Galaxies: observations, physics and evolution

Véronique Buat

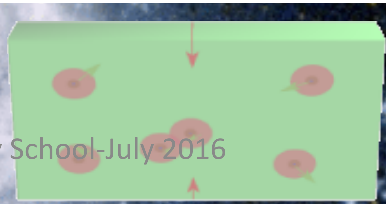
I: The whole Energy Distributions of galaxies: observations of the different components

II:Linking stellar and dust emission: physical processes and related parameters, SFR and stellar masses

I: Galactic (Chemical) Evolution; introduction, examples, abundance measurements, definitions, IMF, SFR, returned fraction.

II: Star Formation Laws; threshold, resolution effects, star formation laws, state of the art of observations, gas measurements.

Samuel Boissier



The whole Energy Distributions of Galaxies

Observation of the different components

Véronique Buat

Outline

- An overview: the « warm » components of a galaxy
- Photometric observations of galaxies
- Main spectral lines and spectral features
- Dust emission

Outline

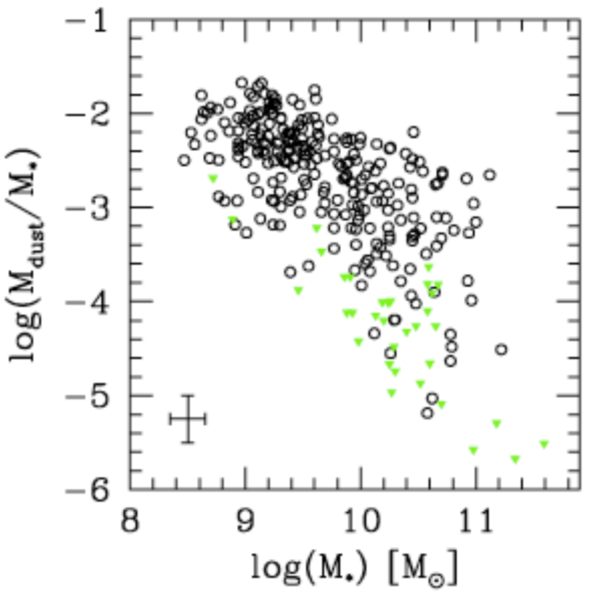
- **An overview: the « warm » components of a galaxy**

  Stars, gas & dust
- Photometric observations of galaxies
- Main spectral lines and spectral features
- Dust component

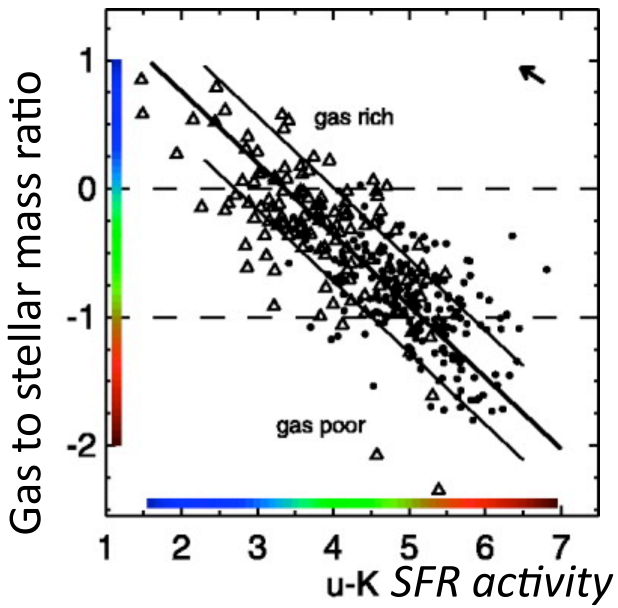
The components of a galaxy

I	Stars:	direct photospheric emission	(UV through mid-IR)
		stellar winds	(emission lines, IR from dust shells)
		accretion phenomena	(binary X-ray sources, the odd SS 433 clone)
II	Gas:	cold	(H I, molecular clouds)
		warm (10^4 K, emission-line gas)	H II regions, planetary nebulae
			(reprocessed stellar ultraviolet ionizing radiation)
		warmer (2-3 x 10^4 K)	supernova remnants, shocked gas
		active nuclei	(whole range of conditions)
		hot (10^7 K)	typically X-ray gas, also seen in absorption lines
III	Dust:	thermal emission	(reprocessed starlight, shock heating)
		quasi-thermal	(transient heating of single grains)
		absorption	against starlight or emission-line sources
		scattering	(via polarization)

