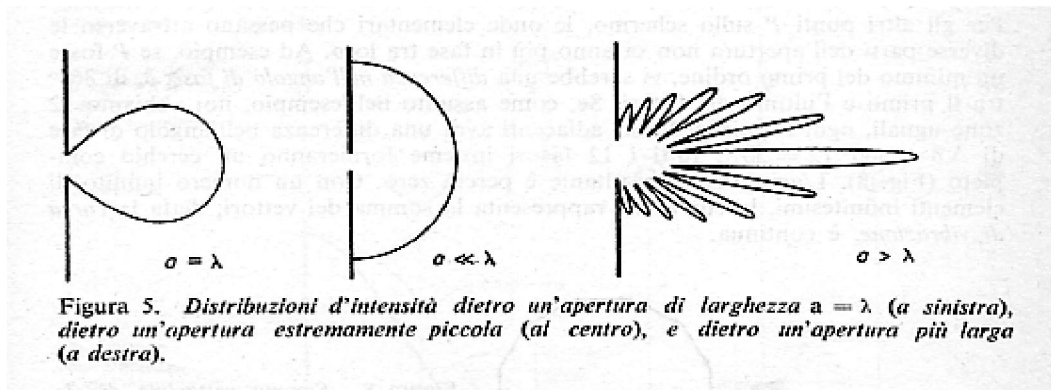
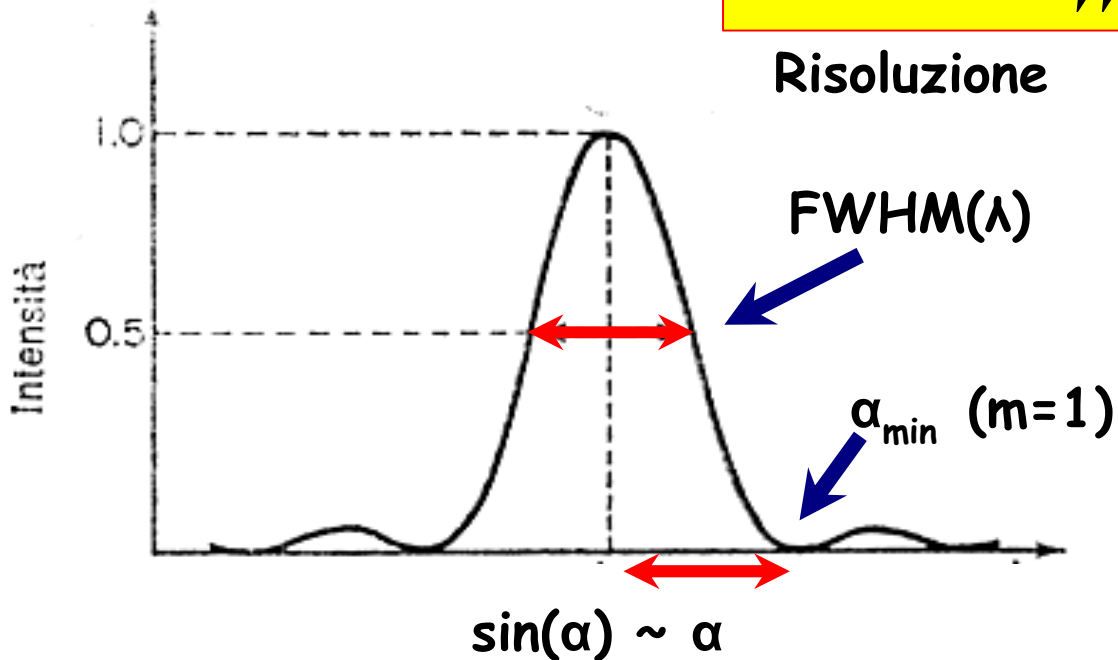


Figura 5. Distribuzioni d'intensità dietro un'apertura di larghezza  $a = \lambda$  (a sinistra), dietro un'apertura estremamente piccola (al centro), e dietro un'apertura più larga (a destra).

# Risoluzione vs. Dispersione

$$\alpha_{\min} \cong m \frac{\lambda}{W}$$

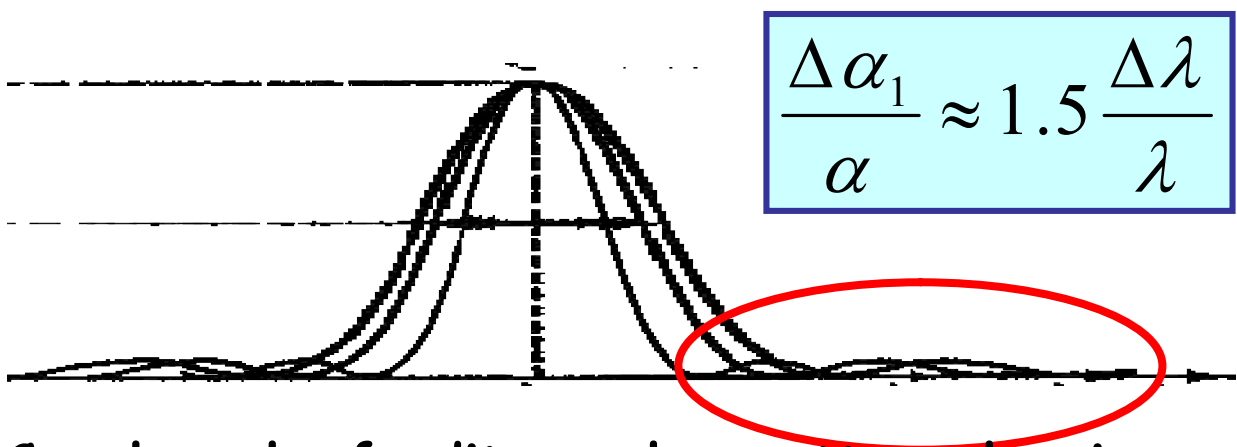
Risoluzione



$$\alpha_{\max 1} \approx 1.5 \frac{\lambda}{W}$$

$$\Delta \alpha_1 \approx \frac{1.5}{W} \Delta \lambda$$

Dispersione



Con la sola fenditura, lo spettro al primo ordine sarebbe totalmente confuso dalla figura di diffrazione all'ordine zero, e quindi inutilizzabile

# Reticoli di diffrazione

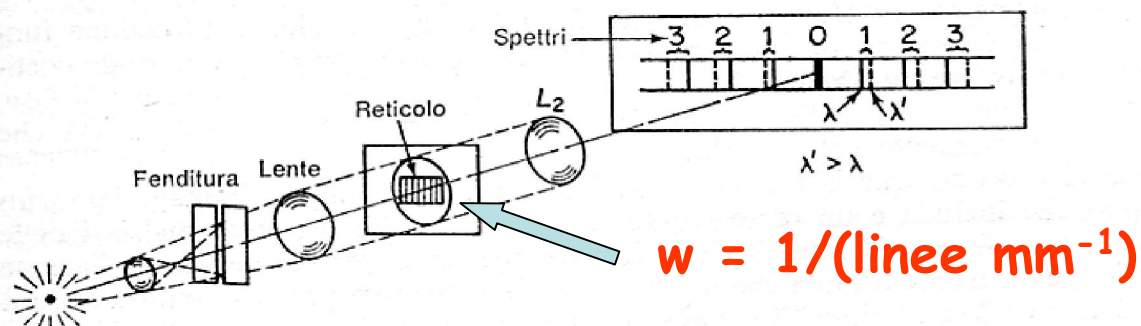


Figura 2. La formazione di una riga spettrale in un reticolo a diffrazione. Viene mostrato lo spettro di una sorgente che emette su due lunghezze d'onda  $\lambda$  e  $\lambda'$ .

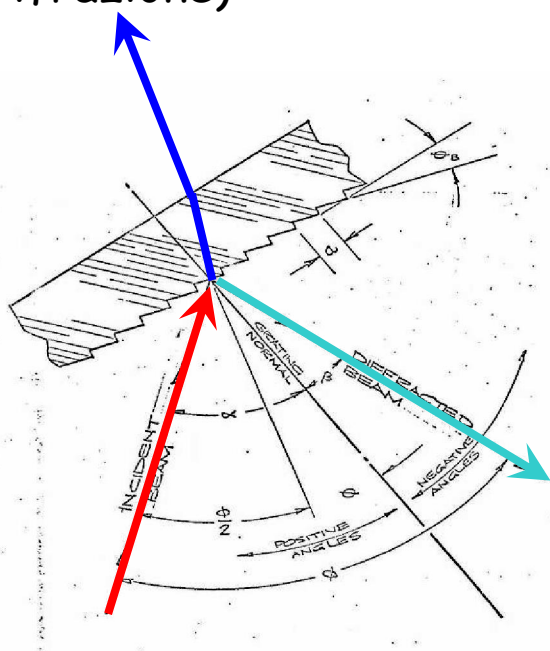
## risoluzione

$$\alpha_{\min} \cong m \frac{\lambda}{W}$$

## dispersione

$$\Delta \alpha_1 \approx \frac{1.5}{w} \Delta \lambda$$

"Grism"  
(per rifrazione)



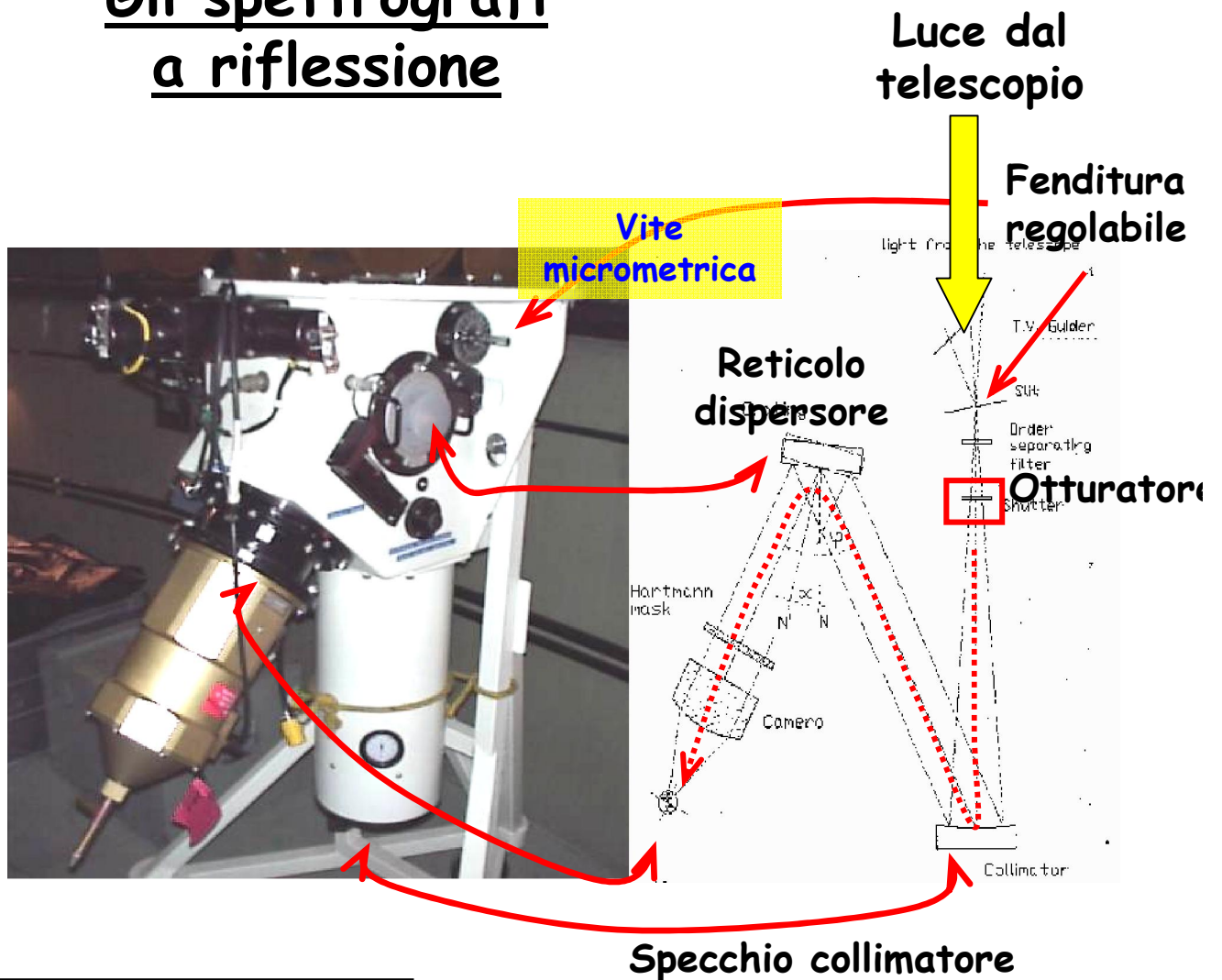
$$\frac{\Delta \alpha}{\alpha} \approx 1.5 \left( \frac{W}{w} \right) \frac{\Delta \lambda}{\lambda}$$

"Grid"  
(per riflessione)

Quindi:

- 1) l'ampiezza della fenditura determina la **RISOLUZIONE**
- 2) La frequenza di linee del grism/grid determina la **DISPERSIONE**

## Gli spettrografi a riflessione

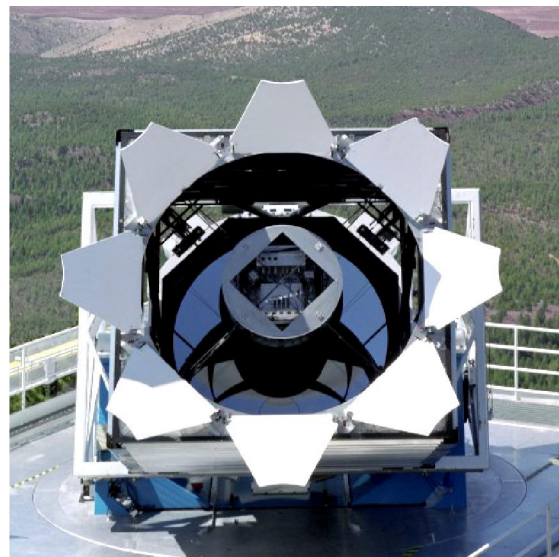


**Böller & Chivens**

# Gli spettrografi a fibre ottiche

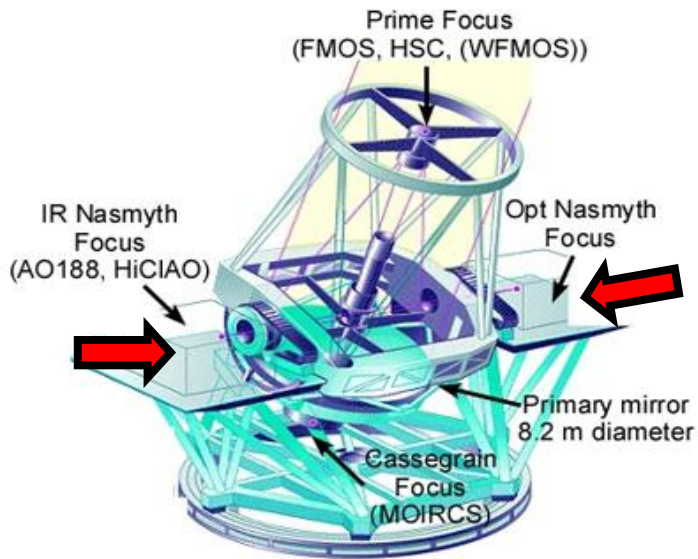


Hydra @KPNO (3.8m) USA



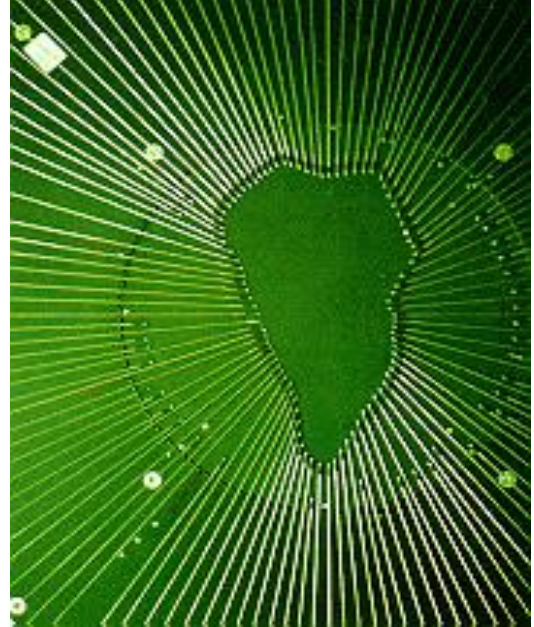
The Sloan Digital Sky Survey's 2.5-meter telescope at Apache Point Observatory, New Mexico

# Spettrografi da "banco"

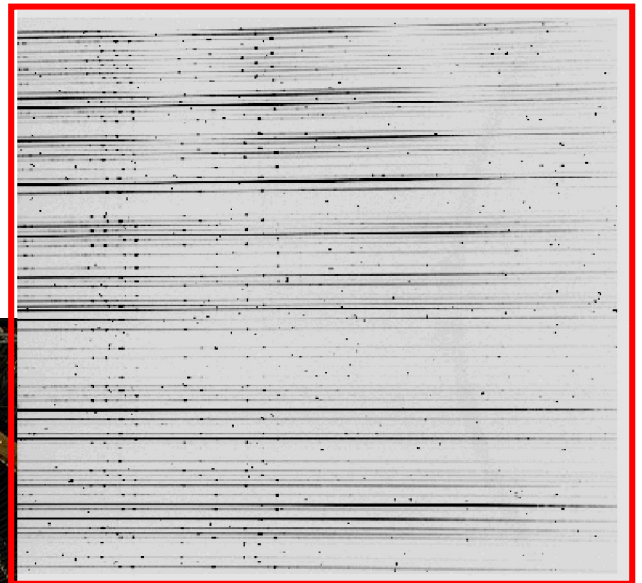
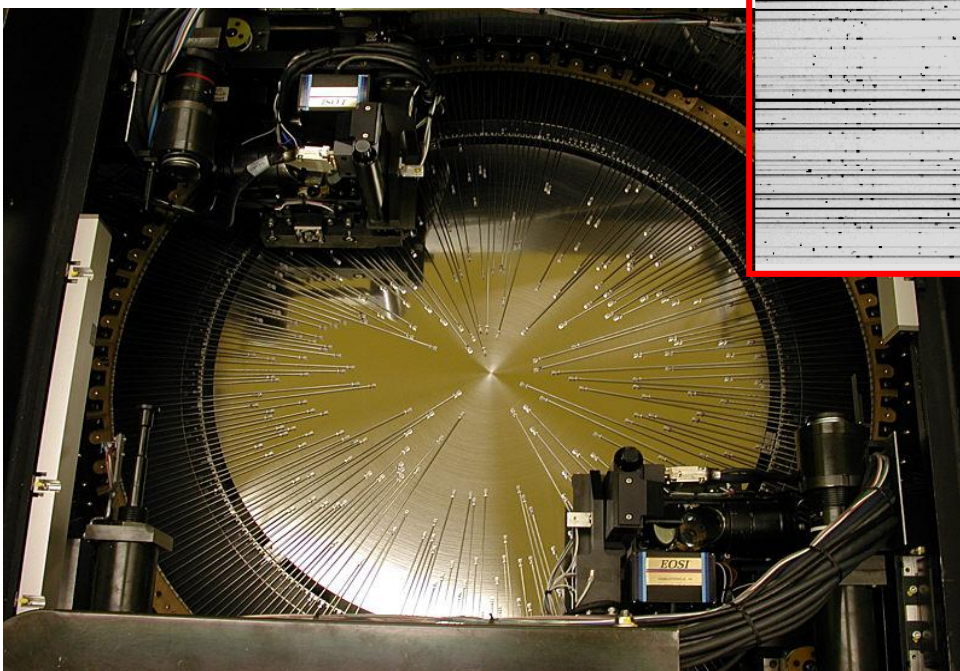


Subaru (8.3m) Japan

Autofib@WHT (4.2m) UK

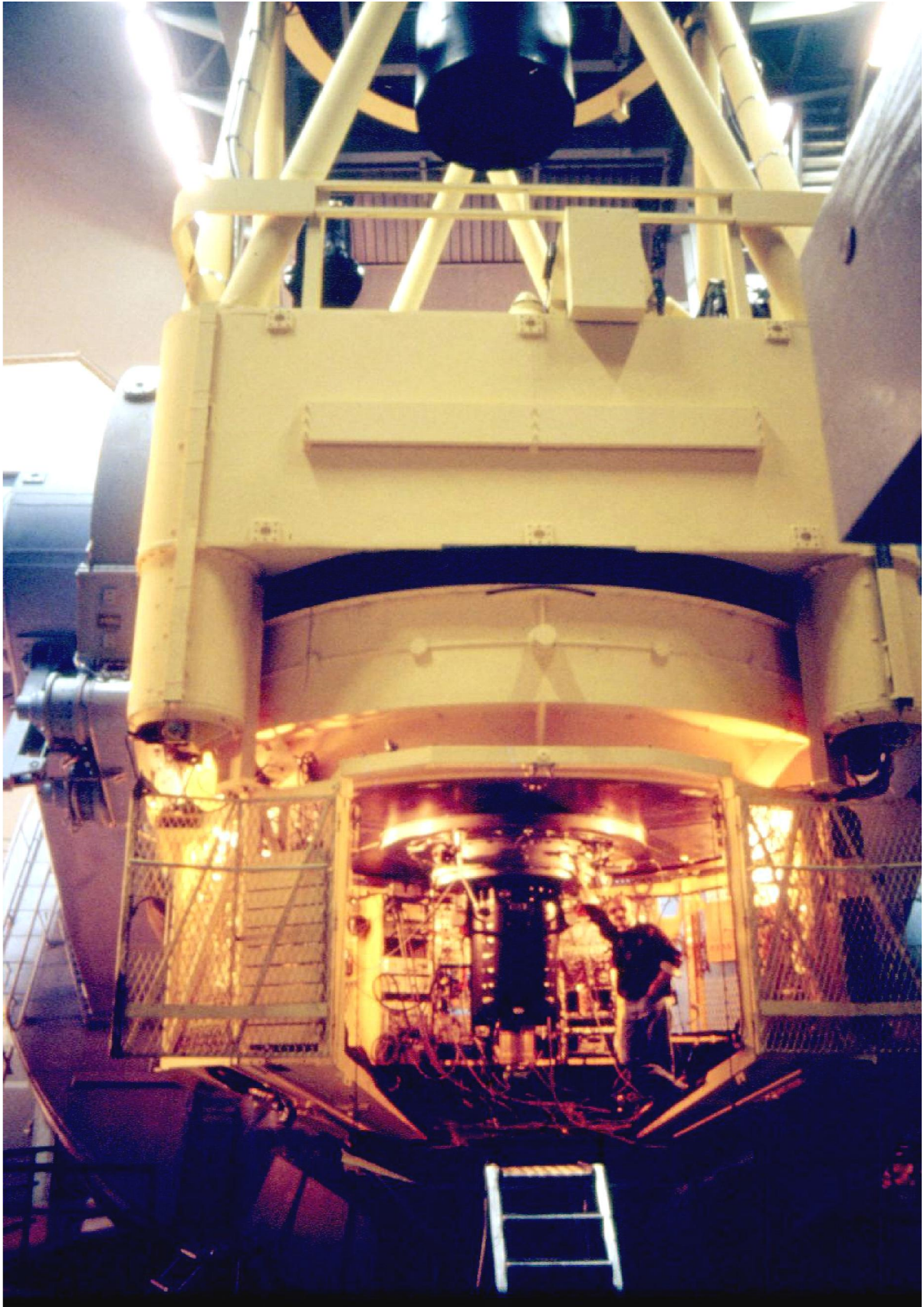


HECTOSPEC@MMT (6.5m)  
Arizona (USA)



Esempio di uscita  
spettrografo a  
fibre

# Le camere FOSC



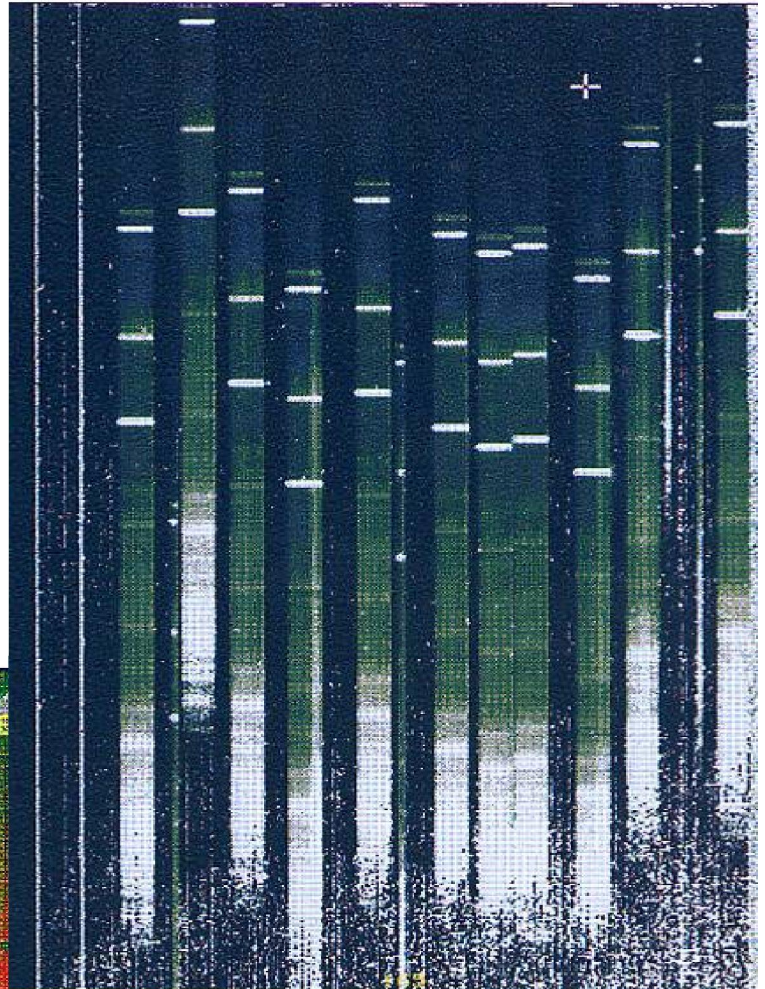
# Spettroscopia "MOS" (multiobject)

Spectral resolution

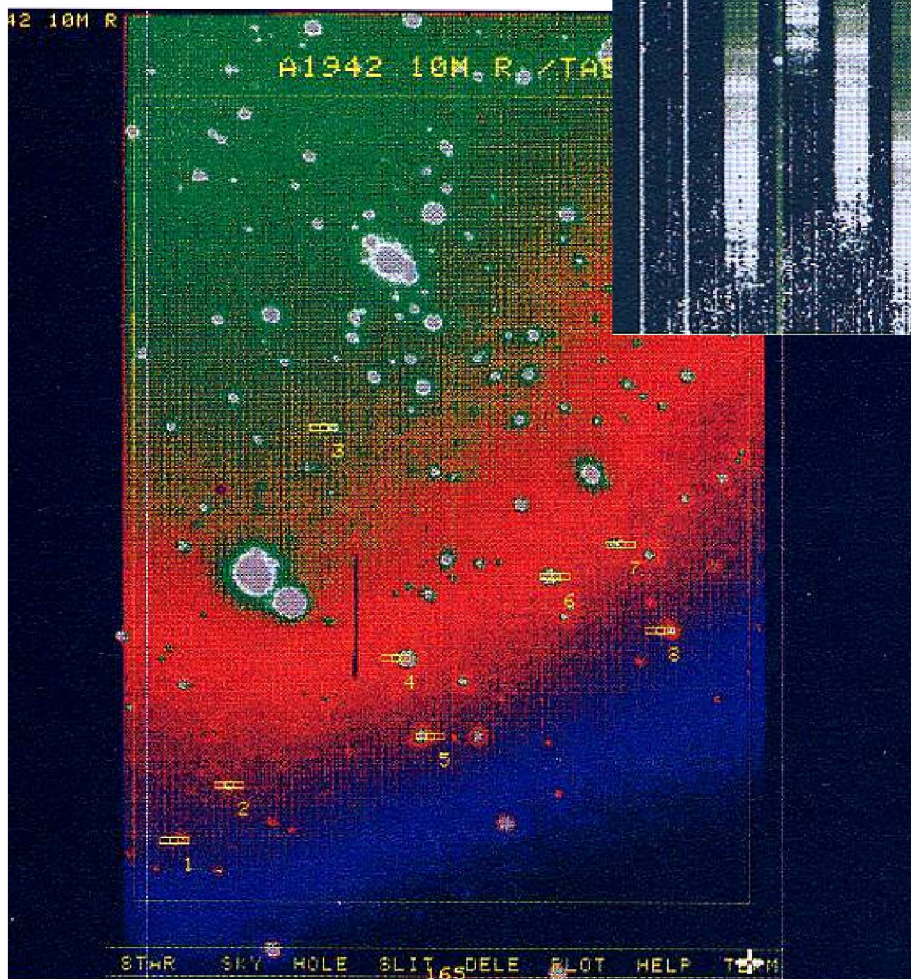
$$\text{FWHM} \sim 2.5 \div 10 \text{ \AA}$$

Resolving power

$$R = \frac{\lambda}{\Delta\lambda} = 500 \Leftrightarrow 2000$$



Esempio di uscita  
spettrografo MOS  
FOSC

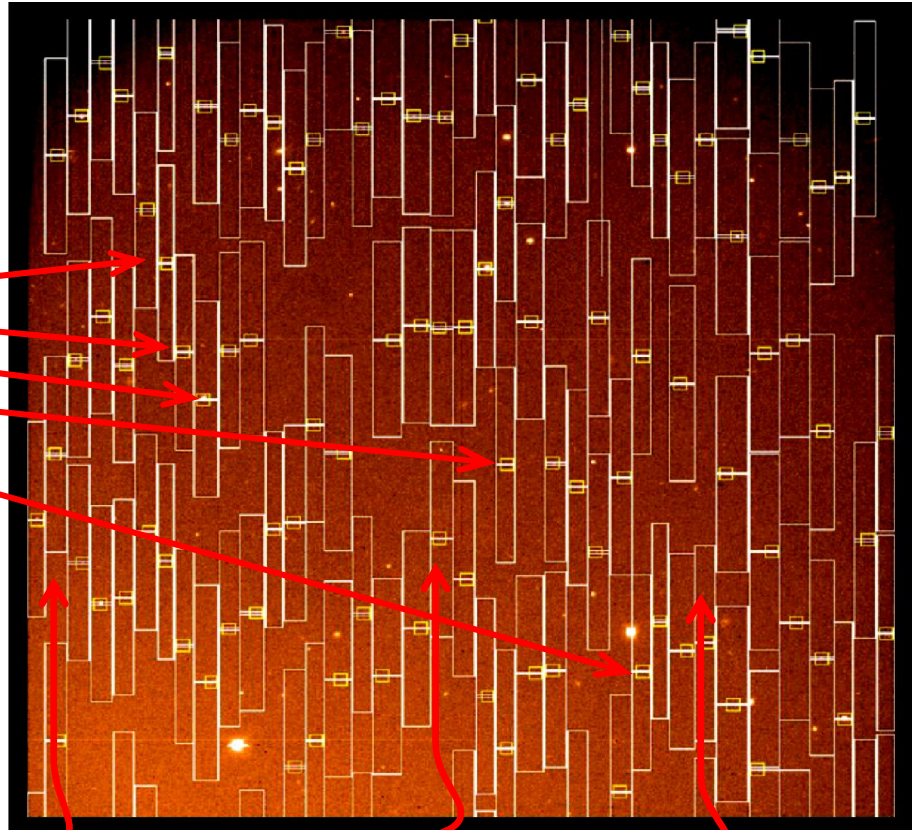


Pre-imaging  
(per vedere gli  
oggetti da puntare)



# VIMOS@VLT (ESO) 8.2m, Chile

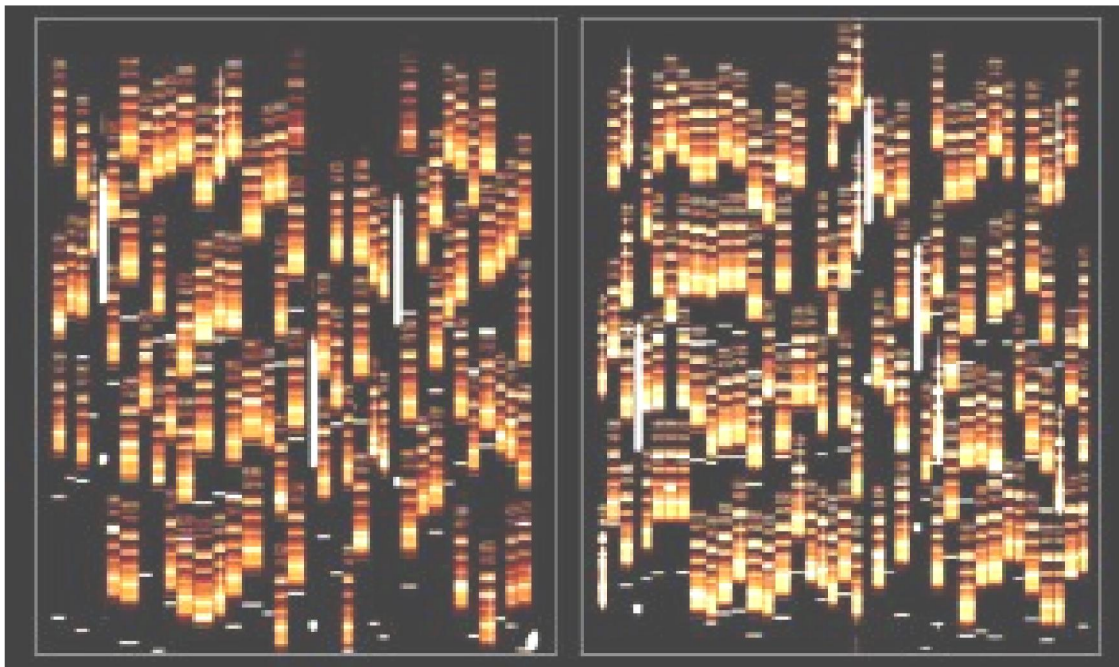
Fenditure posizionabili in y  
etc....



VIMOS Mask Design on Pre Image

ESO PR Photo 09/02 (13 March 2002)

© European Southern Observatory




## Legge di Wien :

$$\lambda_{\max} T \propto \text{const}$$

$$\frac{\lambda_{\max}}{5500} = \frac{5780}{T_K} \longrightarrow \lambda_{\max} \approx \frac{310^7}{T_K} [\text{\AA}]$$

$T_K$	$\lambda_{\max}$	[eV]
100,000	300 \AA	raggi $\gamma$
10,000	3000 \AA	UV
6,000	5000 \AA	Ottico
3,000	10,000 \AA	MIR
1,000	30 $\mu\text{m}$ \AA	FIR



## Equipartizione dell'energia :

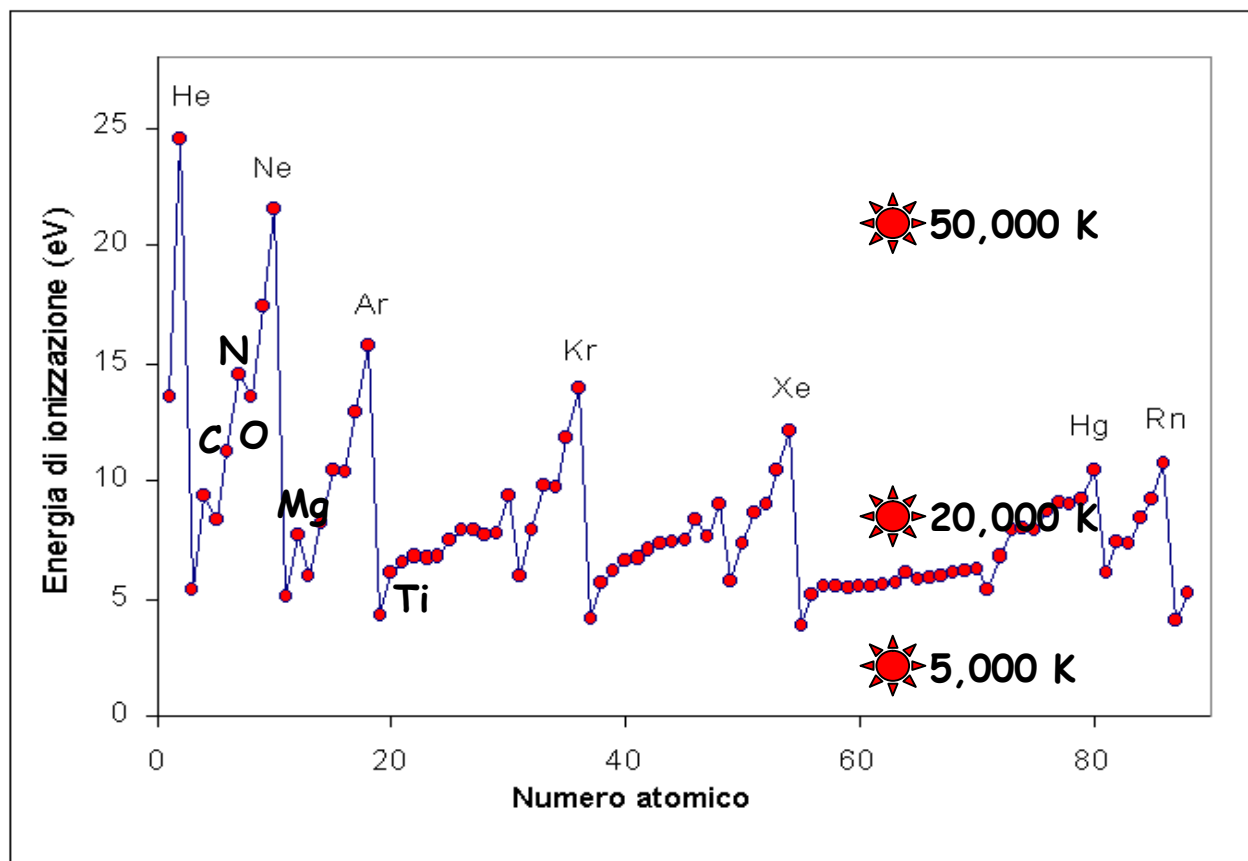
$$E \approx 3kT = 4.2 \cdot 10^{-16} T_K \approx h\nu = \frac{hc}{\lambda}$$

$$\langle \lambda \rangle \approx \frac{hc}{kT} = \frac{6.6 \cdot 10^{-27} \times 3 \cdot 10^{10}}{4.2 \cdot 10^{-16} T_K (10^{-8})} = \frac{4.7 \cdot 10^7}{T_K} [\text{\AA}]$$

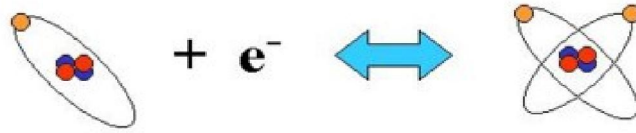
$$T_K \approx 2400 E_{eV}$$

Il potenziale di ionizzazione dell'H e' di 13.6eV. Quindi sono necessarie temperature superiori a circa 35,000 K

Gruppo	1	2	13	14	15	16	17	18
Periodo								
1	H 13.59844							He 24.58741
2	Li 5.39172	Be 9.32263	B 8.29803	C 11.26030	N 14.53414	O 13.61806	F 17.42282	Ne 21.56454
3	Na 5.13908	Mg 7.64624	Al 5.98577	Si 8.15169	P 10.48669	S 10.36001	Cl 12.96764	Ar 15.759
4	K 4.34066	Ca 6.11316	Ga 5.99930	Ge 7.899	As 9.8152	Se 9.75238	Br 11.81381	Kr 13.99961
5	Rb 4.17713	Sr 5.69484	In 5.78636	Sn 7.34381	Sb 8.64	Te 9.0096	I 10.45126	Xe 12.12987
6	Cs 3.89390	Ba 5.21170	Tl 6.10829	Pb 7.4167	Bi 7.2855	Po 8.41671	At 9.2	Rn 10.74850
7	Fr 4.0712	Ra 5.27892						



# Popolazioni ionizzate



$$\log \frac{n_{r+1} P_e}{n_r} = -E_i \frac{5040}{T} + 2.5 \log(T) - 6.48 + \log \frac{2u_{r+1}}{u_r}$$

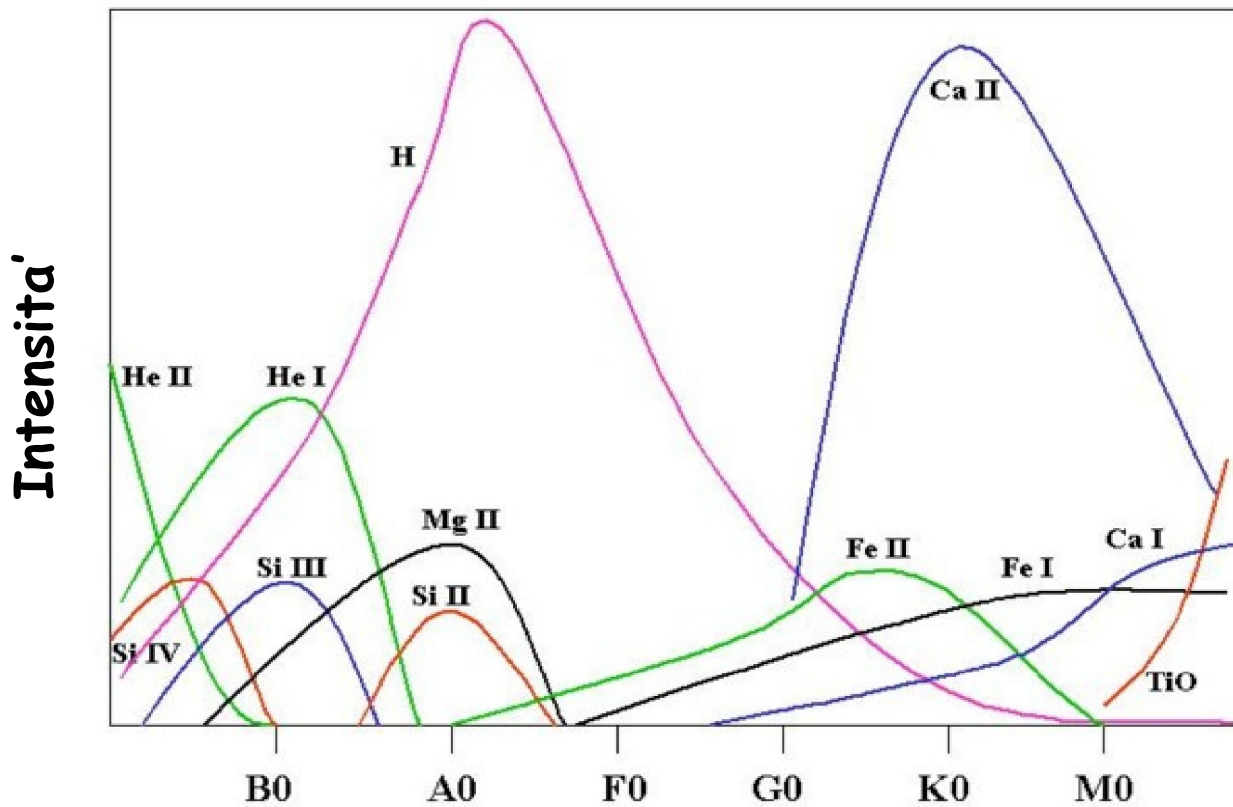
where:

$$u_r = g_0 + \sum_i g_i \cdot e^{-\frac{E_i}{kT}}$$

**Equazione di Saha**

$E_i$  in eV

$P_e$  in atm

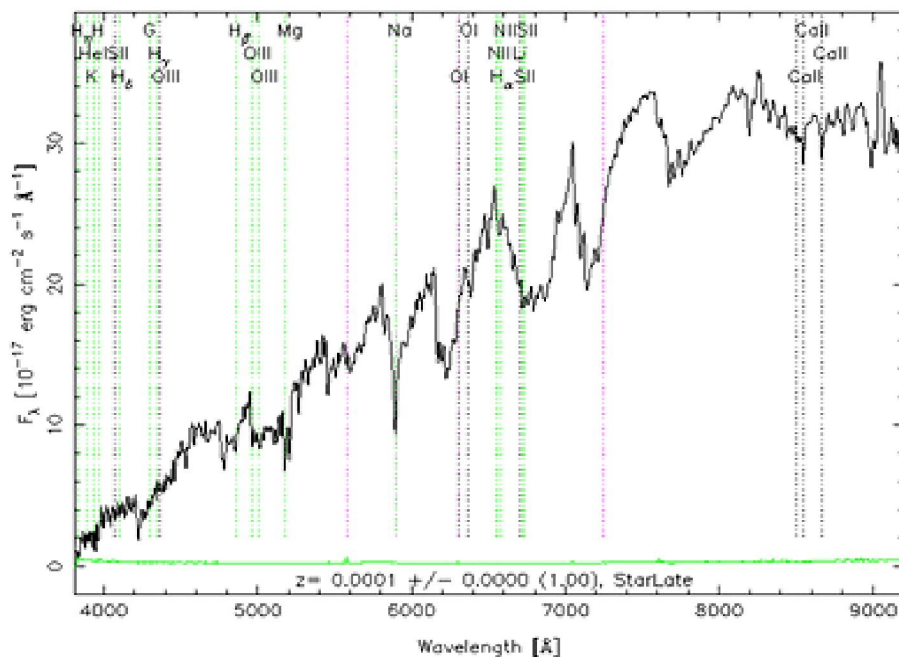


# Le molecole

## Aspetti generali

- La meccanica quantistica è generalmente in grado di prevedere le proprietà delle molecole (configurazione d'equilibrio, energia di legame, spettri)
- I calcoli per fare queste previsioni sono molto complicati (“quantum chemistry”)
- Le regole di selezione sono meno (= più transizioni consentite) che negli atomi
- Gli **spettri** risultanti sono generalmente **più complicati** che quelli degli atomi
- Si distinguono spettroscopie **vibrazionali/rotovibrazionali** (IR e Raman) ed **elettroniche** (assorbimento visibile/UV e fluorescenza)

RA=27.66583, DEC=-1.13947, MJD=51793, Plate= 402, Fiber=204



# Tipi di vibrazione

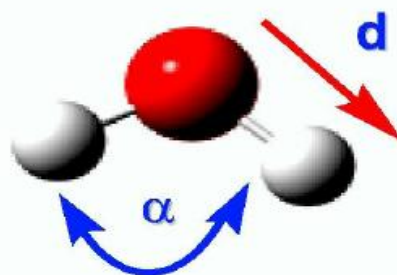
- Legami chimici differenti hanno energie di legame e frequenze di vibrazione differenti e abbastanza caratteristiche
- vibrazioni di **stretching** (stiramento): i legami interatomici si allungano e si accorciano
- vibrazioni di **bending** (piegamento): i legami interatomici si piegano gli uni verso gli altri
- Assorbimento di radiazione IR per determinata frequenza (eccitazione risonante dei livelli vibrazionali molecola)
- Nelle transizioni di solito sono coinvolte contemporaneamente vibrazioni e rotazioni della molecola

## Spettroscopia IR

Le radiazioni IR **non** hanno energia sufficiente per eccitare gli elettroni ma possono indurre transizioni tra i livelli **vibrazionali** e tra quelli **rotazionali** delle molecole

Spettroscopia di assorbimento: radiazioni IR inducono oscillazioni delle:

- distanze ( $d$  – stretching) e negli
- angoli di legame ( $\alpha$  – bending)
- arrangiamento della molecola nello spazio (rotazioni)