The relative contribution of the components



1% (even less) of the ISM is found in solid form (dust) (Cortese+12)



Large variations among galaxies

For the Milky Way:

M(baryons) = 9.5 10^{10} M_{sun}

M(atomic gas) = 8 10^{9} M_{sun}

M(ionized gas) = 2 10^{9} M_{sun}

M(molecular gas) = 2.5 10^{9} M_{sun}

M(dust) ~10^{8} M_{sun}

I. Stars: the global stellar Content

Stellar spectra

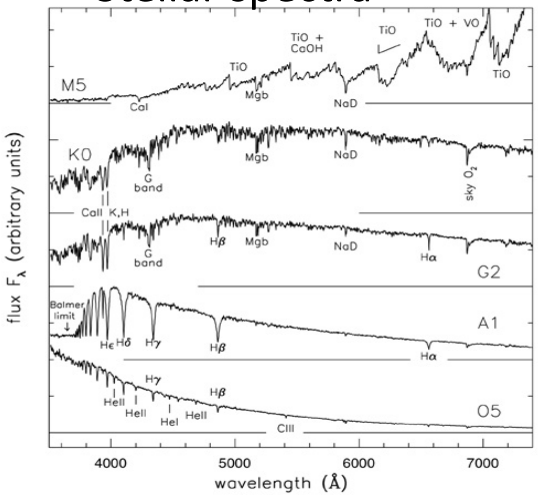


Fig 1.1 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Isochrones

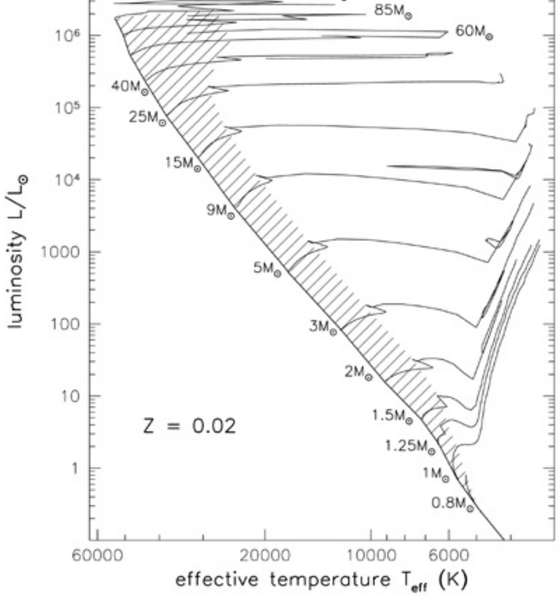
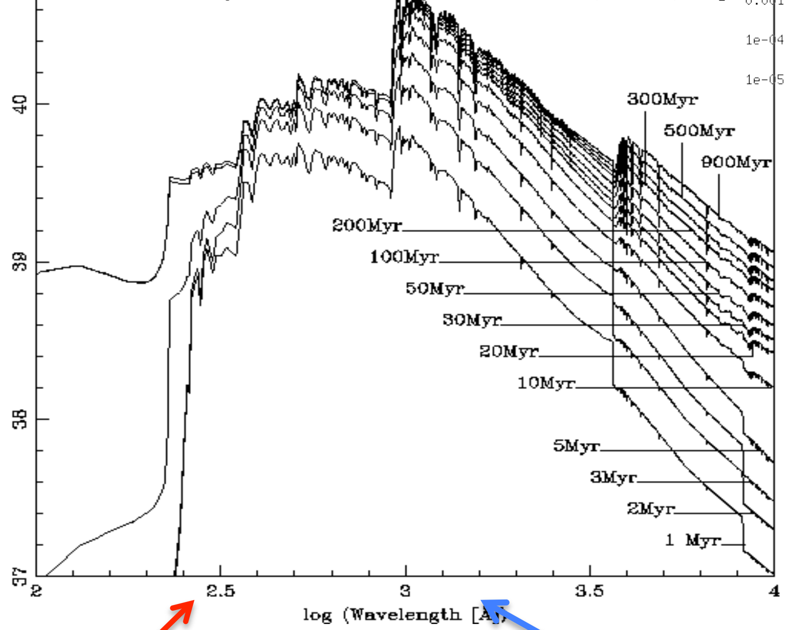
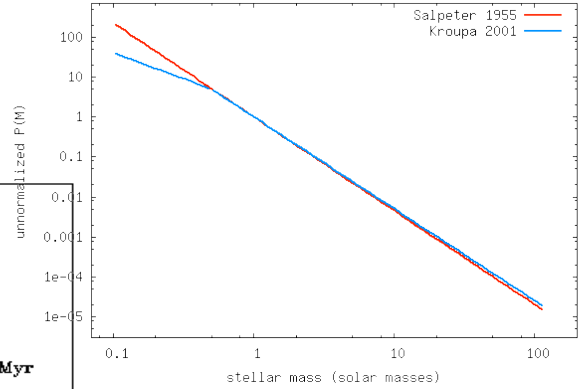