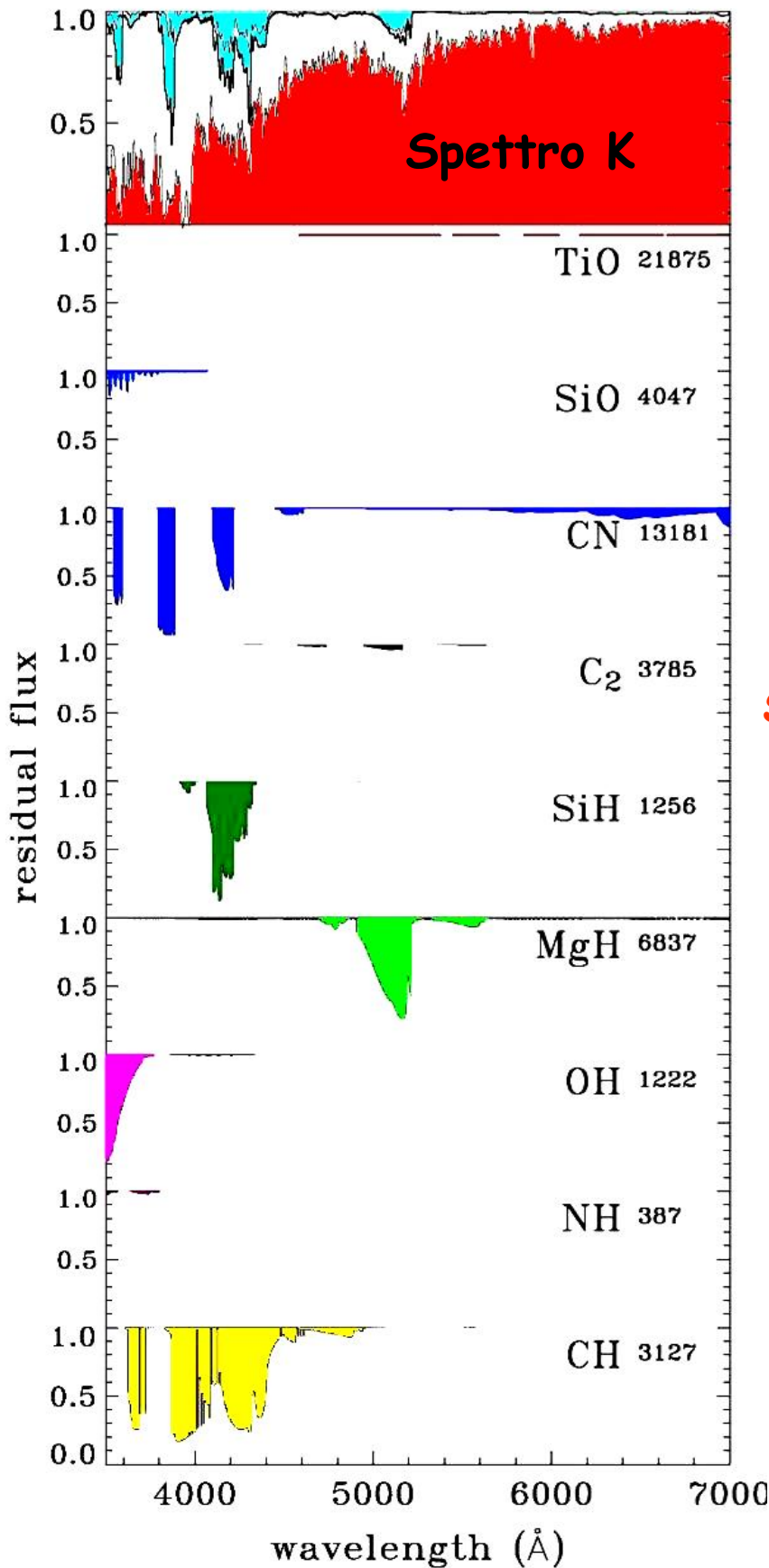


# Molecole

	Molecola	$I_1$ (eV)
<b>Molecole diatomiche omonucleari</b>		
<p>Per le molecole diatomiche omonucleari si nota che i valori delle <math>I_1</math> ricordano quelle dei rispettivi atomi. Si riconosce però nelle molecole <math>H_2</math> e <math>N_2</math> significativi aumenti, meno marcati sono gli aumenti per <math>P_2</math> e <math>C_2</math>. Mentre per <math>O_2</math> e per le molecole degli alogeni il valore dell'energia di ionizzazione è minore rispetto a quello dei loro atomi.</p>	$H_2$	15.42593
	$O_2$	12.0697
	$N_2$	15.581
	$F_2$	15.697
	$Cl_2$	11.481
	$Br_2$	10.517
	$I_2$	9.3074
	$C_2$	11.4
	$P_2$	10.53
	<b>Idruri</b>	
<p>Per le molecole che per convenienza sono state qui tutte classificate come idruri, si osservano somiglianze dei valori con quelli degli atomi legati all'idrogeno, questo è vero in particolare per l'acqua e il solfuro d'idrogeno. Spiccano però i valori dell'ammoniaca e della fosfina che paiono <i>stranamente</i> bassi. Anche per gli alogenuri le energie di ionizzazione sono inferiori rispetto a quelle dei loro atomi. Vi è invece significativo aumento per il metano, il silano e notevole per il borano.</p>	$H_2O$	12.621
	$NH_3$	10.070
	$CH_4$	12.61
	$BH_3$	12.026
	$HF$	16.03
	$HCl$	12.744
	$HBr$	11.68
	$HI$	10.386
	$SiH_4$	11.00
	$PH_3$	9.869
	$H_2S$	10.457
<b>Ossidi</b>		
<p>Le energie di ionizzazione di <math>CO</math> e <math>CO_2</math> sono maggiori di quelle di entrambi gli atomi che le compongono. È vero il contrario per gli ossidi dell'azoto, soprattutto per <math>NO</math> e <math>NO_2</math> che presentano valori decisamente bassi. Per gli ossidi dello zolfo si hanno valori intermedi tra quelli degli atomi presenti nella molecola.</p>	$CO$	14.014
	$CO_2$	13.777
	$NO$	9.2642
	$NO_2$	9.586
	$N_2O$	12.889
	$SO_2$	12.349
	$SO_3$	12.80

# Molecole

4000 >  $T_{\text{eff}}$  > 3000 K



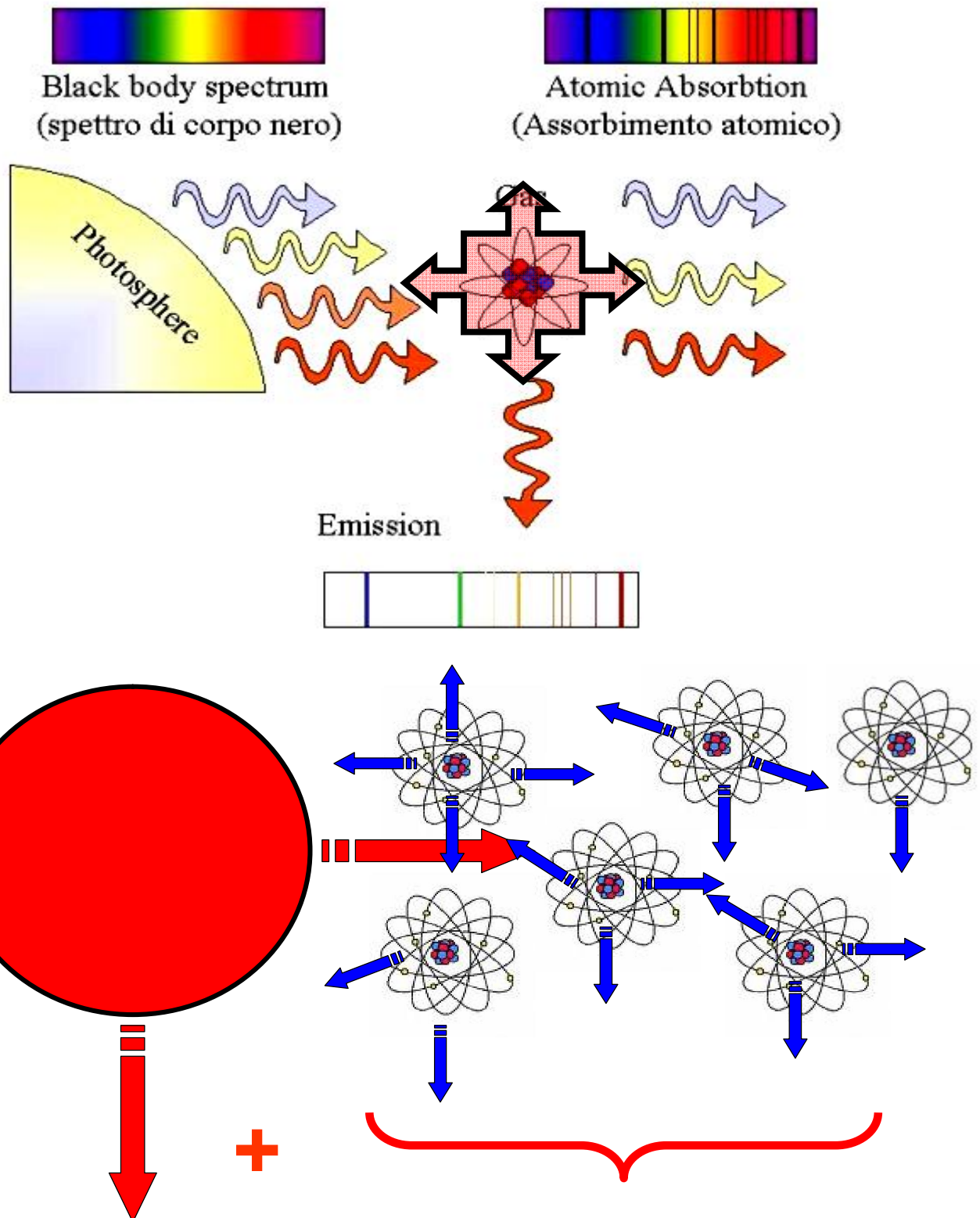
Diatomic molecules  
(i.e. TiO, SiO, CN,  
SiH, MgH, OH, CH...)

3000 K >  $T_{\text{eff}}$

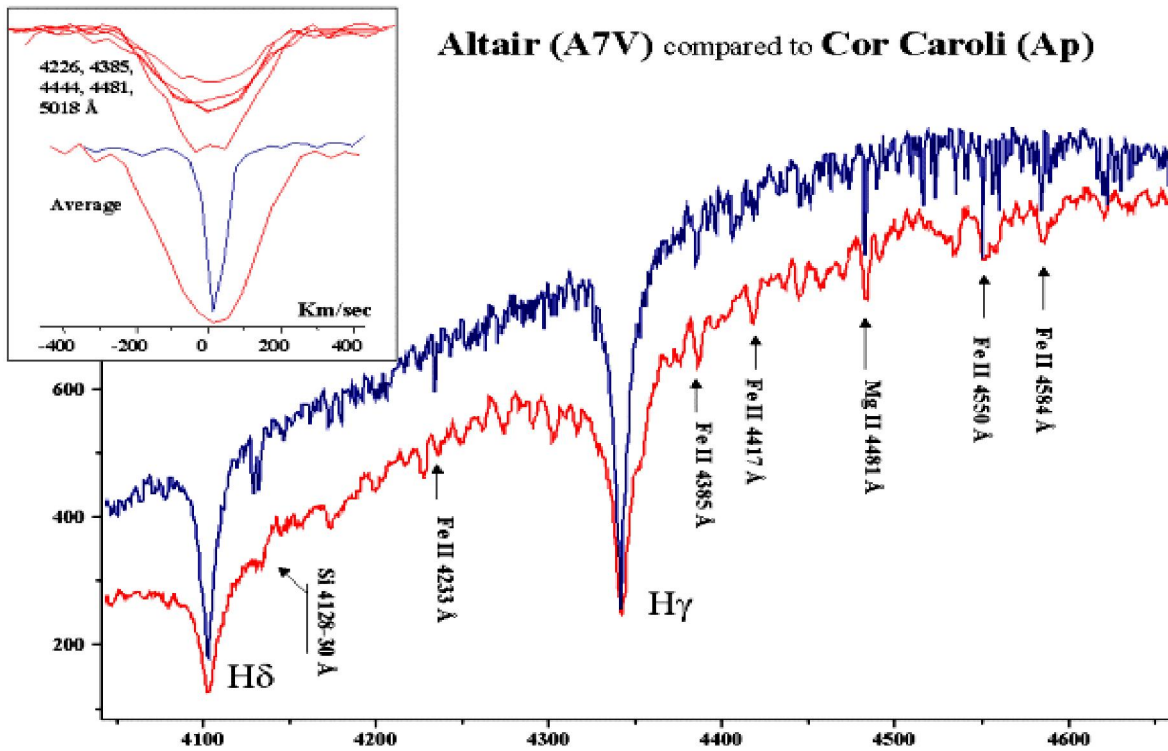
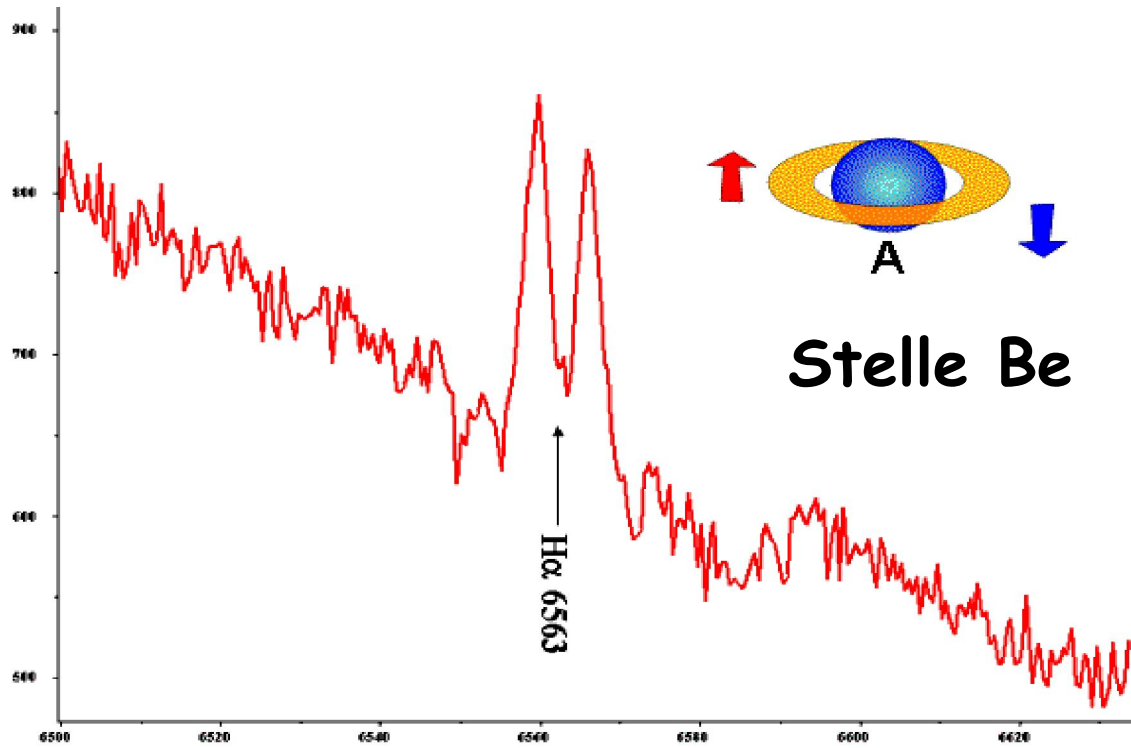
Triatomic molecules  
(Water!)



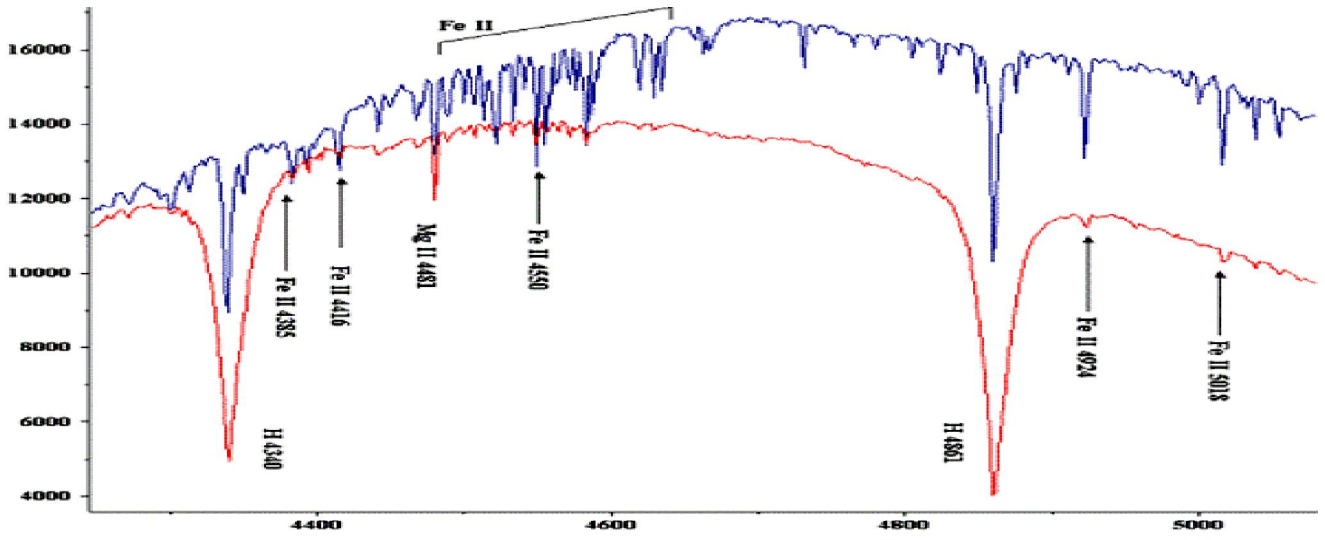
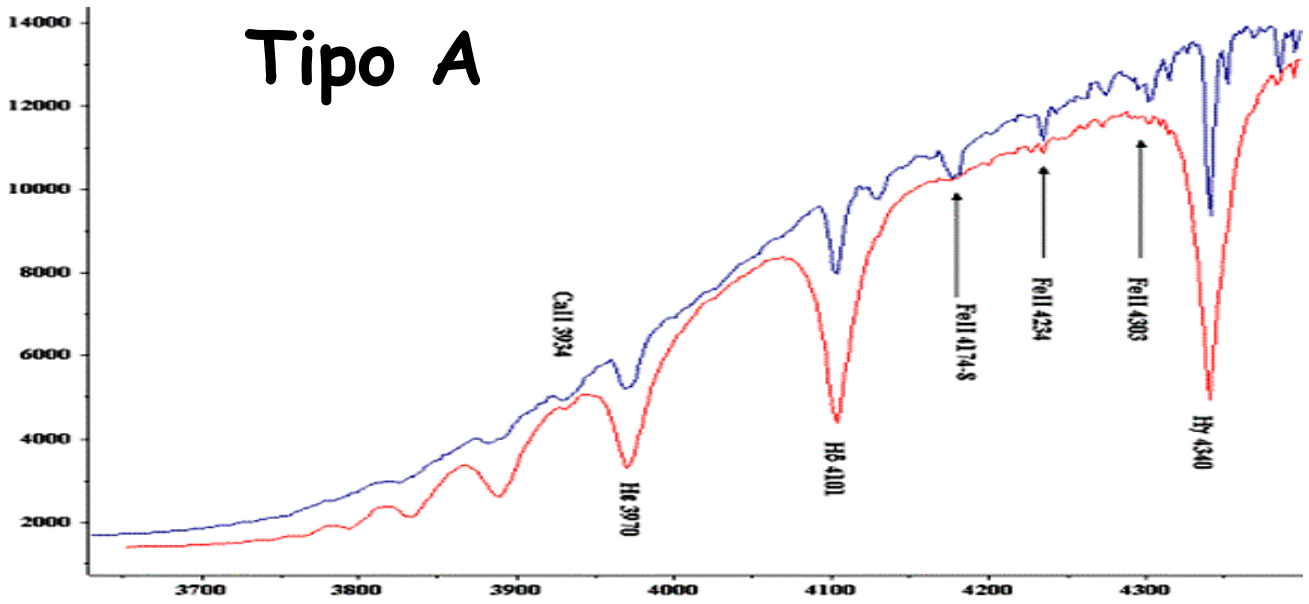
# Emissione & Assorbimento



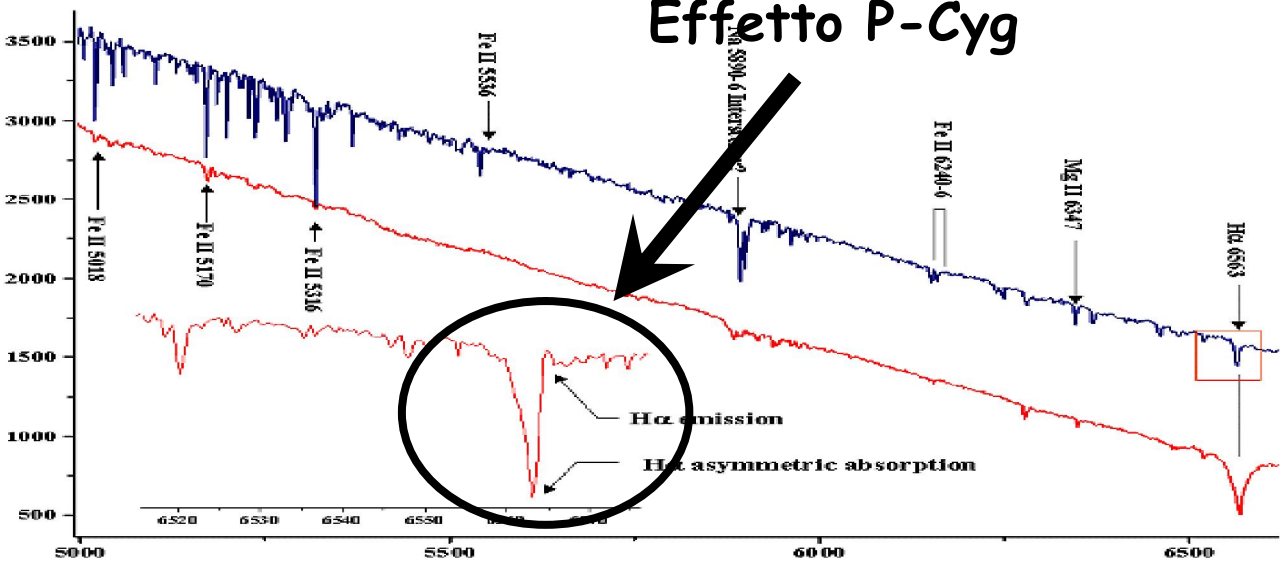
# Effetti della rotazione



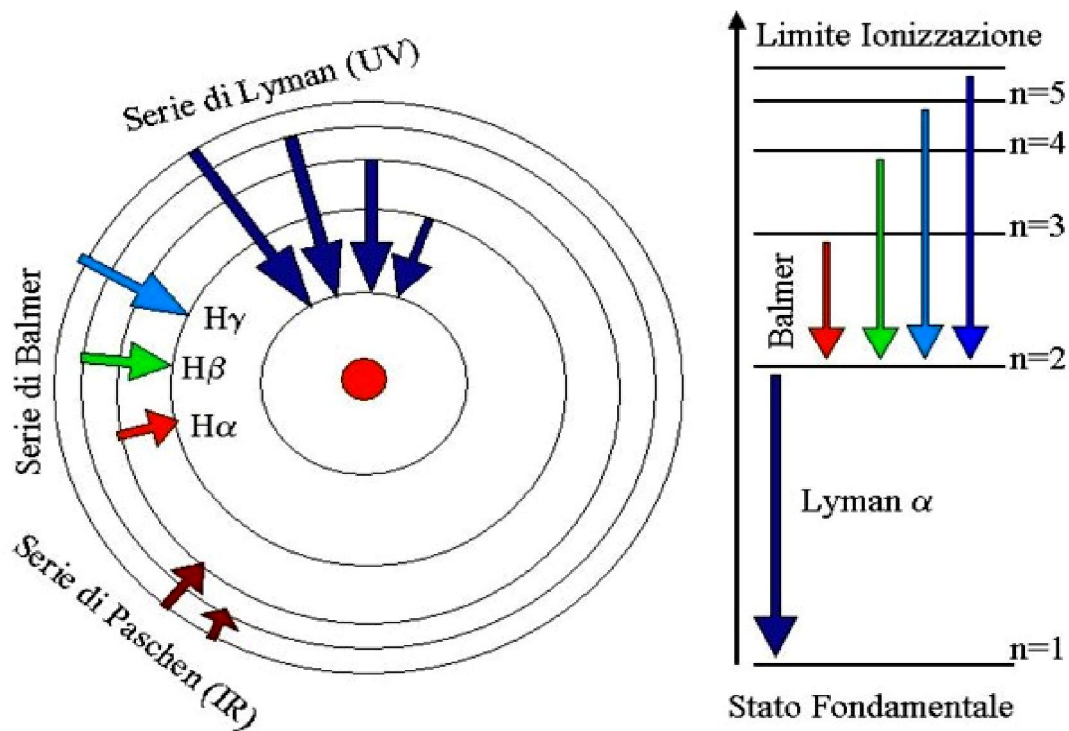
# Tipo A



# Effetto P-Cyg

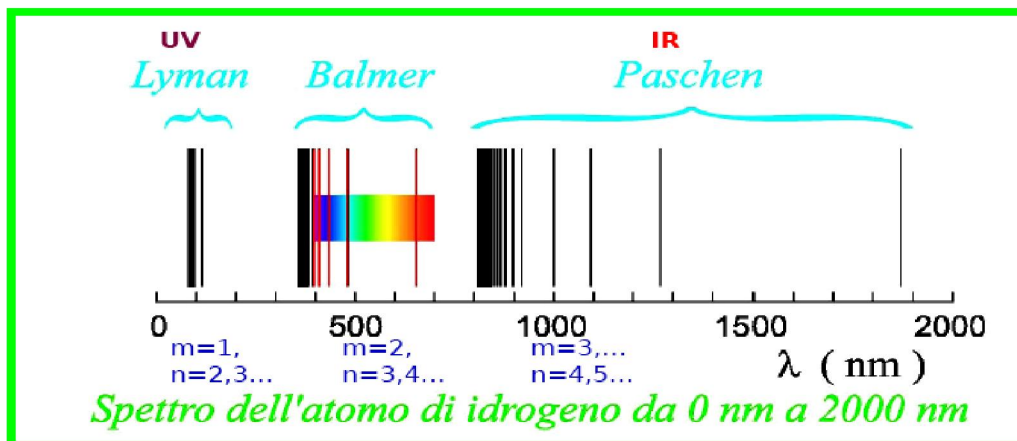


# Le righe dell'Idrogeno



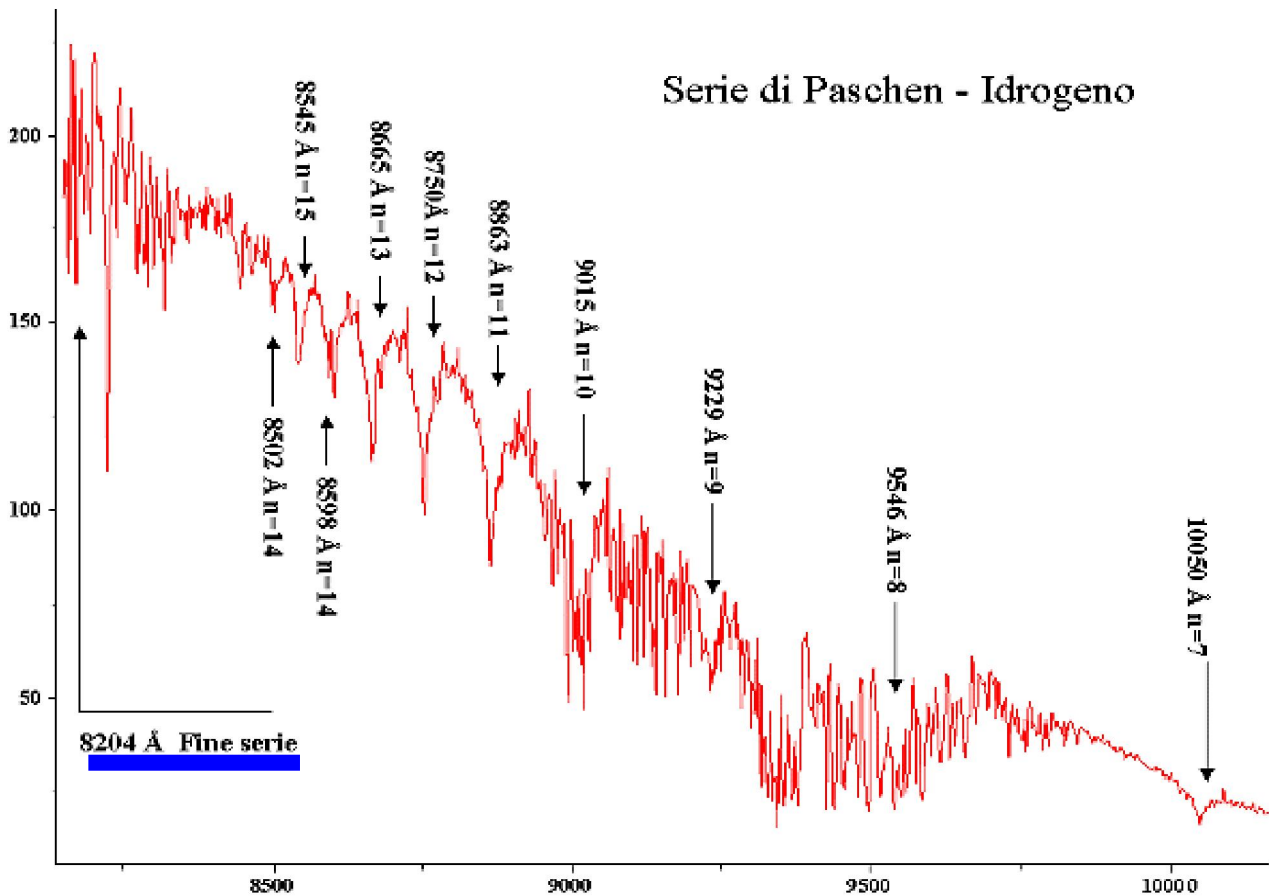
**Righe emesse non solo nel visibile**

$$\frac{1}{\lambda} = R \left( \frac{1}{m^2} - \frac{1}{n^2} \right) \quad m = 1, 2, 3, \dots \quad n = m + 1, \dots$$

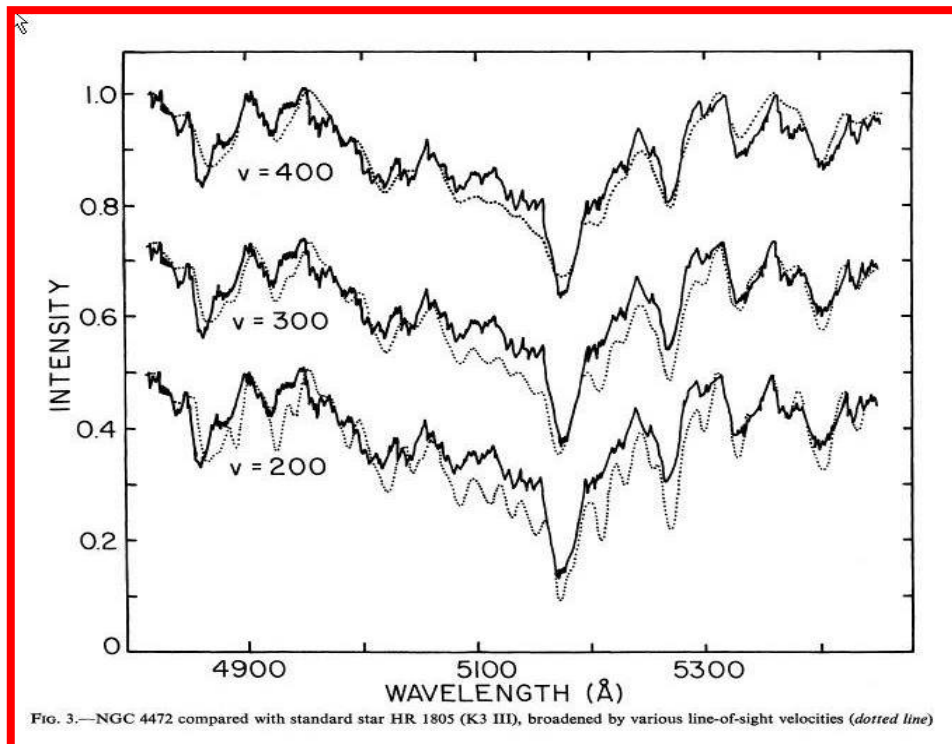
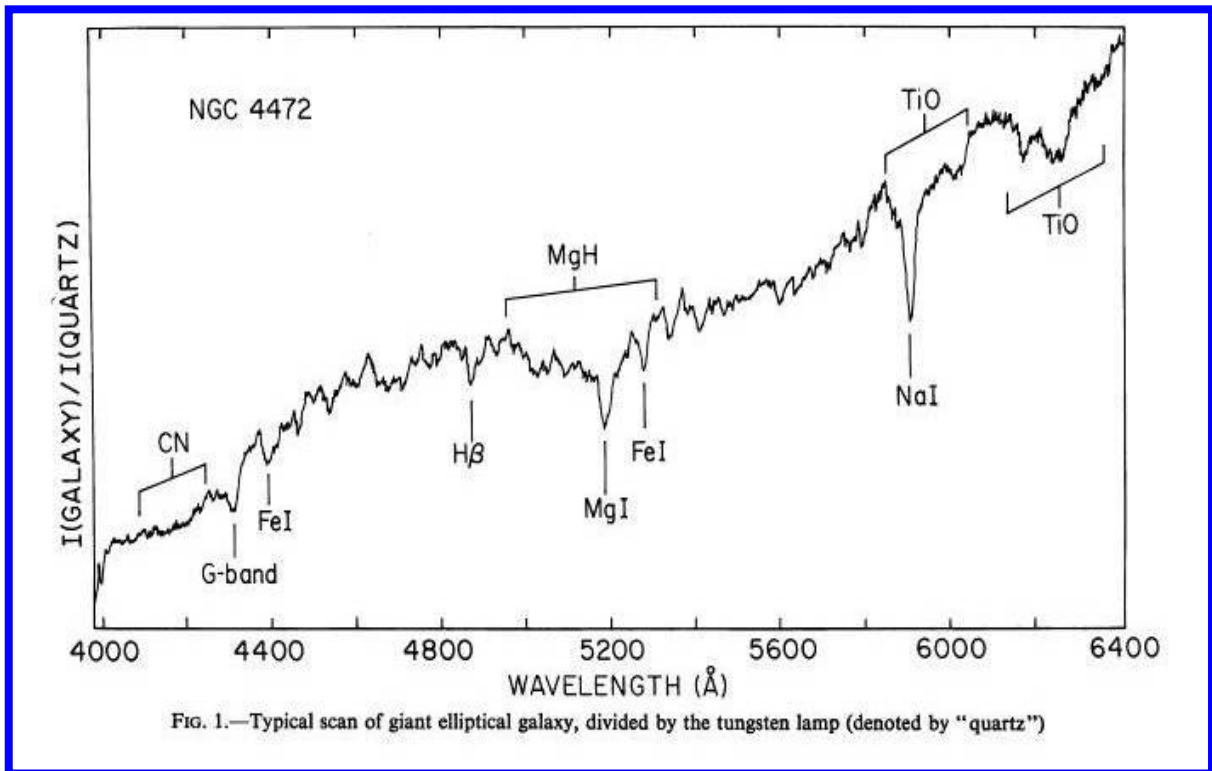


# Le serie di righe

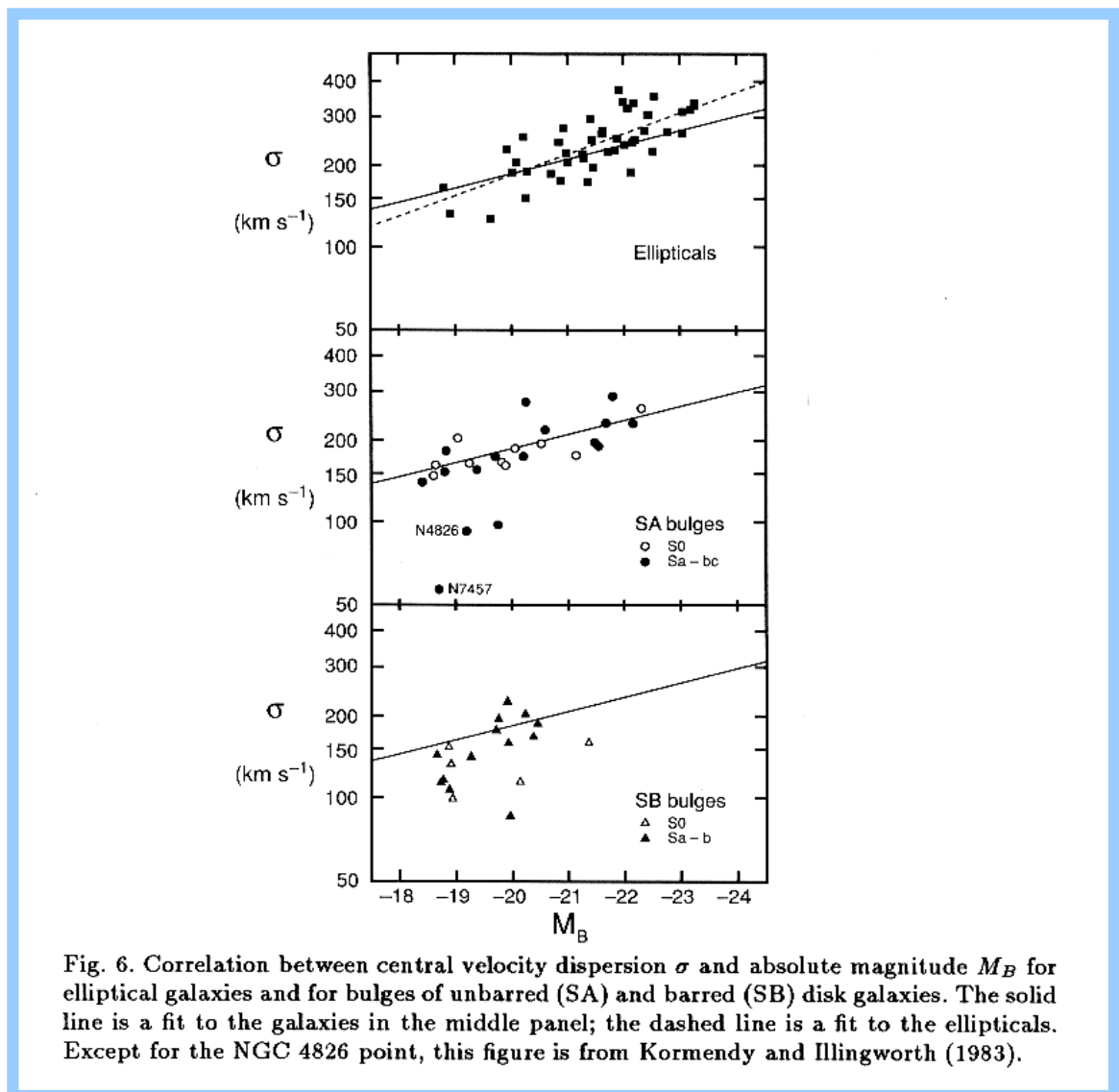
Nome della serie	Anno della scoperta	$m$ nella formula di Rydberg	Limite della serie (nm)	$\lambda_{\max}$ ( $n=m+1$ ) (nm)	Regione spettrale
<b>Lyman</b>	1906-1914	1	<b>91.126</b>	<b>121.5</b>	UV lontano
<b>Balmer</b>	(1885)	2	<b>364.506</b>	<b>656.1</b>	Visibile-UV
<b>Paschen</b>	1908	3	<b>820.14</b>	<b>1874.6</b>	Infrarosso
<b>Brackett</b>	1922	4	<b>1458.03</b>	<b>4050.1</b>	Infrarosso
<b>Pfund</b>	1924	5	<b>2278.17</b>	<b>7455.8</b>	Infrarosso
<b>Humphreys</b>	1953	6	<b>3280.56</b>	<b>12365.1</b>	Infrarosso
<b>Hansen-Strong</b>	1973	7	<b>4465.21</b>	<b>19051.5</b>	Infrarosso



# Spettri & masse delle galassie



# La legge di Faber-Jackson (1976)



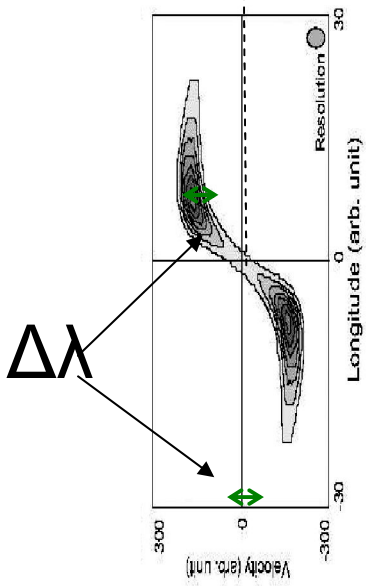
$$\left\{ \begin{array}{l} v^2 \approx \frac{GM}{R} \\ \mu = \frac{L}{\pi R^2} \approx \text{const} \\ \left( \frac{M}{L} \right) = \text{const} \end{array} \right.$$

Se il moto e' caotico,  
allora  $v^2 \equiv \sigma^2$

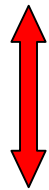
$$\sigma^4 \propto \mu L$$



# Spettri & Massa delle Spirali



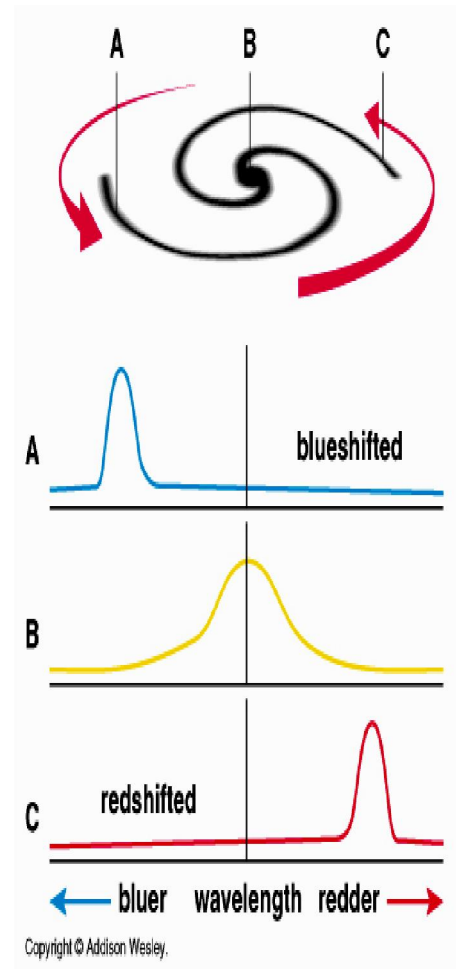
$$\frac{\Delta \lambda}{\lambda} = \frac{v}{c}$$



$$\frac{v^2}{R} = \frac{GM}{R^2}$$

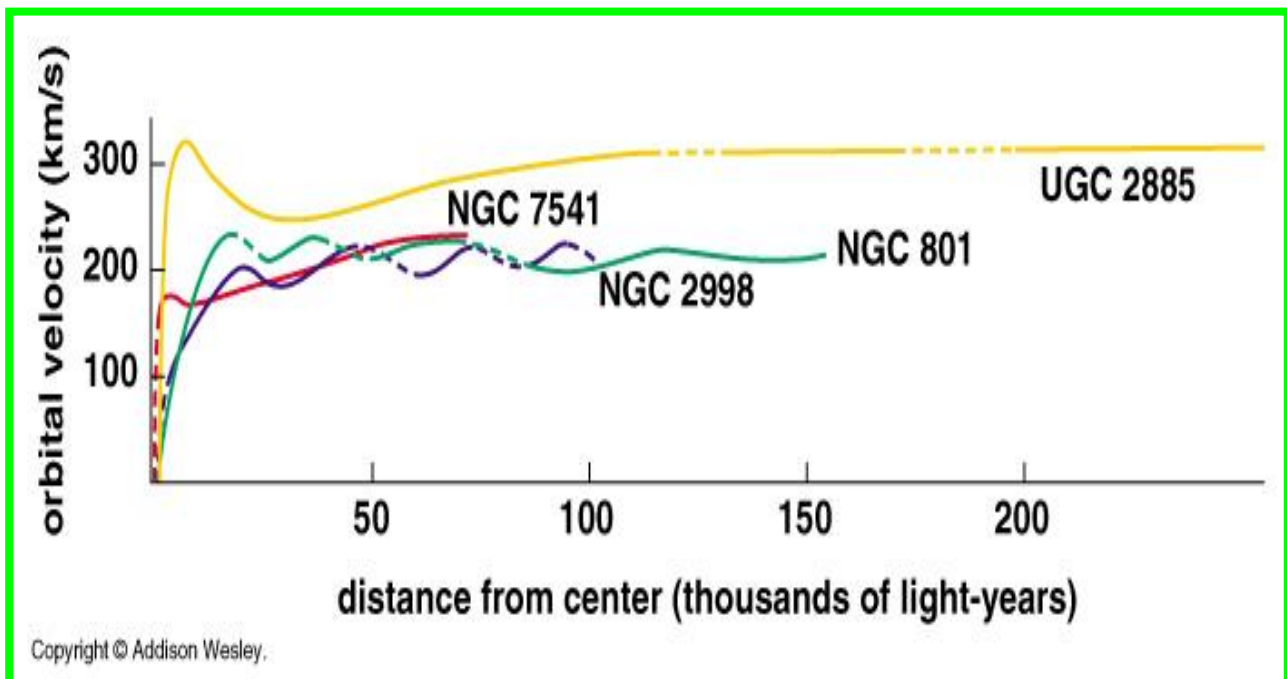
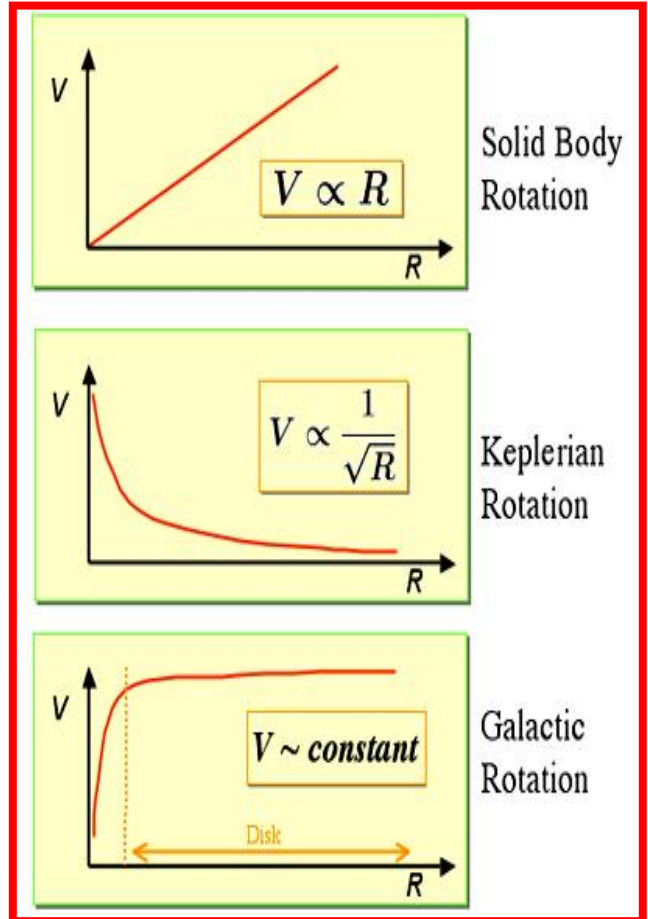
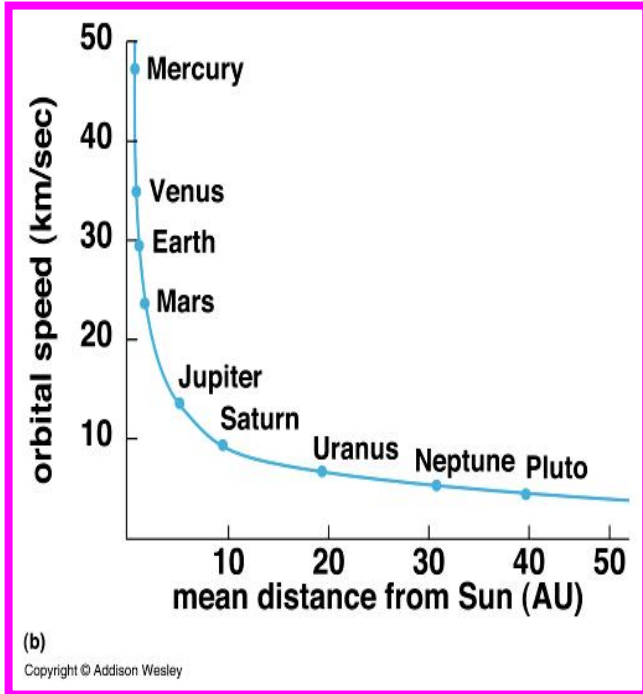
Acc. centrifuga

Acc. gravitazionale

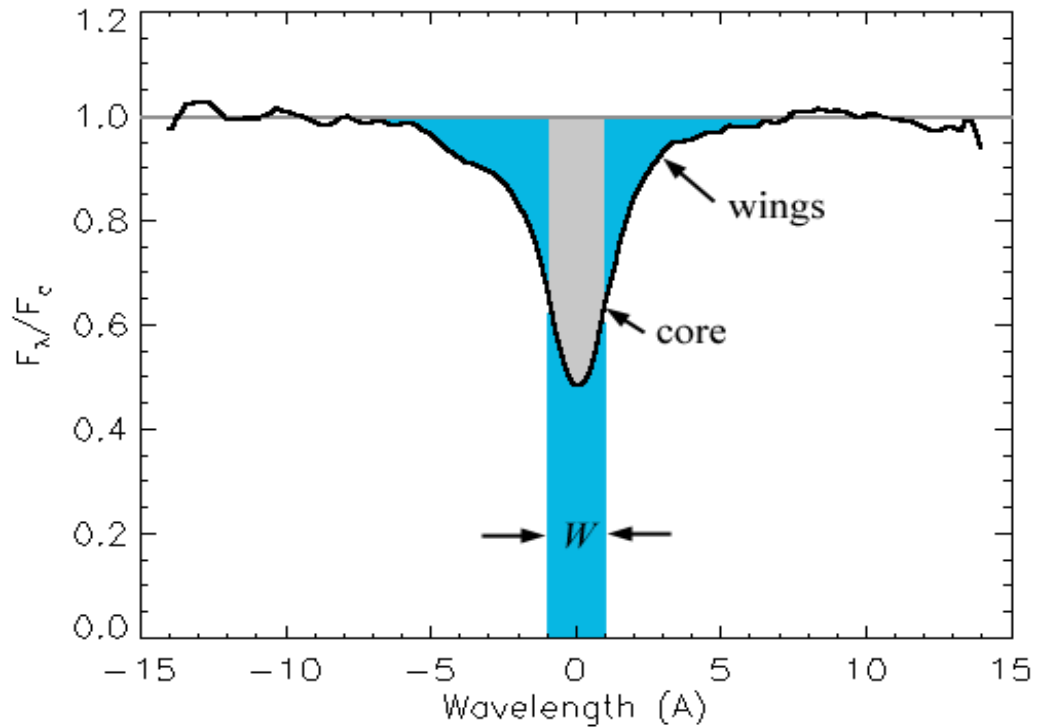




# La materia oscura

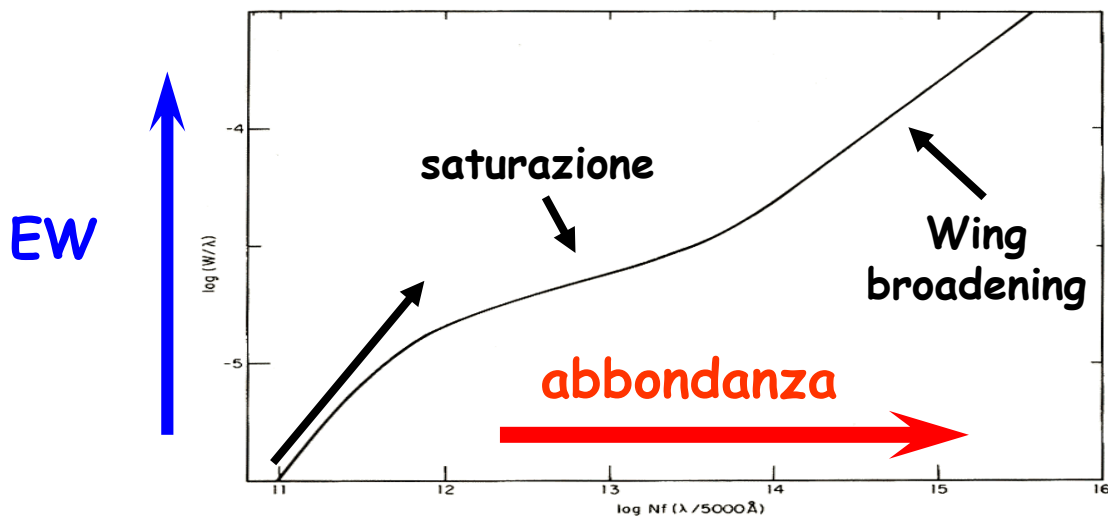


# Forza di indice e Ampiezza equivalente

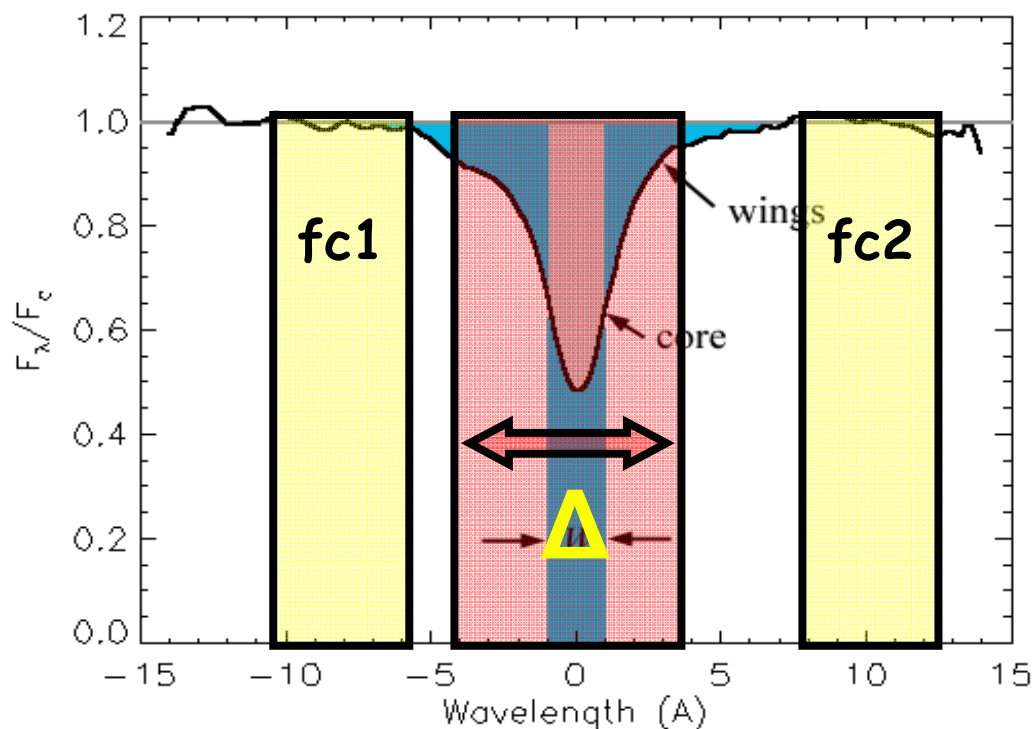


$$EW = \int \frac{f_c - f_f}{f_c} d\lambda$$

a  $T_{eff}$  fissato!!