Fig 1.4 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

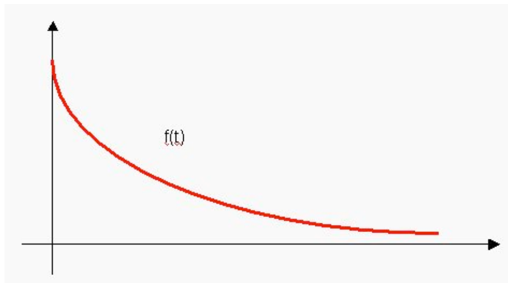
StellarPopulation Synthesis (SPS)



Initial Mass Function



Star formation history

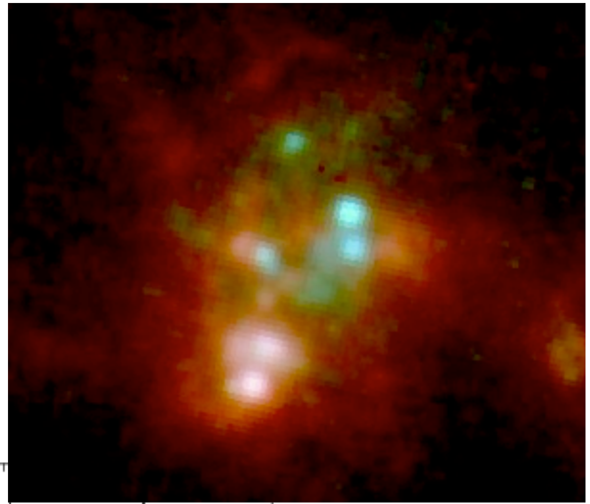