# Indici in EW e in magnitudini



Tipicamente,

- se la riga e' **atomica**, l'indice si misura in **EW**
- se la banda e' **molecolare** si misura in **mag**

$$I_A = \Delta \frac{(f_c - f_f)}{f_c}$$

$$I_{\text{mag}} = -2.5 \log \left[ 1 - \left( \frac{I_A}{\Delta} \right) \right]$$

$$I_{\text{mag}} = -2.5 \log \left( \frac{f_f}{f_c} \right)$$

$$I_A = \Delta \left[ 1 - 10^{-0.4 I_{\text{mag}}} \right]$$

# Gli indici di Fanelli (Far-UV) (1987)

TABLE 1  
FAR-ULTRAVIOLET WAVELENGTH SEQUENCE

$\lambda(\text{\AA})^a$	Code <sup>b</sup>	Comments
1240.....	L	N v (1238, 1242) resonance lines, P Cygni profile in early supergiants.
1280.....	C	
1305.....	L	Si II (1304) resonance transition; Si III multiplet no. 4 (1295–1303, six lines) O I (1302, 1304, 1306). Prominent in B2 to B9 stars.
1355.....	C	
1397.....	L	Si IV (1394, 1403) resonance lines, prominent in early B stars, maximum at B1. P Cygni profile in early supergiants.
1425.....	L/C	Feature present from O8 to B2 in dwarfs, to B5 in supergiants. Possibly blend of Fe IV, Fe V, and C III multiplets.
1450.....	L/C	Broad line feature present from O2 to B0. Probably Fe V + Fe IV blend.
1485.....	C	
1510.....	C	
1540.....	L	C IV (1548, 1551) resonance lines prominent in O and early B stars. P Cygni profile in supergiants earlier than B0 and in O3–6 dwarfs.
1550.....	L	
1560.....	L	
1590.....	C	
1620.....	L/C	Wide ( $\Delta\lambda \approx 20 \text{\AA}$ ) feature present in O to early B supergiants and O7 to B0 dwarfs. Probably blend of Fe lines. Stronger in supergiants.
1680.....	L/C	Stars later than B8 show Al II (1671).
1710.....	C	N IV (1719) may be present in early O dwarfs and supergiants to B1.
1813.....	C	
1855.....	L	Wide blend: Al II (1858, 1862), Al III (1855, 1863), Fe II, Fe III. Increase in strength from B2 to mid A.

<sup>a</sup> Central wavelength of bandpass. All bandpasses have a width of 20  $\text{\AA}$ .

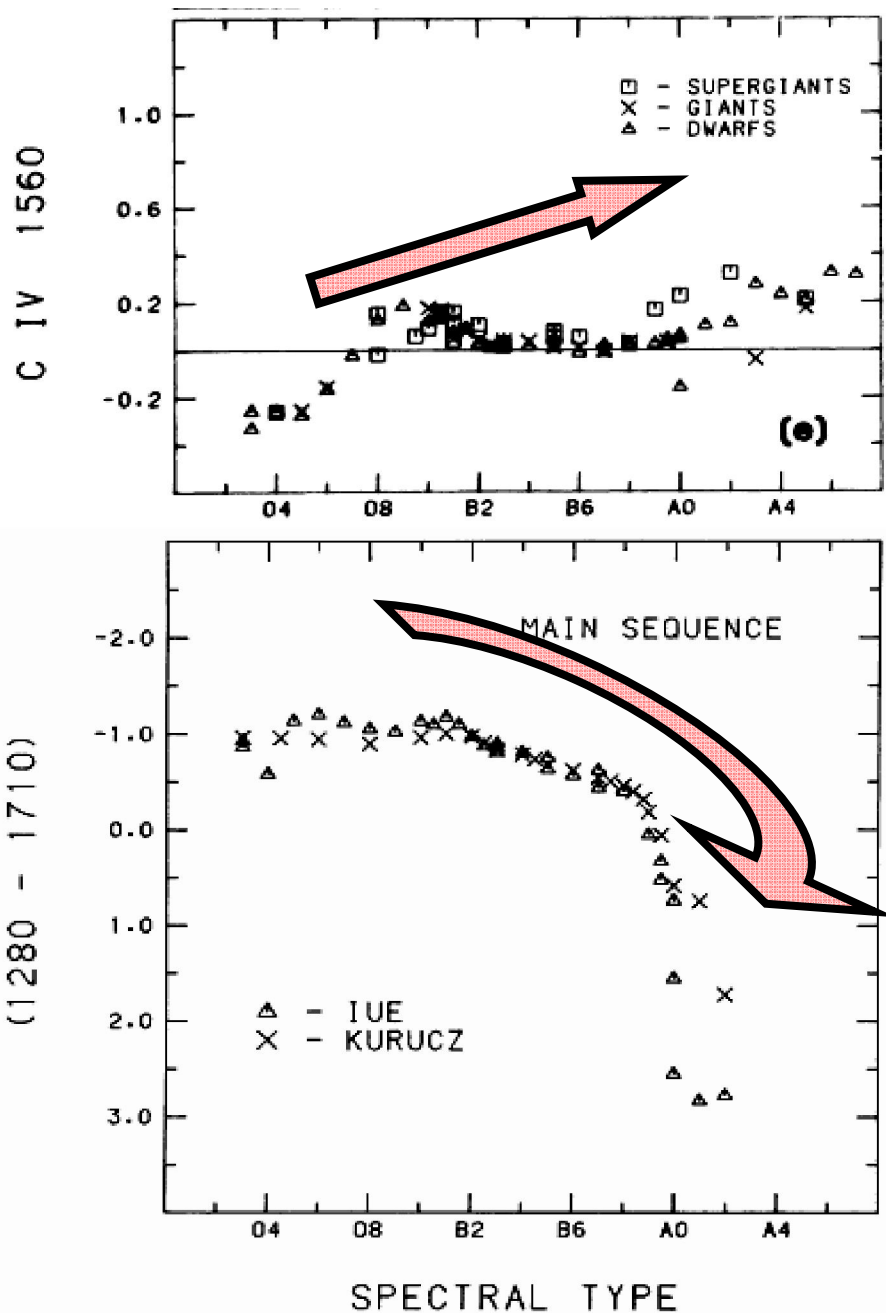
<sup>b</sup> L = line, C = continuum, L/C = both, depending on spectral type.

TABLE 4  
SPECTRAL INDICES<sup>a</sup>

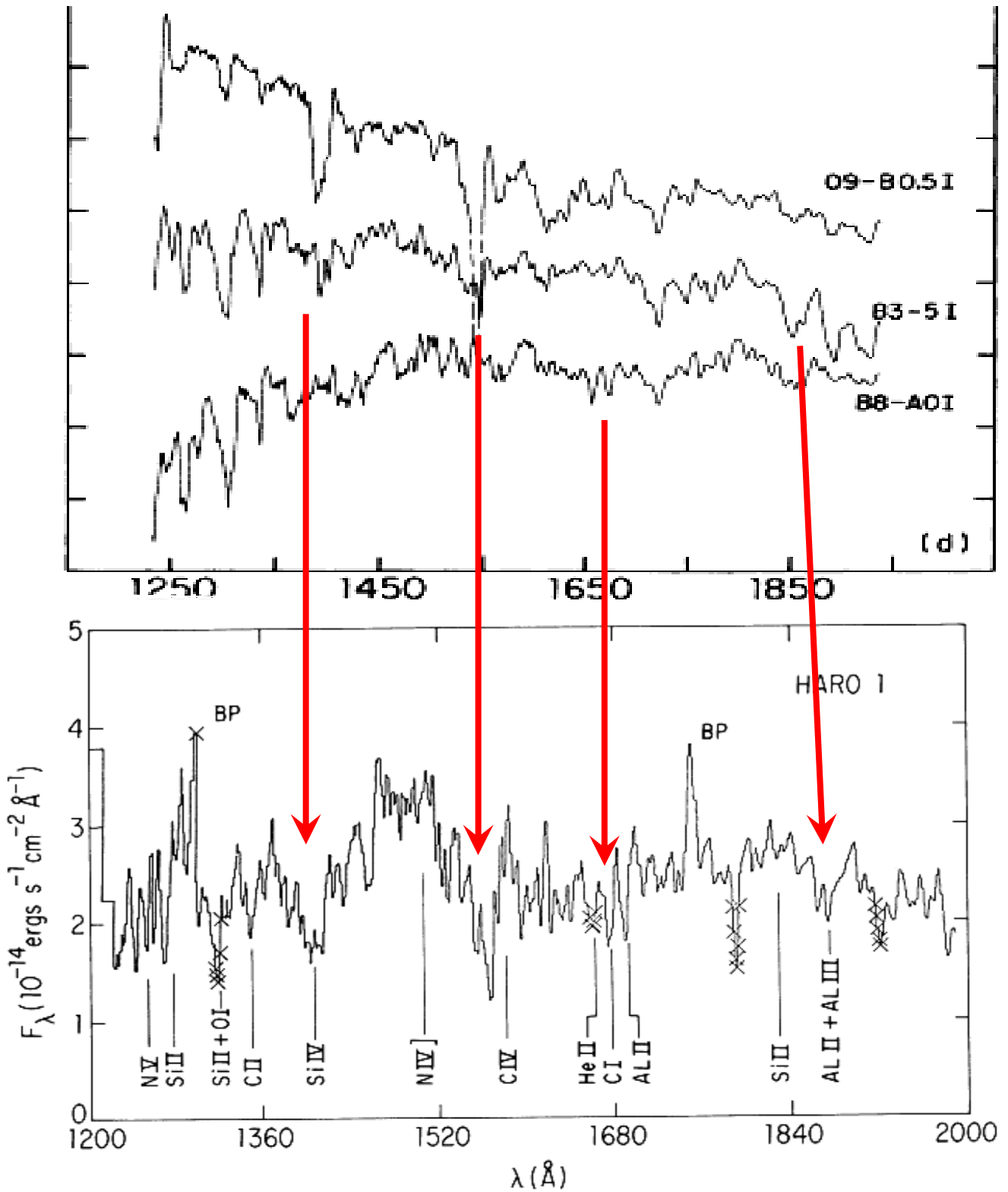
Index Name and Wavelength	Sidebands
1305 Å blend .....	1280, 1355
Si IV 1397 .....	1355, 1425
C IV 1550 .....	1510, 1590
C IV abs 1540 .....	1510, 1590
C IV ems 1560 .....	1510, 1590
C IV P Cygni <sup>b</sup> .....	(1540/1560)
1620 Å blend .....	1590, 1680

## Indici di (pseudo)-continuo & linea

**FWHM = 6Å**



# UV indices & diagnostics di Star-forming galaxies



# Indici di Mid-UV (1990)

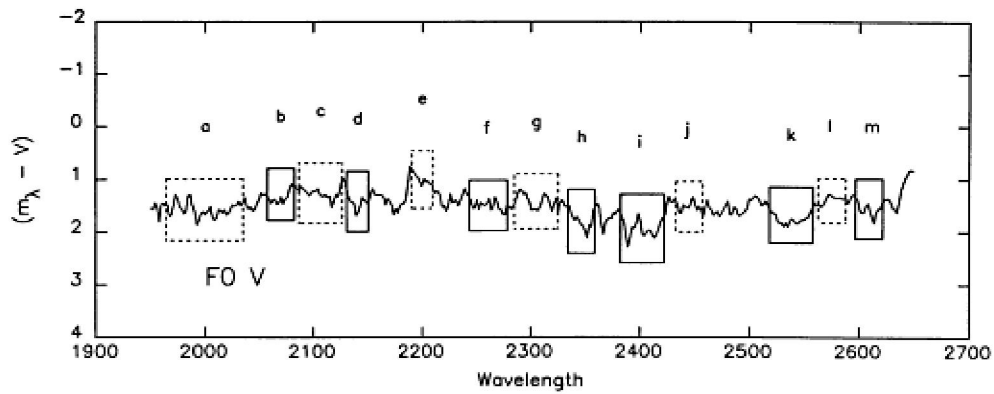


FIG. 3a

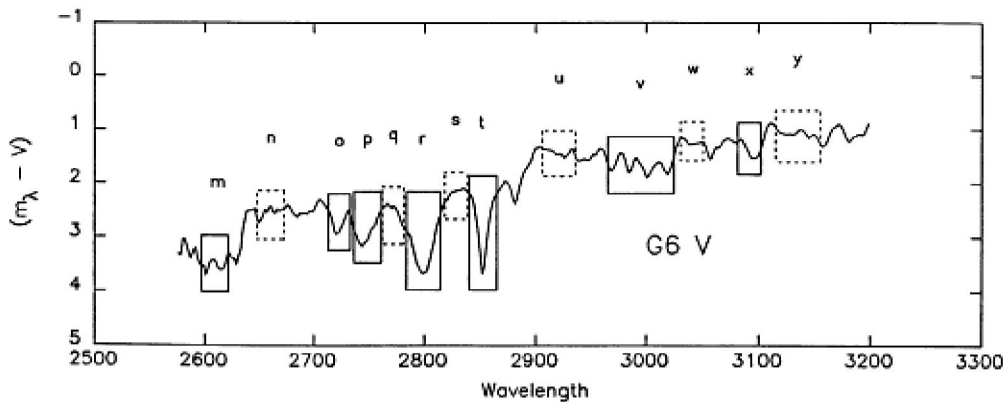


TABLE 3  
MID-ULTRAVIOLET WAVELENGTH SEQUENCE

ID (1)	$\lambda_t$ (2)	$\lambda_r$ (3)	$\Delta\lambda$ (4)	Code* (5)	Comments (6)
a	1965	2035	70	C	
b	2057	2083	26	L	
c	2087	2127	40	C	
d	2131	2151	20	L	
e	2190	2210	20	C	
f	2243	2279	36	L	
g	2285	2325	40	C	
h	2333	2359	26	L	Fe II (3), 2338.0, 2344.3, 2343.5, 2348.3
i	2382	2422	40	L	Fe II (2), blend of ~10 lines
j	2432	2458	26	C	
k	2520	2556	36	L	Uncertain, Fe I?
l	2562	2588	26	C	
m	2596	2622	26	L	Fe II (1), blend of ~10 lines
n	2647	2673	26	C	
o	2713	2733	20	L	
p	2736	2762	26	L	Fe I, 2744.1, Fe II 2747.0, 2746.5, Cr I 2748.3
q	2762	2782	20	C	
r	2784	2814	30	L	Mg II (1) 2795.5, 2802.7
s	2818	2838	20	C	
t	2839	2865	26	L	Mg I (1) 2852.1
u	2906	2936	30	C	
v	2965	3025	60	L	Fe I 2967.0, 2973.3, 2994.4, 3020.6
w	3031	3051	20	C	
x	3086	3106	20	L	Al I 3092.7, Fe I 3091.6, Ni I?
y	3115	3155	40	C	

\* C = continuum; L = line.

# Il Magnesio (MgII & MgI)

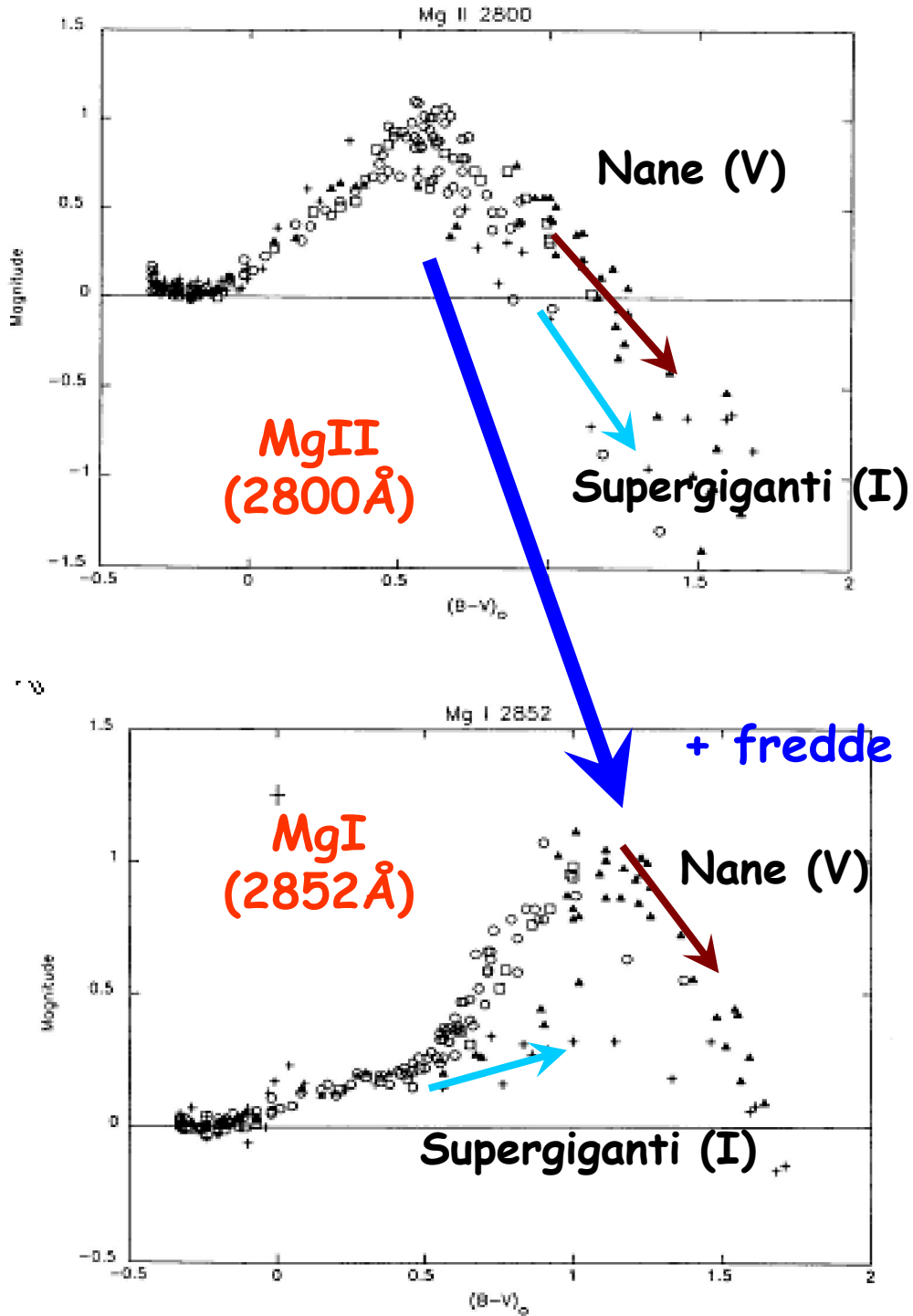


FIG. 5d



# Il sistema di Lick

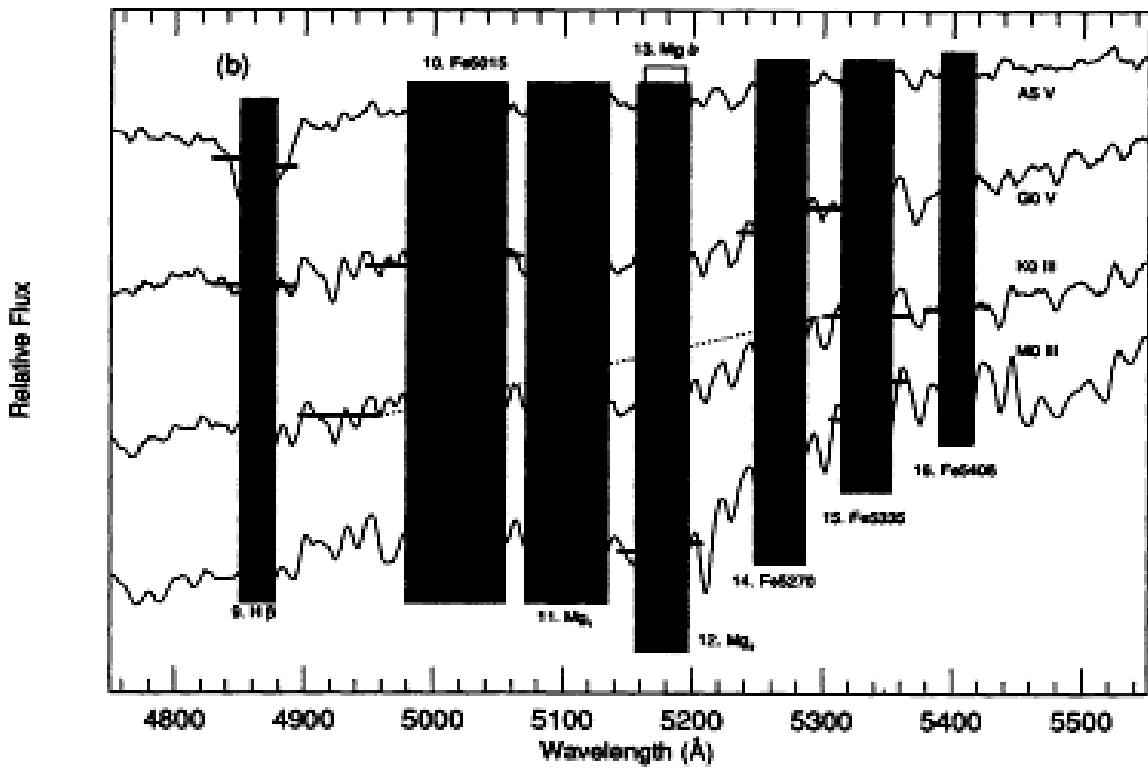
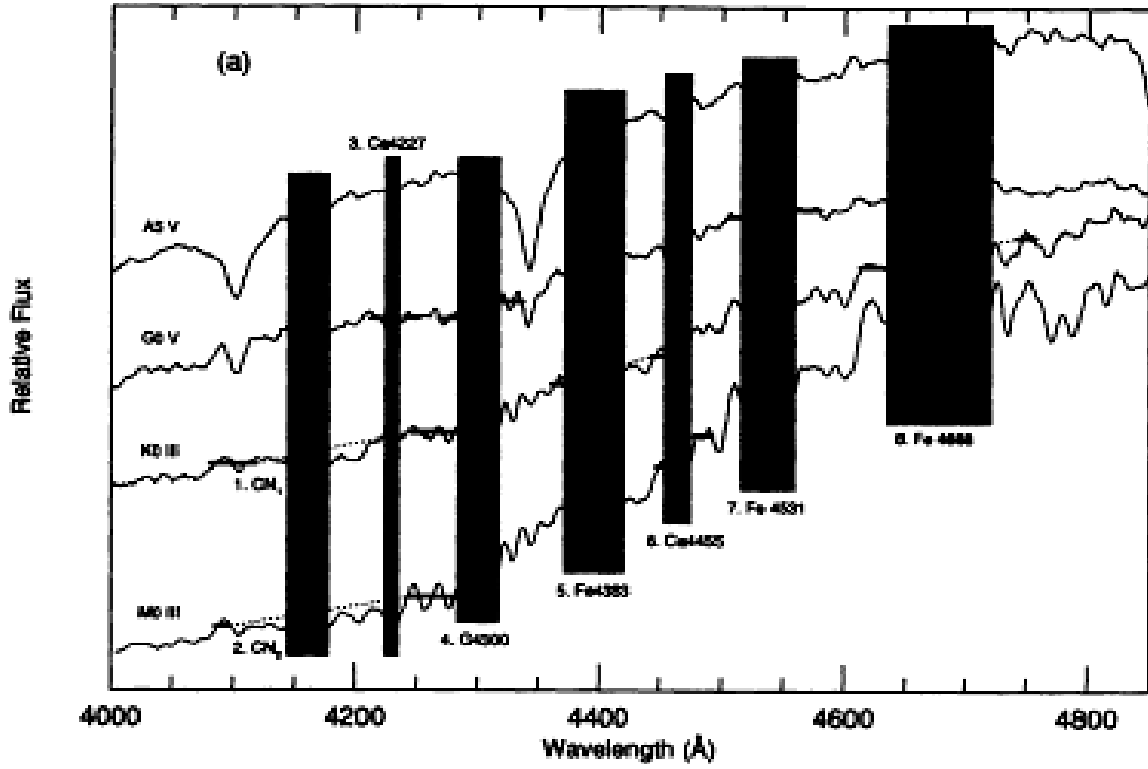
TABLE 1  
INDEX DEFINITIONS

Name	Index Bandpass	Pseudocontinua	Units	Measures	Error <sup>1</sup>	Notes
01	CN <sub>1</sub>	4143.375-4178.375	4081.375-4118.875 4245.375-4285.375	mag	CN, Fe I	0.021
02	CN <sub>2</sub>	4143.375-4178.375	4085.125-4097.625 4245.375-4285.375	mag	CN, Fe I	0.023 2
03	Ca4227	4223.500-4236.000	4212.250-4221.000 4242.250-4252.250	Å	Ca I, Fe I, Fe II	0.27 2
04	G4300	4282.625-4317.625	4267.625-4283.875 4320.125-4336.375	Å	CH, Fe I	0.39
05	Fe4383	4370.375-4421.625	4360.375-4371.625 4444.125-4456.625	Å	Fe I, Ti II	0.53 2
06	Ca4455	4453.375-4475.875	4447.125-4455.875 4478.375-4493.375	Å	Ca I, Fe I, Ni I, Ti II, Mn I, V I	0.25 2
07	Fe4531	4515.500-4560.500	4505.500-4515.500 4561.750-4580.500	Å	Fe I, Ti I, Fe II, Ti II	0.42 2
08	Fe4668	4635.250-4721.500	4612.750-4631.500 4744.000-4757.750	Å	Fe I, Ti I, Cr I, Mg I, Ni I, C <sub>2</sub>	0.64 2
09	Hβ	4847.875-4876.625	4827.875-4847.875 4876.625-4891.625	Å	Hβ, Fe I	0.22 3
10	Fe5015	4977.750-5054.000	4946.500-4977.750 5054.000-5065.250	Å	Fe I, Ni I, Ti I	0.46 2,3
11	Mg <sub>1</sub>	5069.125-5134.125	4895.125-4957.625 5301.125-5366.125	mag	MgH, Fe I, Ni I	0.007 3
12	Mg <sub>2</sub>	5154.125-5196.625	4895.125-4957.625 5301.125-5366.125	mag	MgH, Mg b, Fe I	0.008 3
13	Mg b	5160.125-5192.625	5142.625-5161.375 5191.375-5206.375	Å	Mg b	0.23 3
14	Fe5270	5245.650-5285.650	5233.150-5248.150 5285.650-5318.150	Å	Fe I, Ca I	0.28 3
15	Fe5335	5312.125-5352.125	5304.625-5315.875 5353.375-5363.375	Å	Fe I	0.26 3
16	Fe5406	5387.500-5415.000	5376.250-5387.500 5415.000-5425.000	Å	Fe I, Cr I	0.20 2,3
17	Fe5709	5698.375-5722.125	5674.625-5698.375 5724.625-5738.375	Å	Fe I, Ni I, Mg I, Cr I, V I	0.18 2
18	Fe5782	5778.375-5798.375	5767.125-5777.125 5799.625-5813.375	Å	Fe I, Cr I, Cu I, Mg I	0.20 2
19	Na D	5878.625-5911.125	5862.375-5877.375 5923.875-5949.875	Å	Na I	0.24
20	TiO <sub>1</sub>	5938.375-5995.875	5818.375-5850.875 6040.375-6105.375	mag	TiO	0.007
21	TiO <sub>2</sub>	6191.375-6273.875	6068.375-6143.375 6374.375-6416.875	mag	TiO	0.006

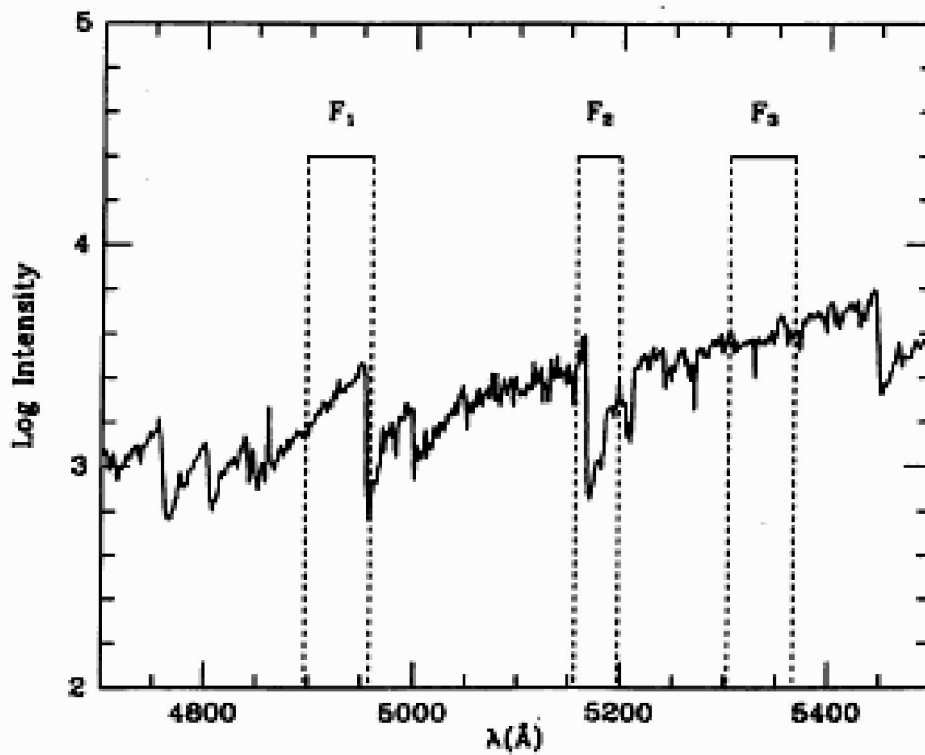
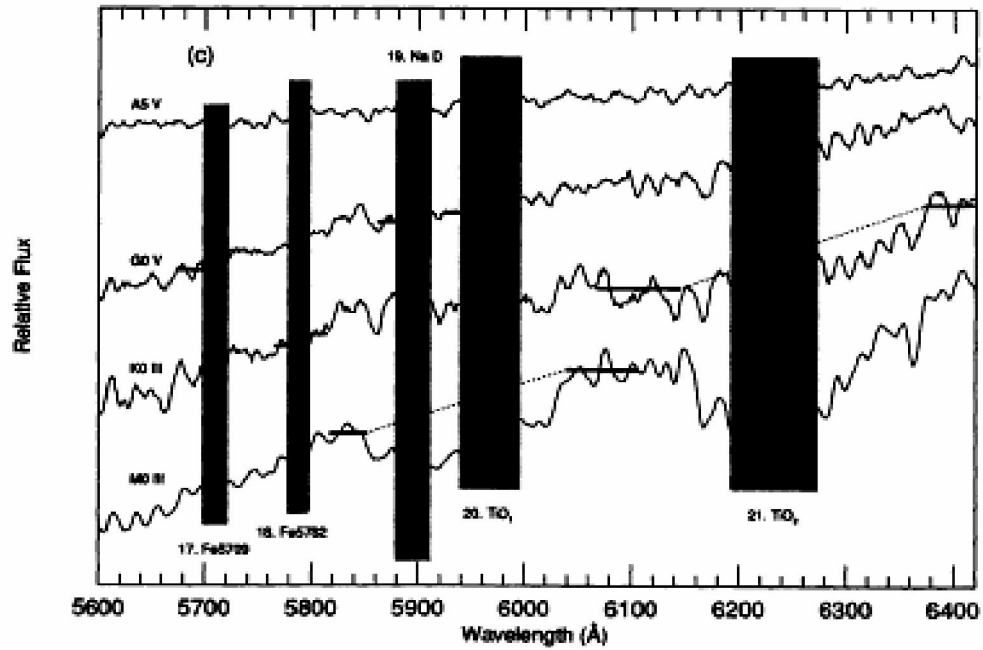
FWHM = 8.5Å

Worthey et al. (1994)  
+ Trager et al. (1998)

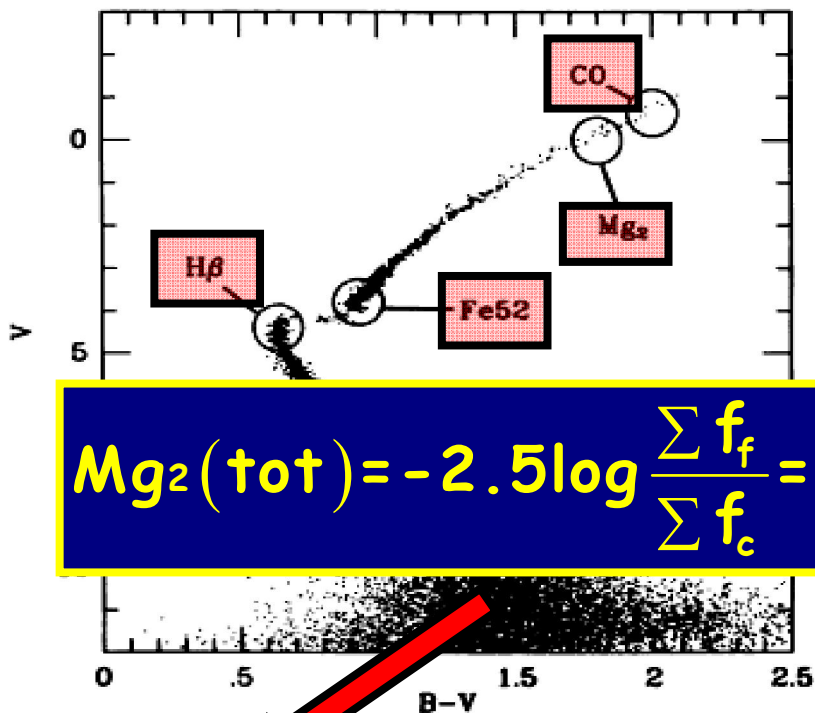
# Indici Blu-Vis



# Indici Rossi

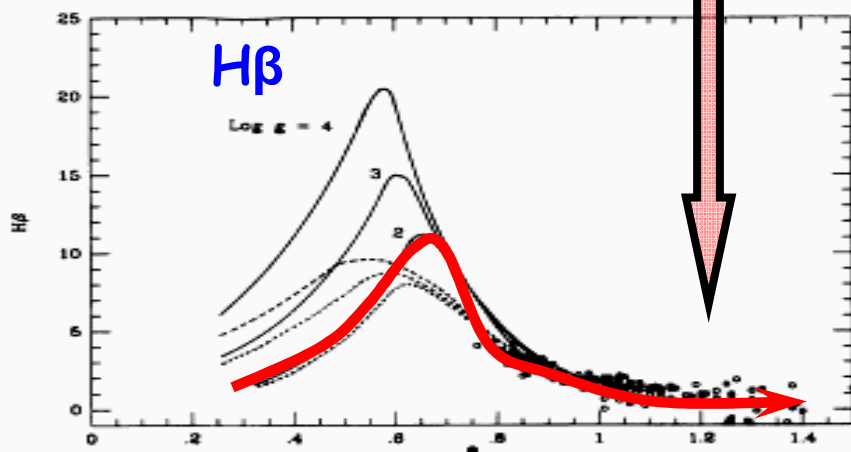
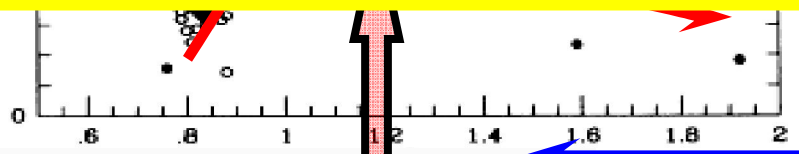


# Indici e analisi "tomografica" delle pop stellari



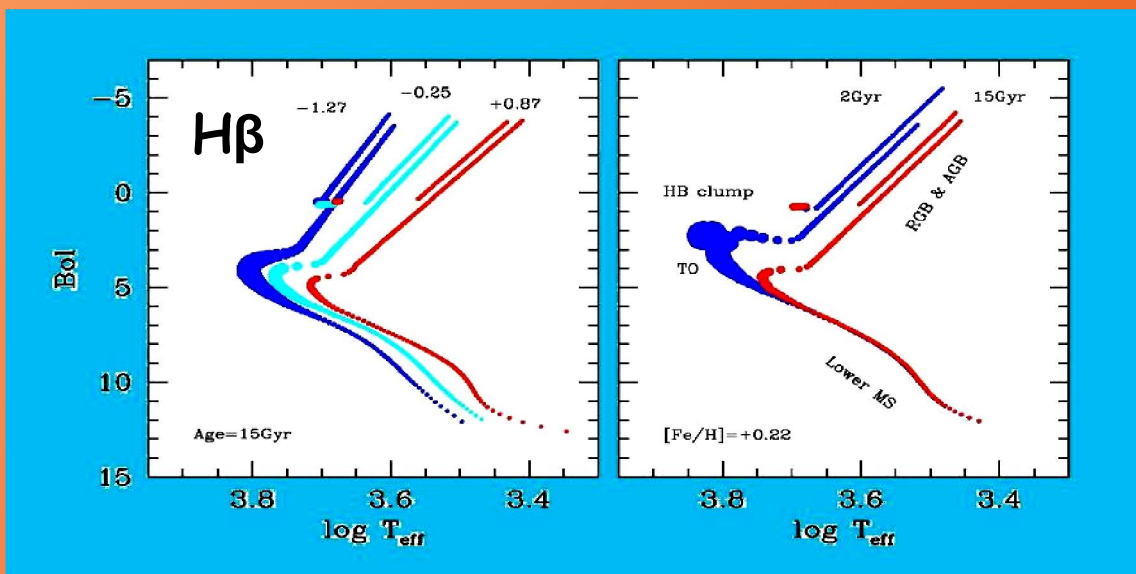
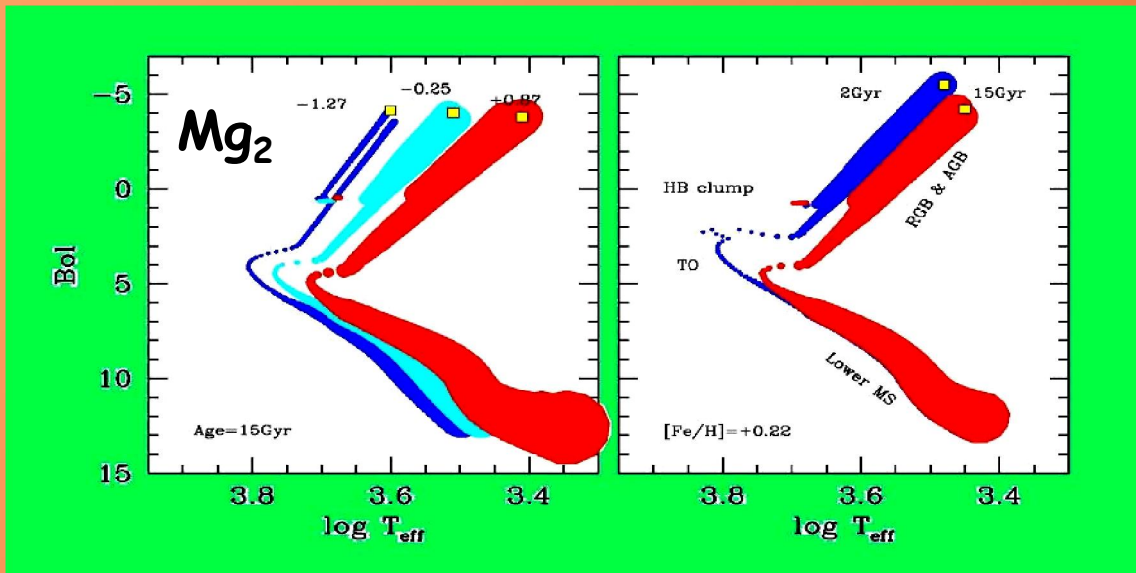
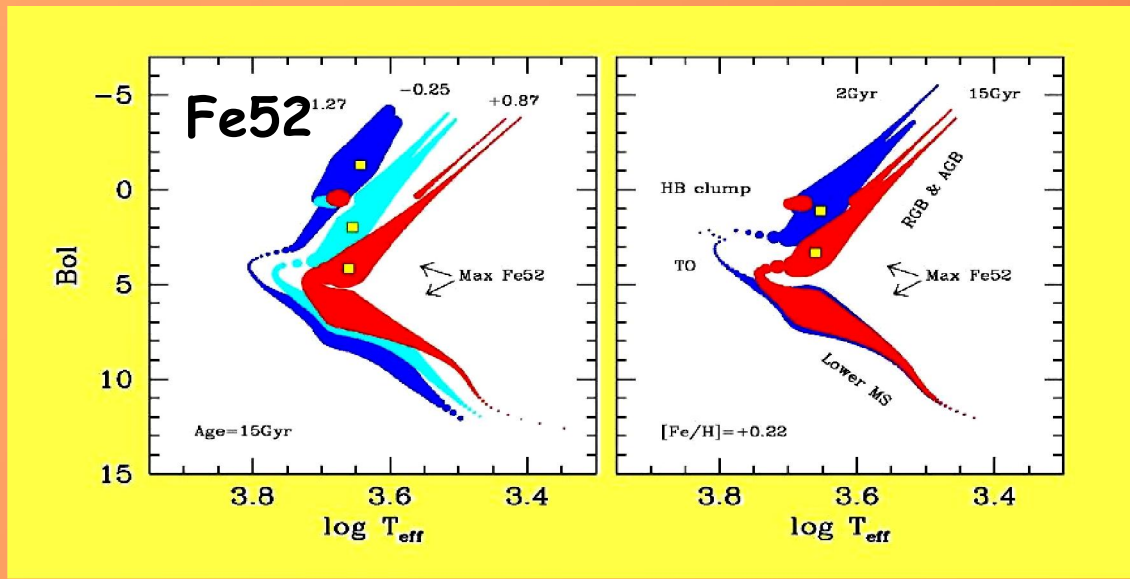
$$Mg_2(\text{tot}) = -2.5 \log \frac{\sum f_f}{\sum f_c} =$$

$$I_{\text{tot}} = -2.5 \log \left[ \frac{\sum (f_f / f_c) * f_c}{\sum f_c} \right] = -2.5 \log \left[ \frac{\sum f_c 10^{-0.4I}}{\sum f_c} \right]$$



Temperatura

# Narrow-band indices & SSP tomography



**Articoli consigliati (vedi Webpage):**

<http://www.bo.astro.it/~eps/lezioni/lezioni.html>

- Galaxy Spectral Atlas (Kennicutt1)
- Galaxy Spectral Atlas (Kennicutt2)
- Balmer break (Hamilton)
- Lick indices (Worthey)
- UV indices (Fanelli)
- Faber & Jackson
- M/L clusters (Girardi)

# Il bias di Malmquist

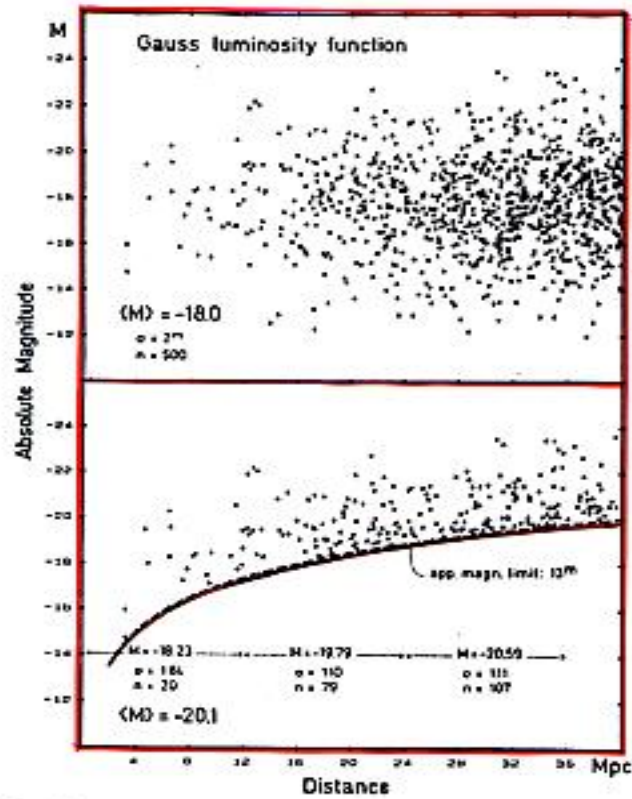
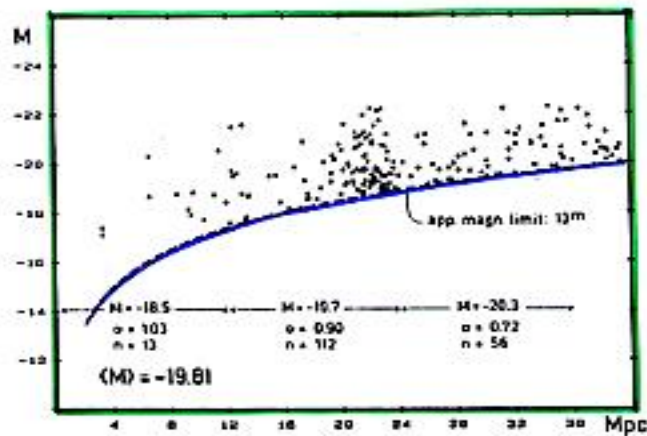


Fig. 1. Upper panel: Monte Carlo distribution in distance and absolute magnitude of 500 galaxies within 38 Mpc. Constant space density and a mean absolute magnitude of  $\langle M \rangle = -18^m$  with a Gauss standard deviation of  $\sigma_M = 2^m$  are assumed. Lower panel: The same sample cut by an apparent-magnitude limit of  $m = 13^m$ . Note the increase of the galaxian luminosities with increasing distance and the small effective (observable) scatter  $\sigma_M$  within individual distance intervals.