+ metallicity dependence

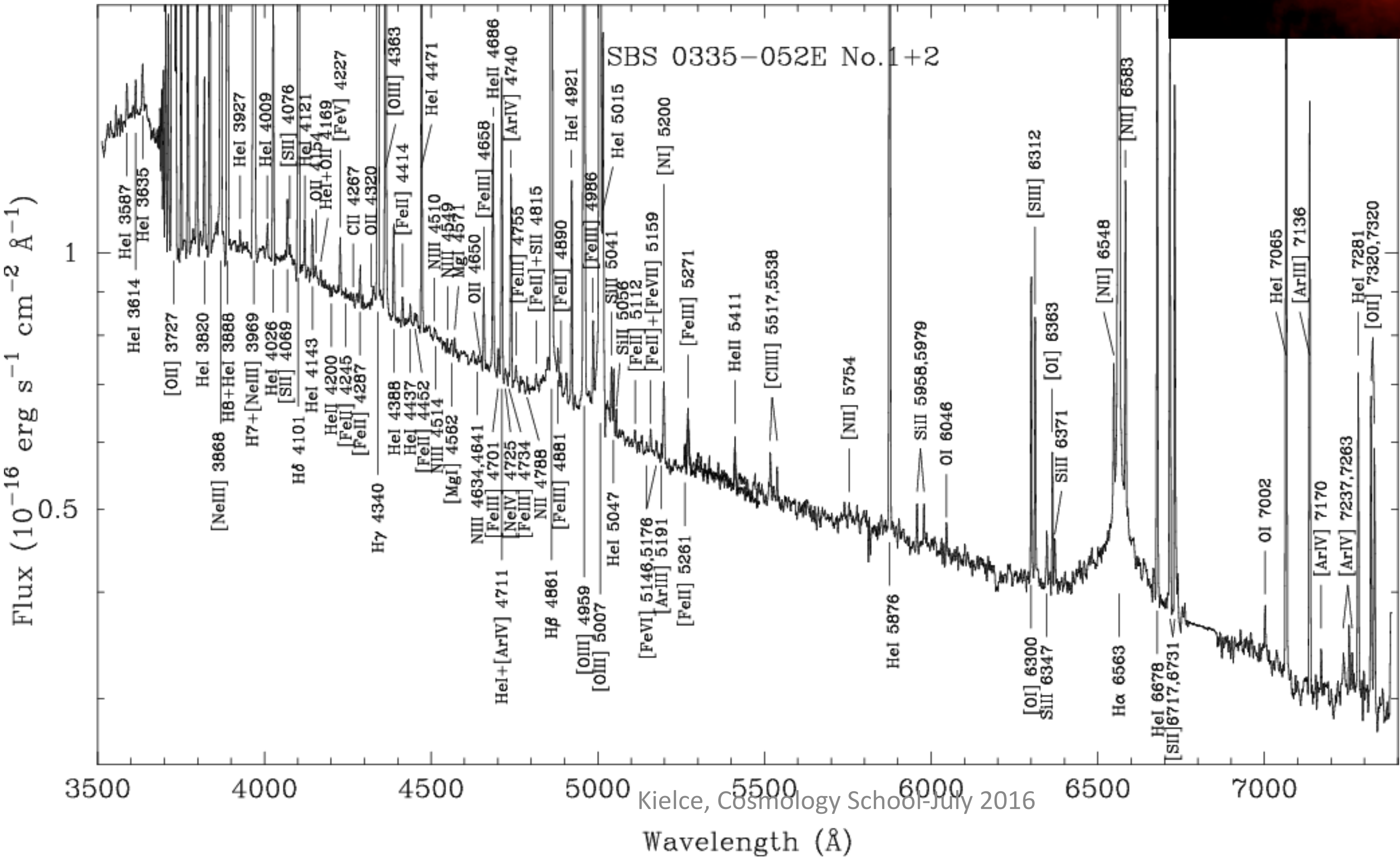
II gas: The (warm) gas content

- HI: 21 cm line → Samuel's talk
- H_2 (and its tracers) → Samuel's talk
- HII-→ recombination lines overimposed on the stellar continuum.