THE VALUE OF  $1/q$

333

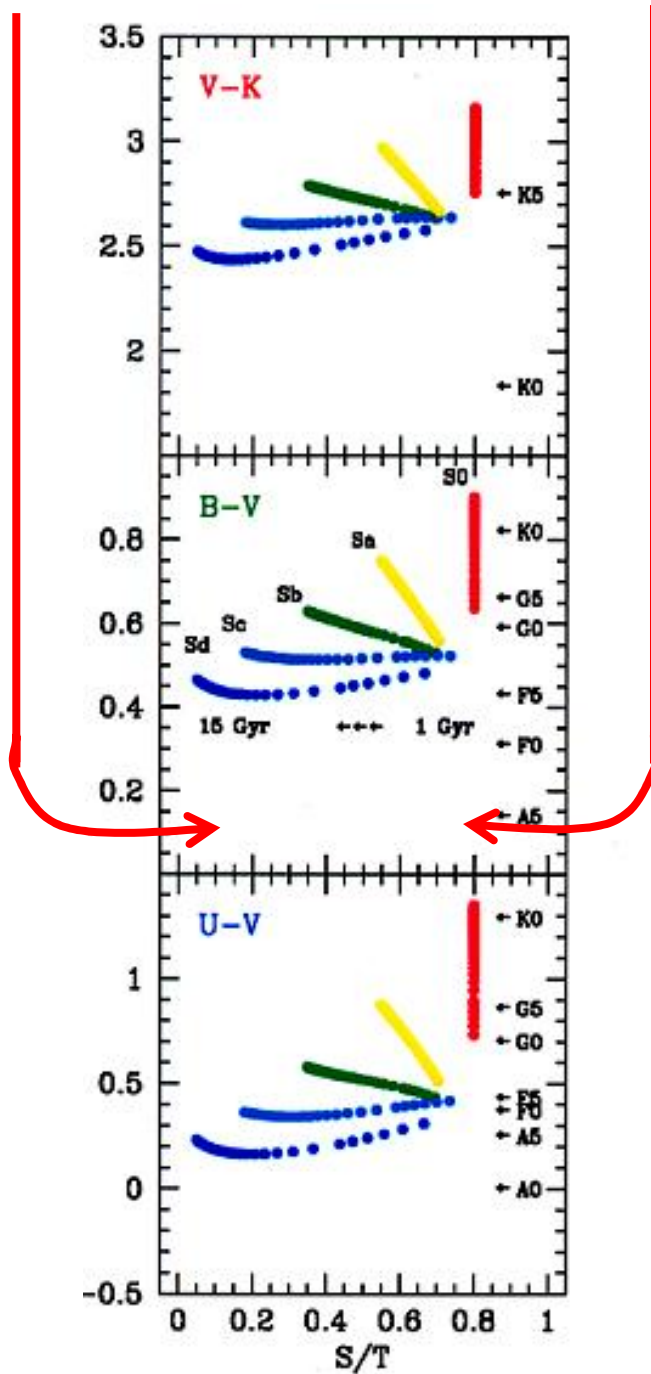


[http://en.wikipedia.org/wiki/Malmquist\\_bias](http://en.wikipedia.org/wiki/Malmquist_bias)

# Bias morfologico & Bias fotometrico

Disk-dominated

Bulge-dominated



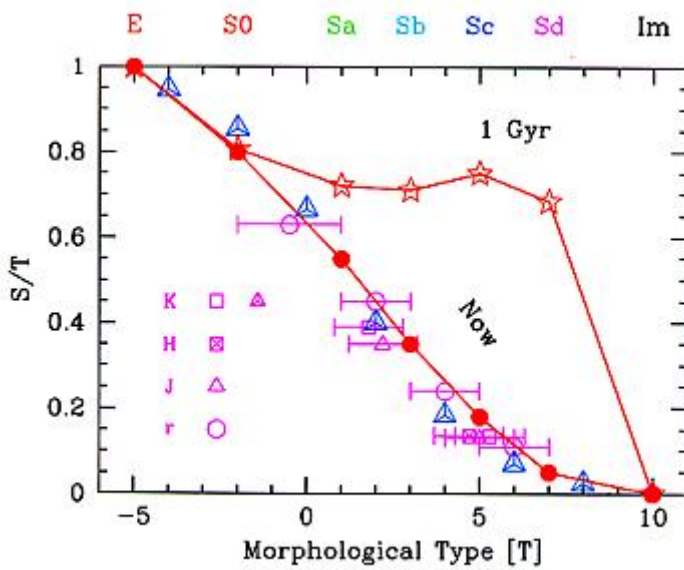
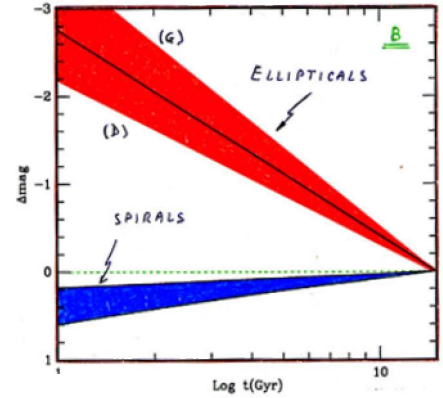
$L(\text{Spheroid})/L(\text{Tot})$



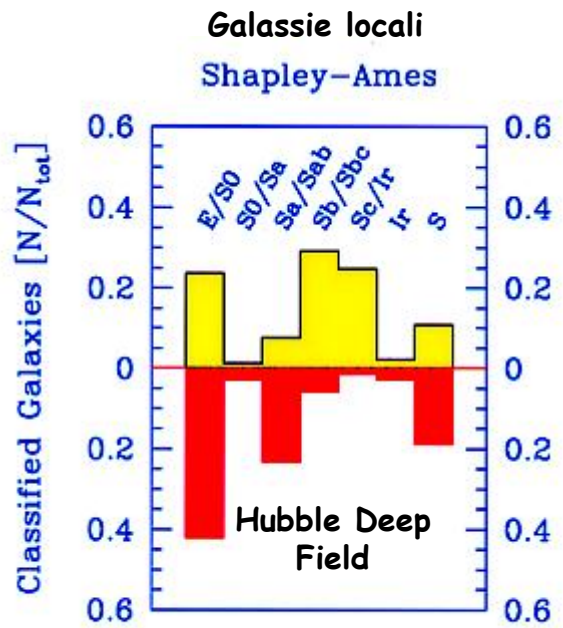
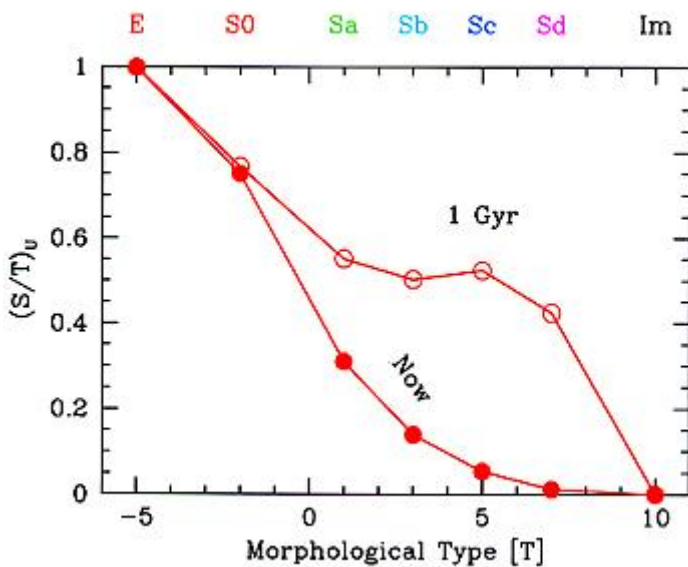
# Bias Morfologico

All'aumentare del redshift

- 1) Andiamo indietro nel tempo (bulge + luminoso e disco -luminoso)
- 2) La morfologia tende ad essere quella nell'Ultravioletto



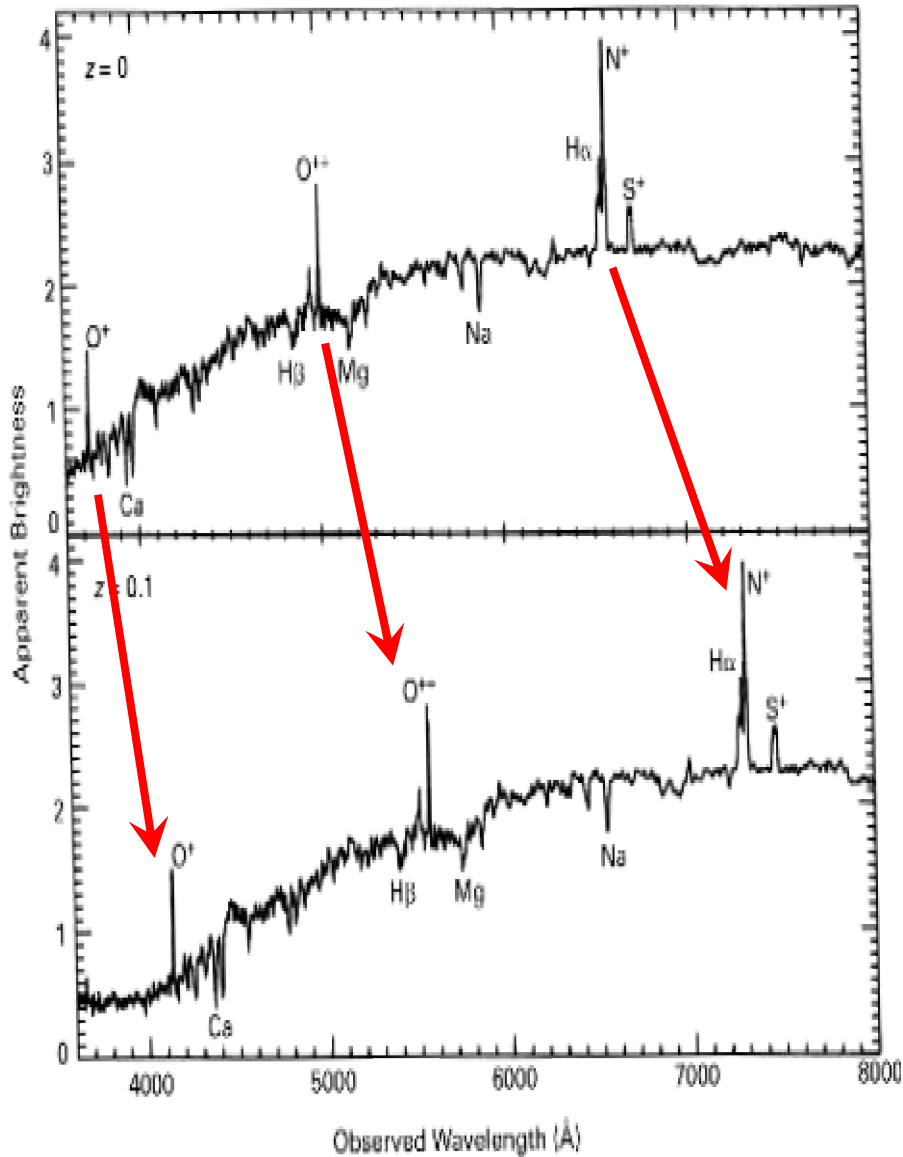
Buzzoni (2005)



Hubble Deep Field

Van den Bergh et al. (1996)

# II Redshift



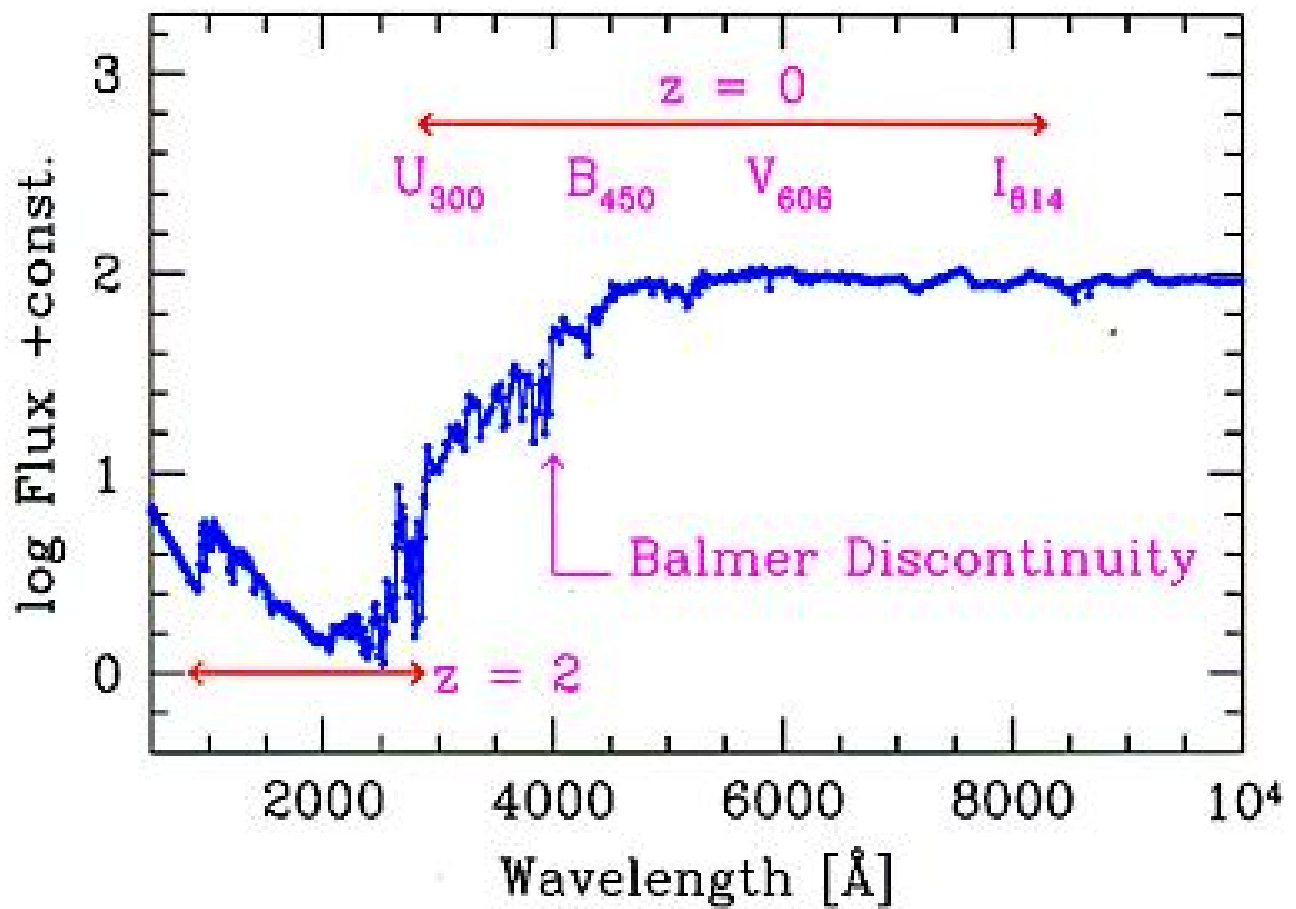
A. H. Epton and R. J. Taylor

$$\frac{\lambda_{\text{oss}} - \lambda_{\text{lab}}}{\lambda_{\text{lab}}} = z$$

$$\frac{\Delta\lambda}{\lambda} = \frac{v}{c} = z$$

$$\frac{\lambda_{\text{oss}}}{\lambda_{\text{lab}}} = (1 + z)$$

# L'effetto di "stretching"



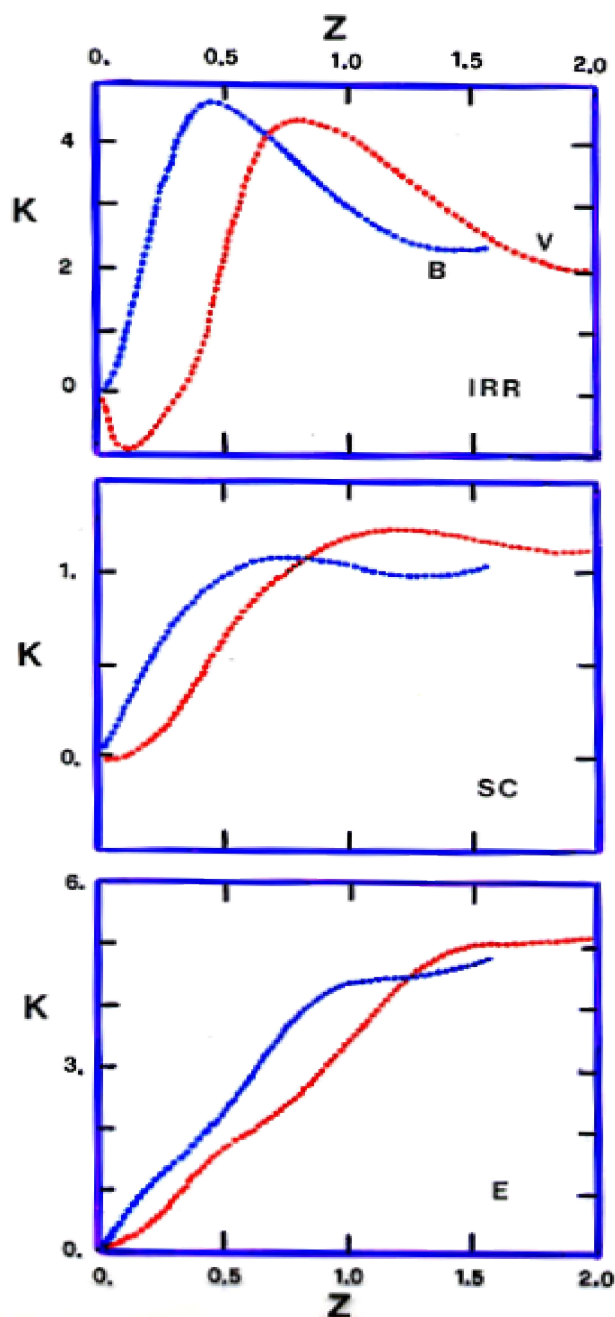
Massarotti et al. (2001)

# Correzione k

$$M - M_0 = 5 \text{Log} \frac{\ell}{\ell_0} + K(z) + \epsilon(z)$$

$$K(z) = 2.5 \text{Log}(1+z) - 2.5 \text{Log} \left\{ \frac{\int F(\lambda/(1+z)) R_\lambda d\lambda}{\int F_\lambda R_\lambda d\lambda} \right\}$$

$$\epsilon(z) = -2.5 \text{Log} \left\{ \frac{\int F(\lambda/(1+z); t_z) R_\lambda d\lambda}{\int F(\lambda/(1+z); 0) R_\lambda d\lambda} \right\}$$



Notare che  $\nabla$  morfologia

$$\lim_{z \rightarrow 0} k = +2.5 \text{Log}(1+z)$$

Dato che  $F(\lambda/(1+z)) \rightarrow F(\lambda)$

# Esempi di correzione k passiva (k) ed evolutiva (k+e)

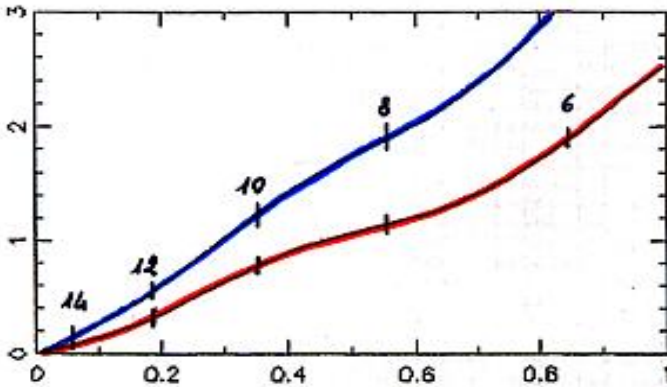
— WITHOUT } EVOLUTION  
— WITH

**Importante!:**

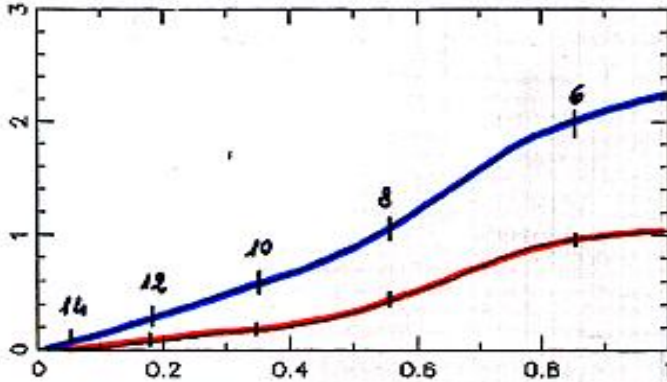
La correzione evolutiva  $e(z)$  dipende dal modello cosmologico assunto

$H_0 = 50 \quad q_0 = 0.$

$k(g)$



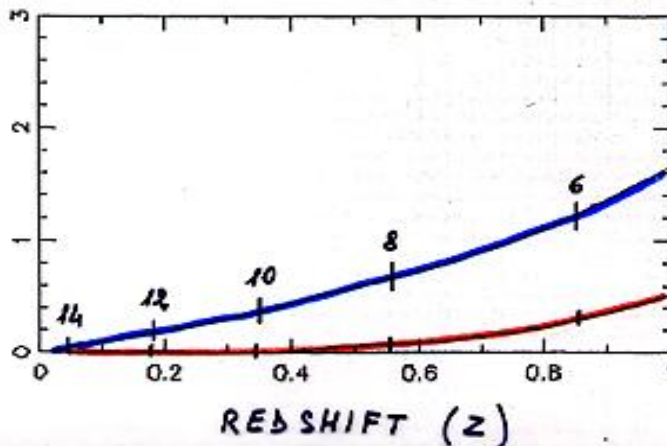
$k(\tau)$



$k(z)$

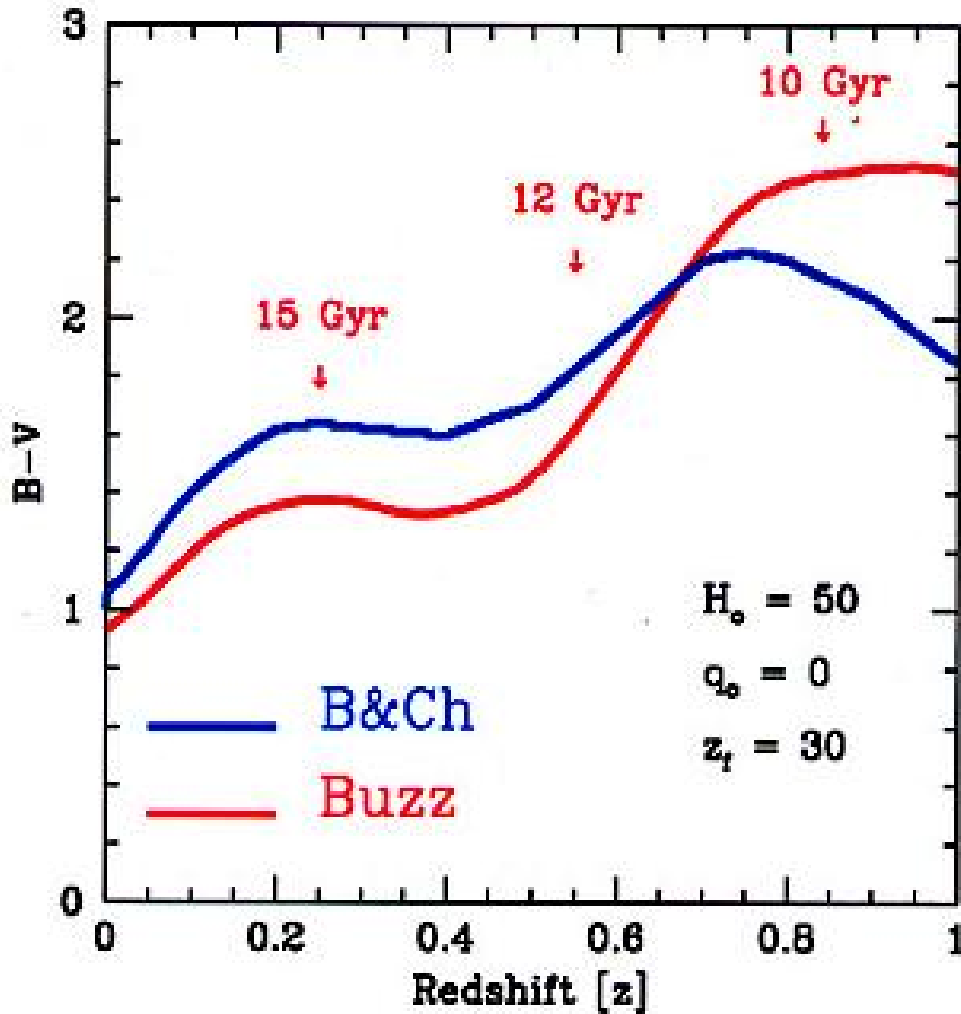
$k(z)+e(z)$

$k(i)$




REDSHIFT (z)

# Apparent Color vs. Redshift



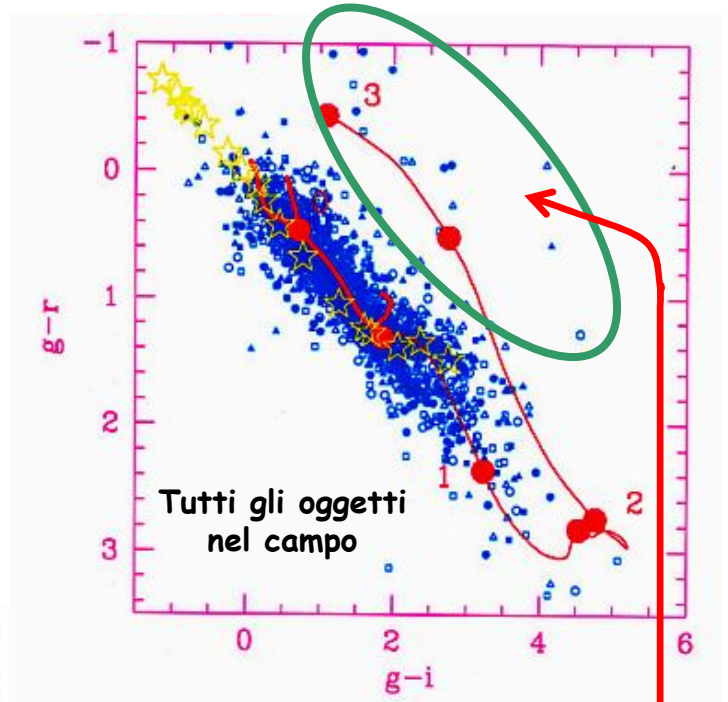
$$(B-V)_z = (B-V)_o + (k_B - k_V) + (e_B - e_V)$$

  
 Colore  
 apparente

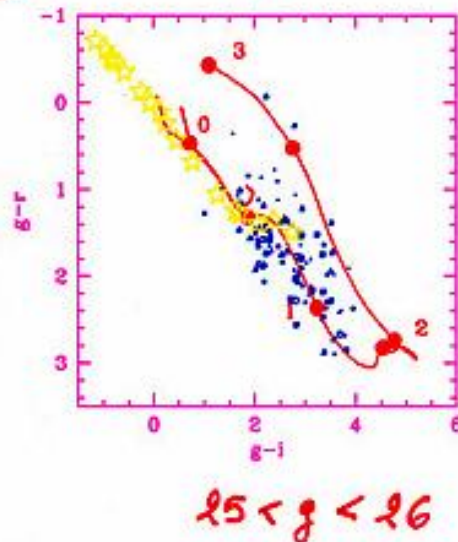
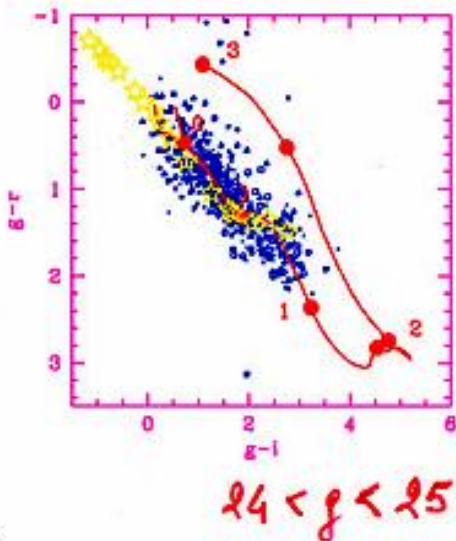
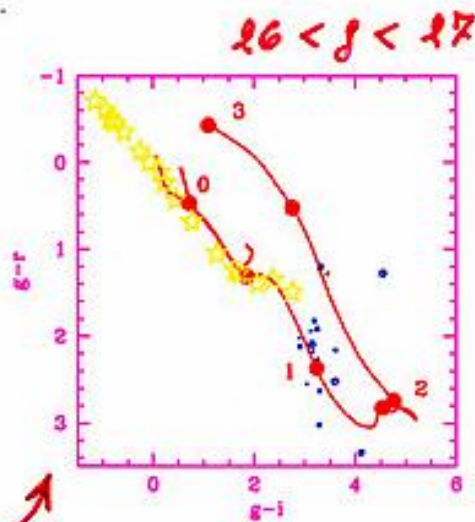
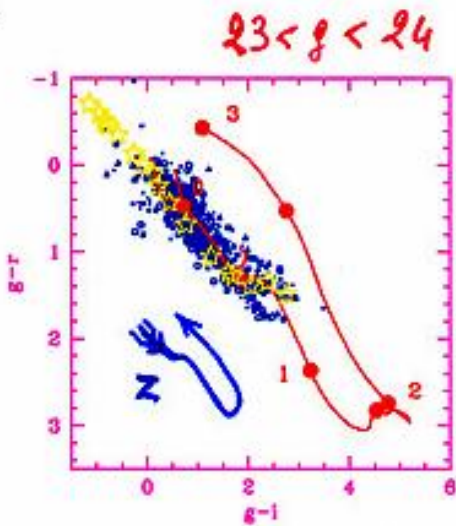
  
 Colore  
 restframe

  
 Opzionale, nel caso si voglia/possa  
 tenere in conto della evoluzione  
 con z

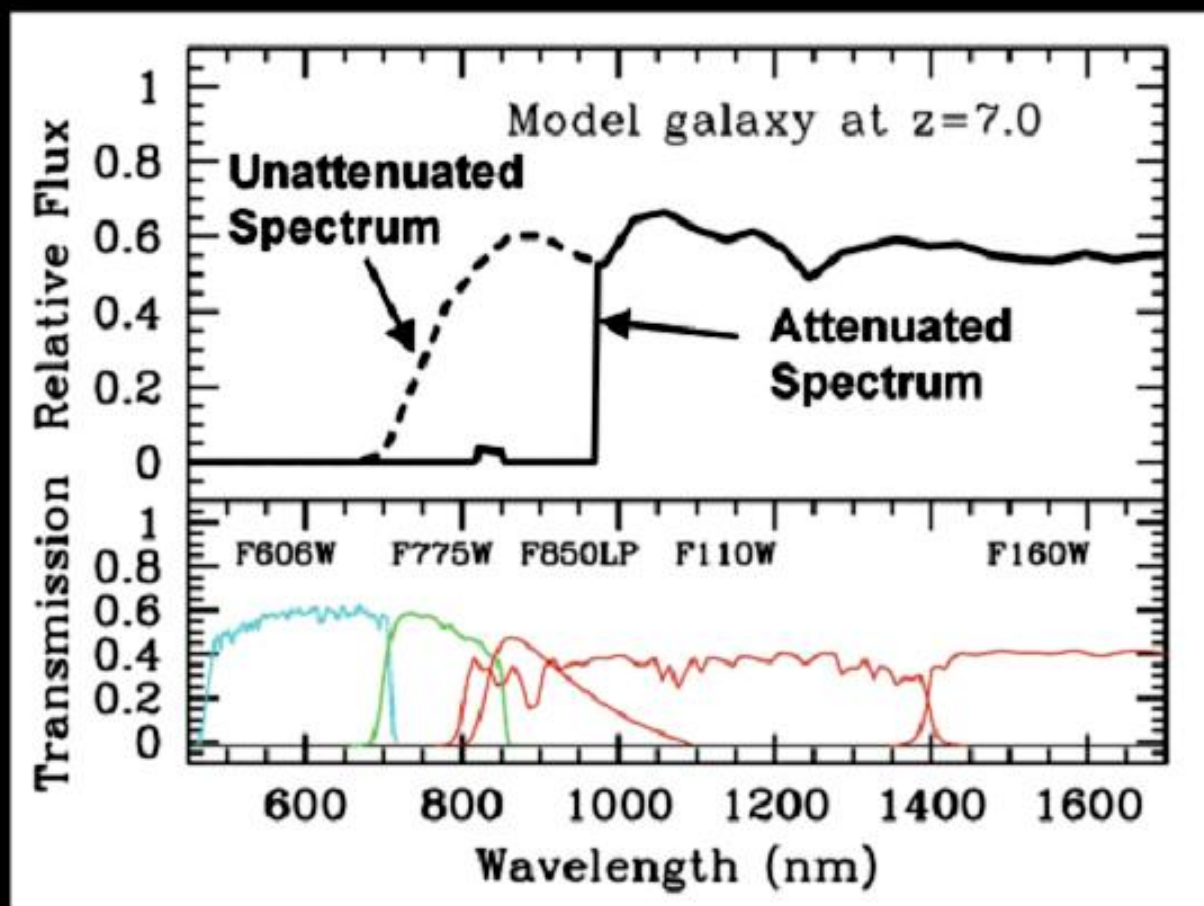
# Selezione fotometrica delle galassie ad alto redshift: un esempio



Galassie ellittiche a  $z > 2$



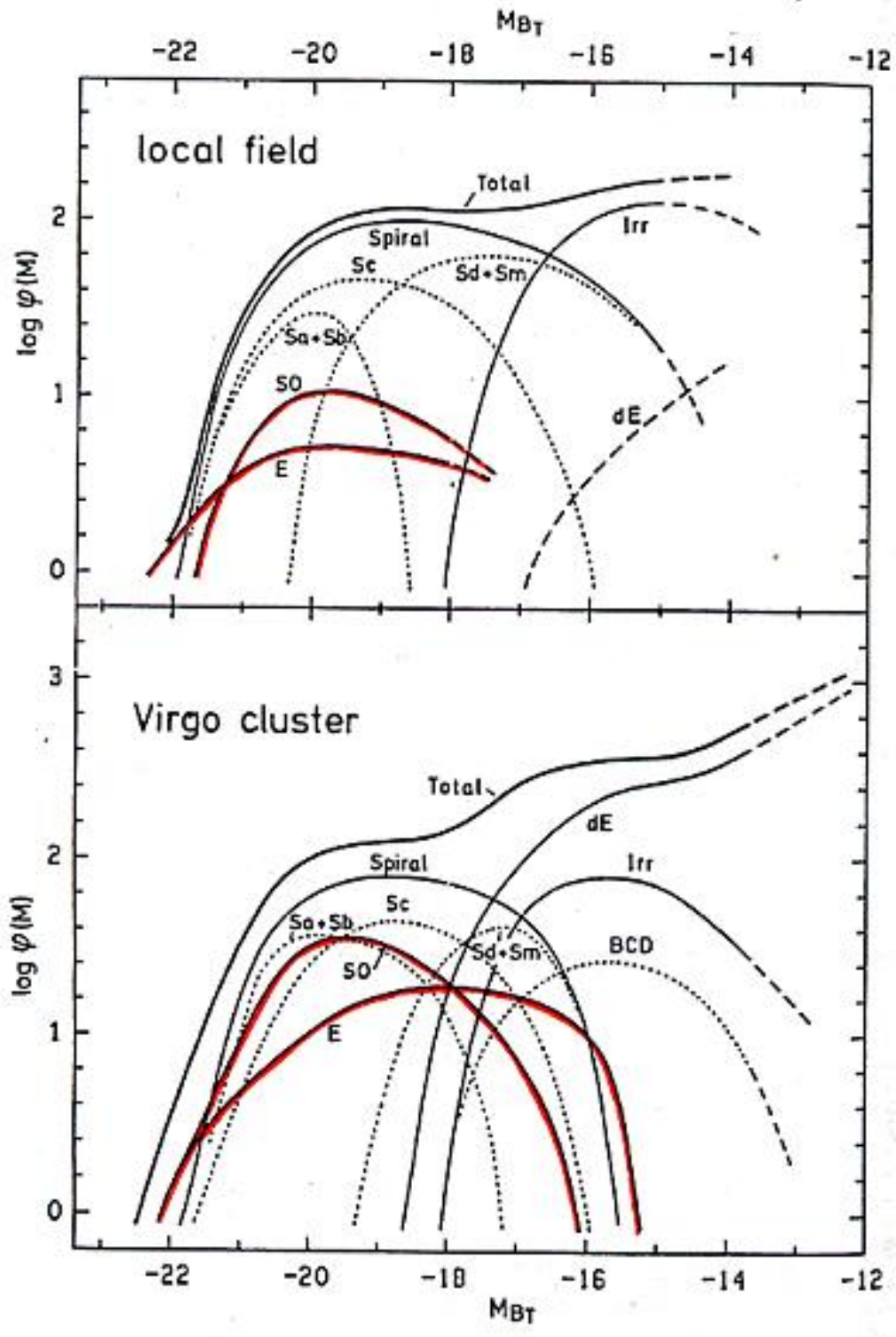
# Selezione fotometrica delle galassie ad alto redshift: "Dropout galaxies"



Steidel et al. (1996)

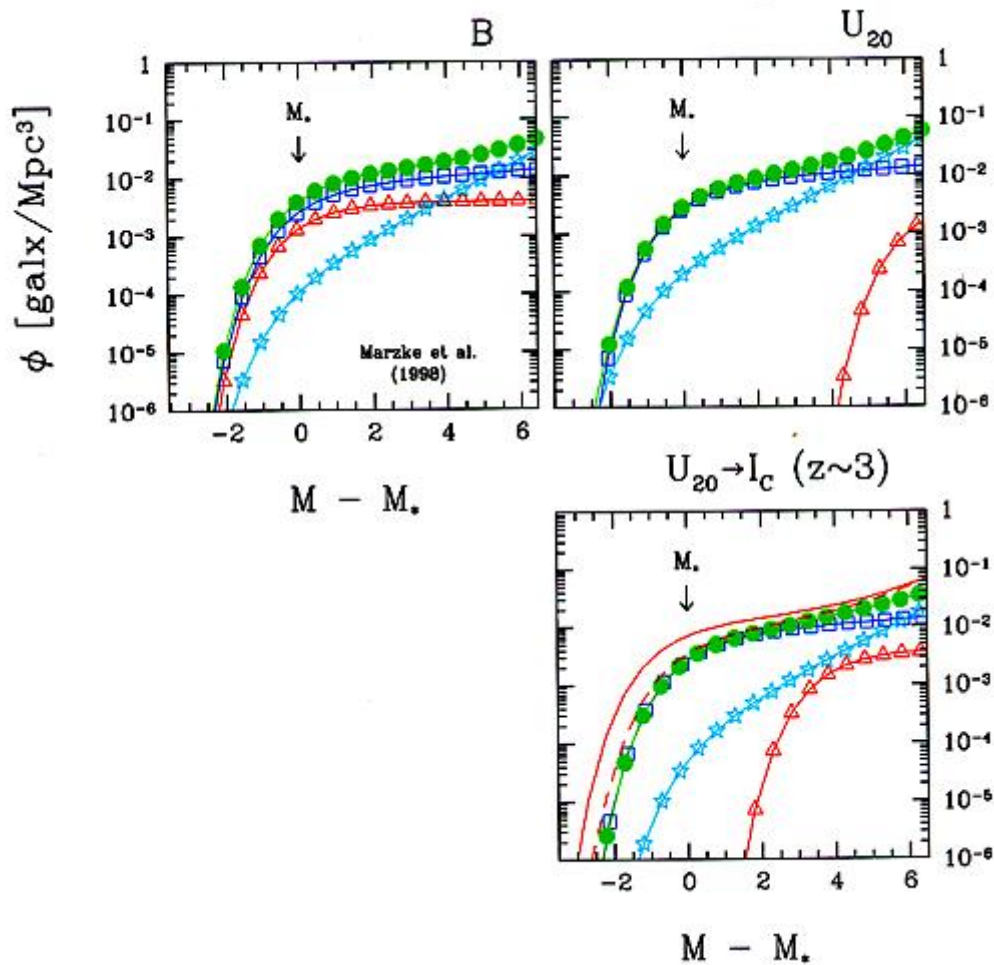


# Funzione di luminosita' delle galassie



Binggeli, Sandage & Tammann (1988)

# Evoluzione con il redshift



## Formula di fit di Schechter (1976)

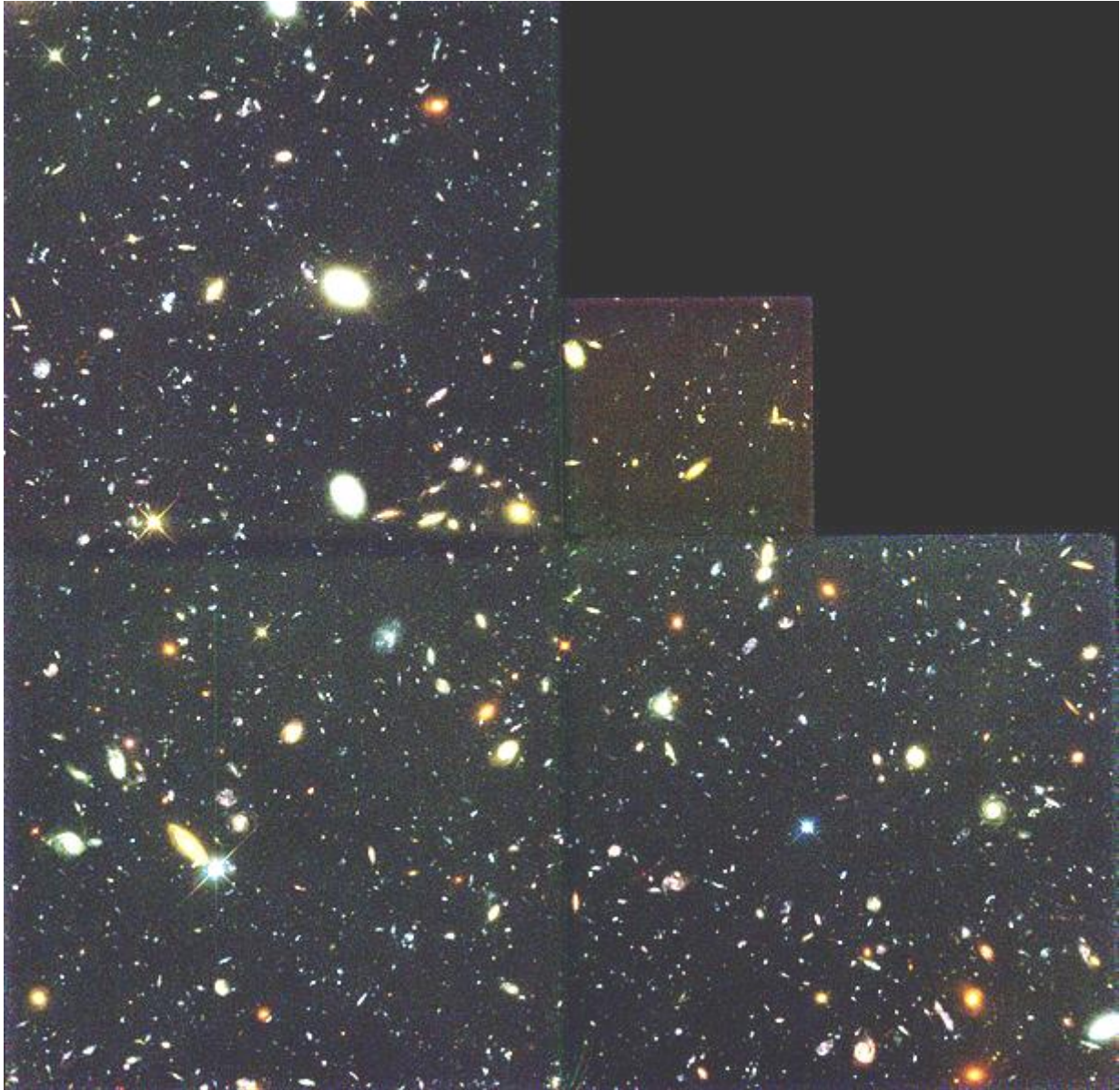
$$n(x) dx = \phi^* x^\alpha e^{-x} dx,$$

Il suo equivalente, nel dominio delle magnitudini è

$$n(M) dM = 0.4 \ln 10 \phi^* [10^{-0.4(M-M^*)}]^{\alpha+1} \exp[-10^{-0.4(M-M^*)}] dM.$$

[http://en.wikipedia.org/wiki/Luminosity\\_function\\_\(astronomy\)](http://en.wikipedia.org/wiki/Luminosity_function_(astronomy))

# Le surveys profonde: l' Hubble Deep Field



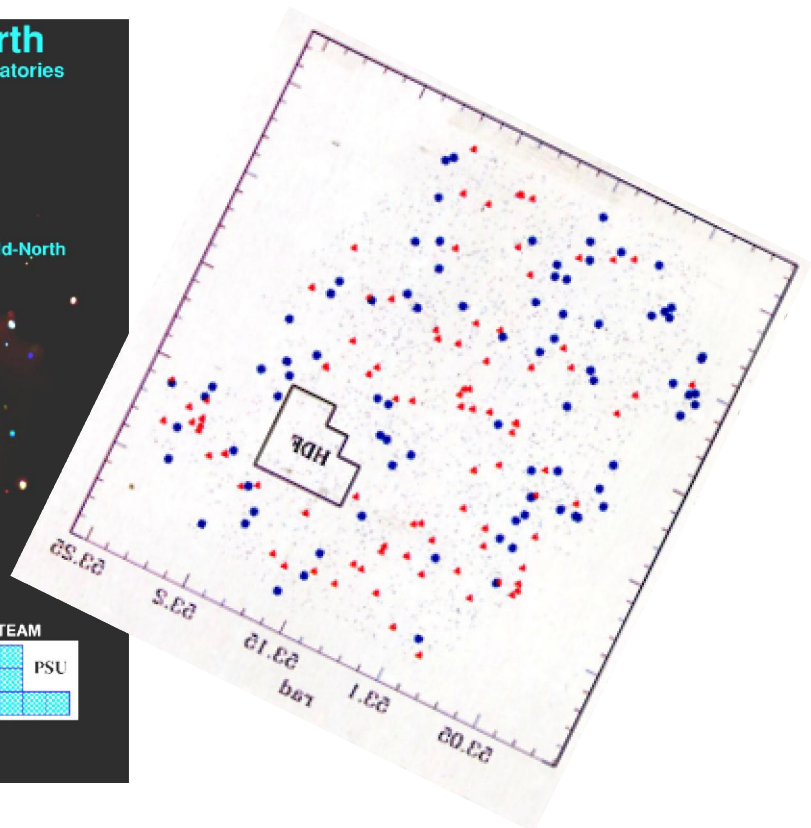
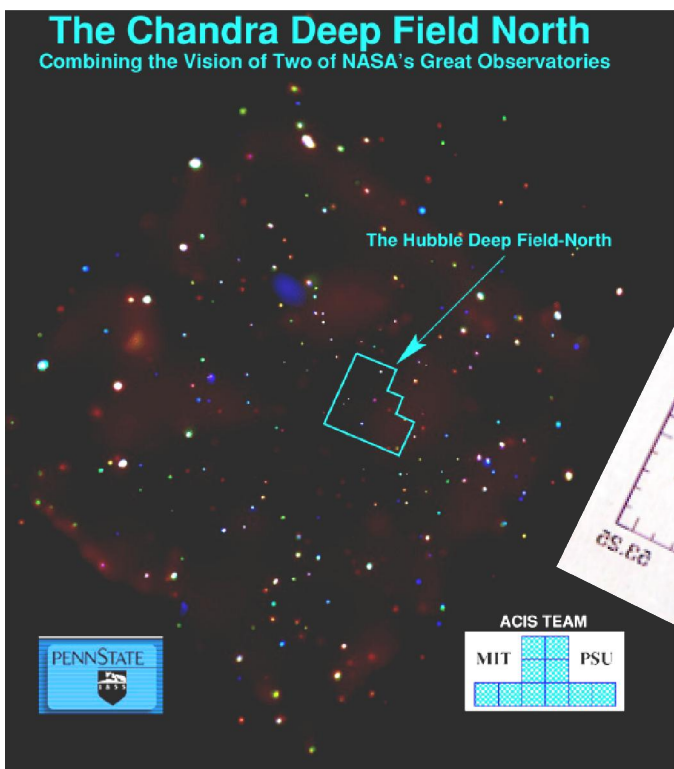
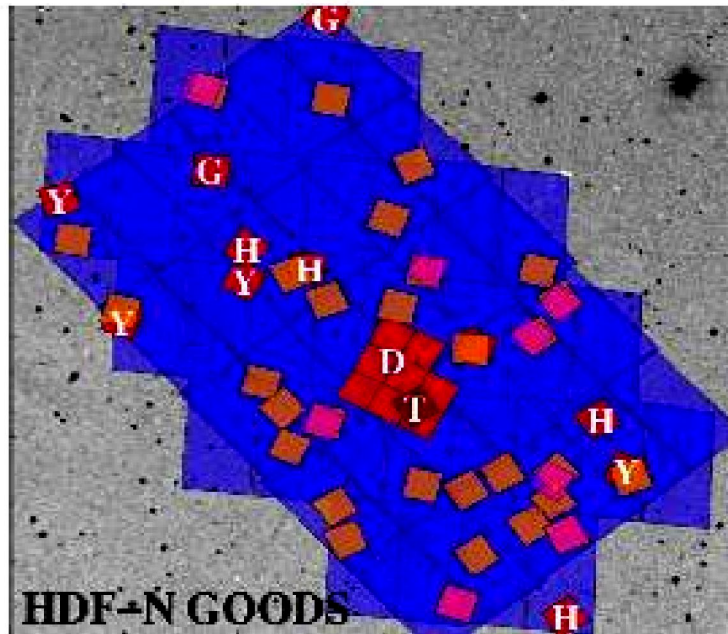
**2.5 arcmin × 2.5 arcmin**

10 giorni di integrazione: dal 18 al 28 Dicembre 1995

3000 oggetti trovati

[http://en.wikipedia.org/wiki/Hubble\\_Deep\\_Field](http://en.wikipedia.org/wiki/Hubble_Deep_Field)

# Surveys multiwavelength: HDFN + GOODS + CHANDRA



<http://it.wikipedia.org/wiki/GOODS>

<http://chandra.harvard.edu/photo/2003/goods/>

**Articoli consigliati (vedi Webpage):**

<http://www.bo.astro.it/~eps/lezioni/lezioni.html>

- Faber & Jackson
- M/L clusters (Girardi)
- Galaxy Colors (Buzzoni)
- K-correction (Hogg et al.)
- LF & cosmological test (Brown & Tinsley)
- LF (Schechter)
- LF evolution (Buzzoni)
- LF evolution (Marzke)
- Dropout galaxies (Madau)
- Galaxy Spectral Atlas (Kennicutt1)
- Galaxy Spectral Atlas (Kennicutt2)
- Balmer break (Hamilton)
- Grandi Surveys Extragalattiche