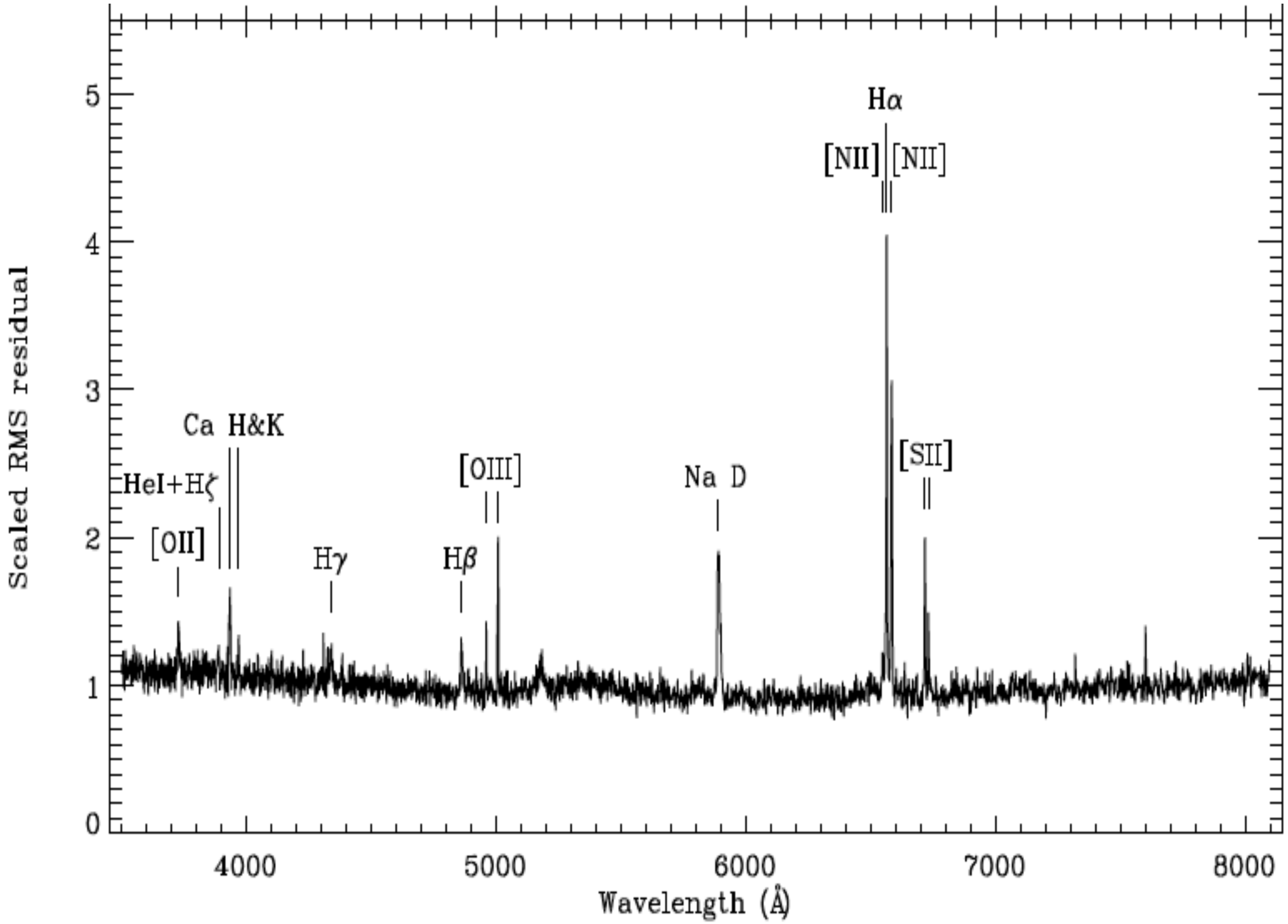
SBS 0335-052:
 a blue compact dwarf galaxy system
Extremely metal poor galaxy:
12+log(O/H)=7



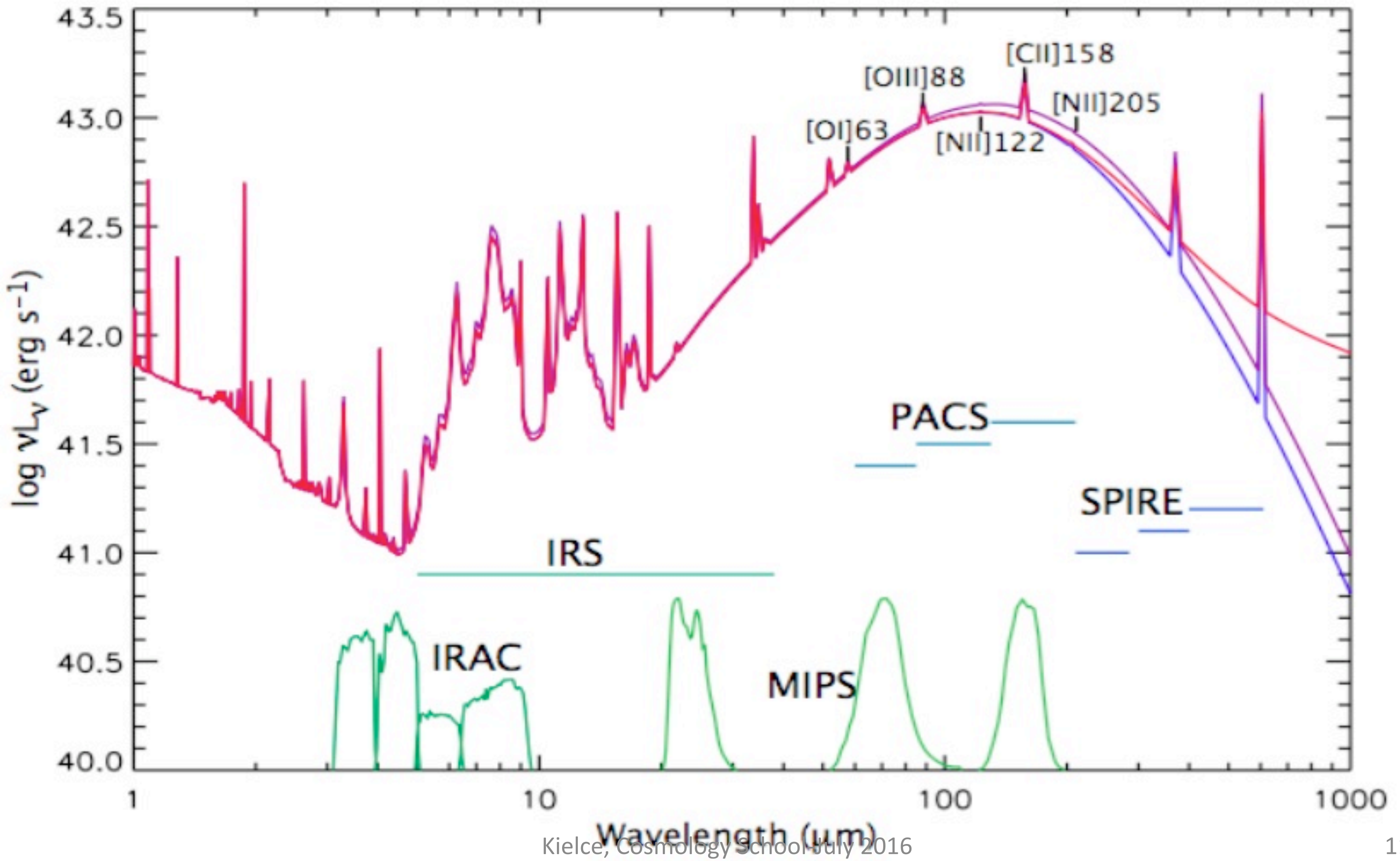
Izotov+09, VLT/FORS spectrum

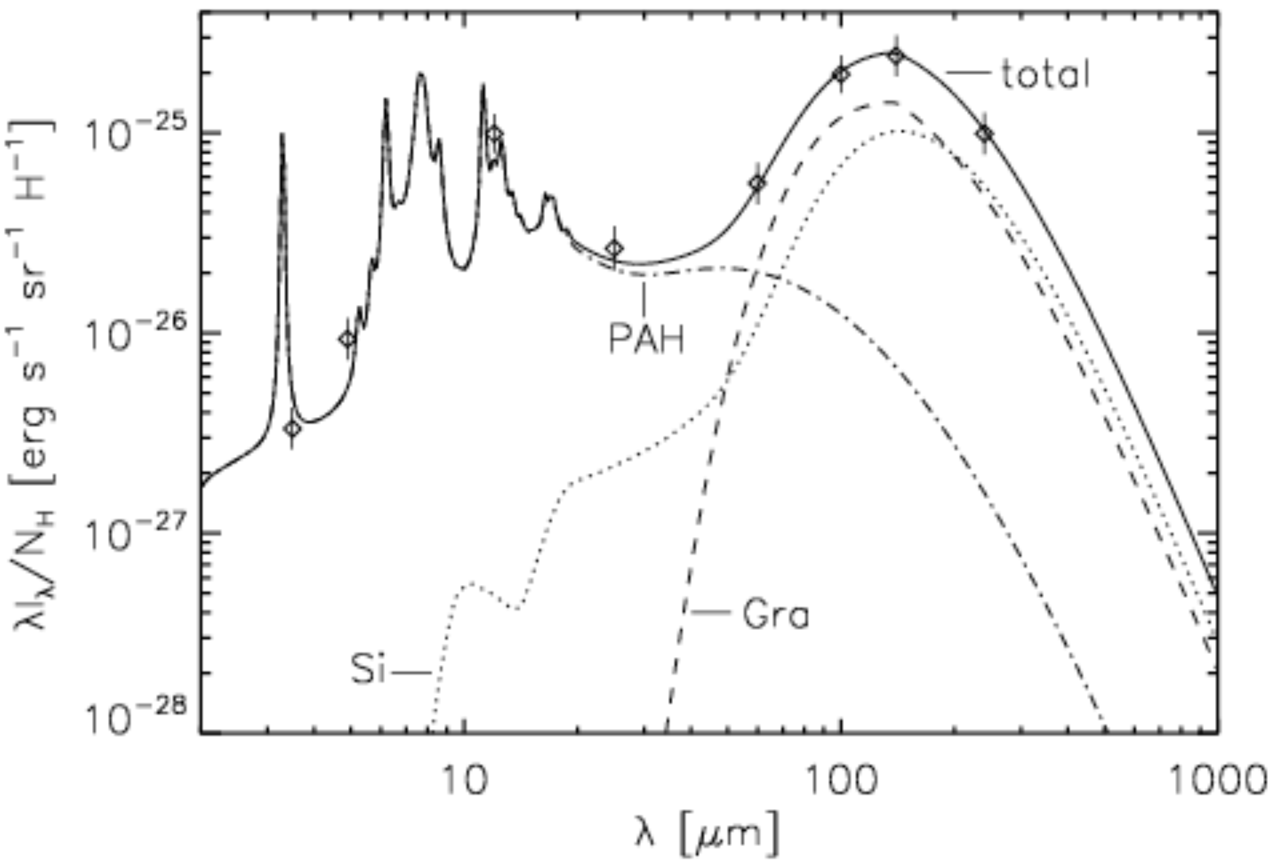


More representative of star forming galaxies: Mostly Hydrogen and Oxygen lines



III Dust: the dust emission



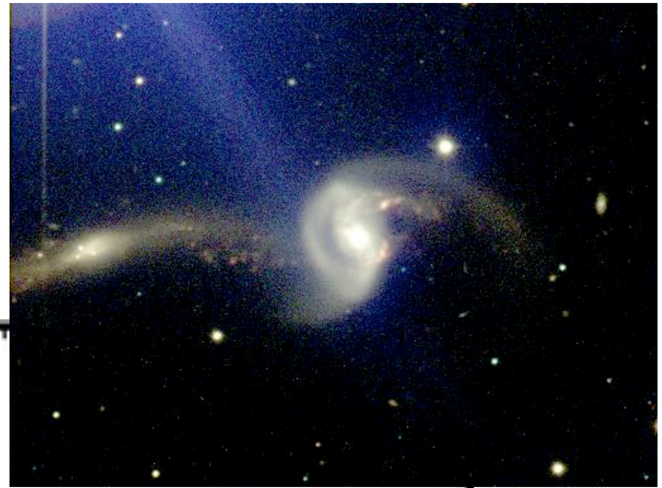


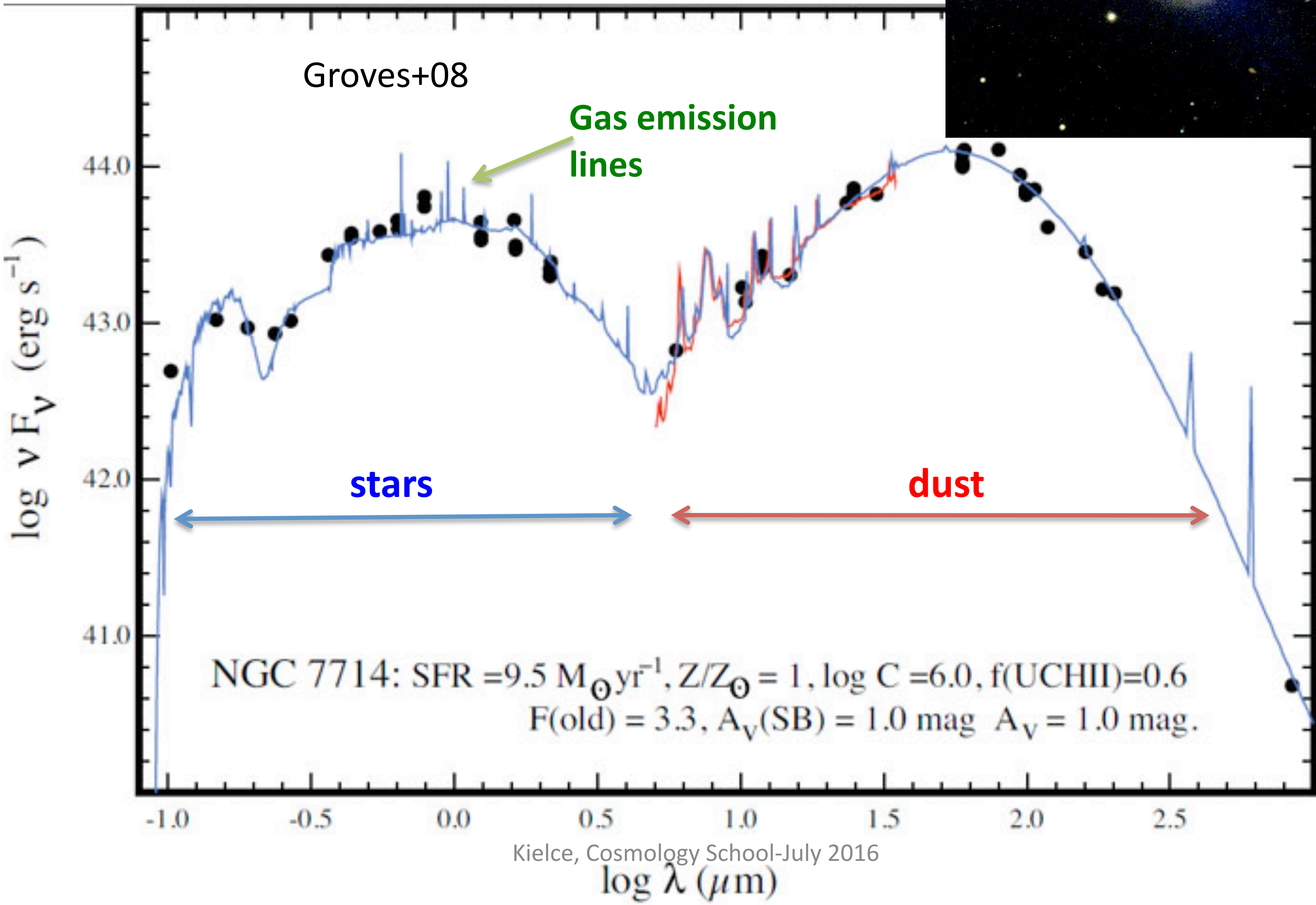
total
PAH
Gra
Si
10^{-25}
10^{-26}
10^{-27}
10^{-28}
10
100
1000
$\lambda I_\lambda/N_H$ [erg s^{-1} sr^{-1} H^{-1}]
λ [μm]

Popescu+11

Spectral Energy Distribution (SED) of a galaxy :

NGC 7714 (a nearby starburst)





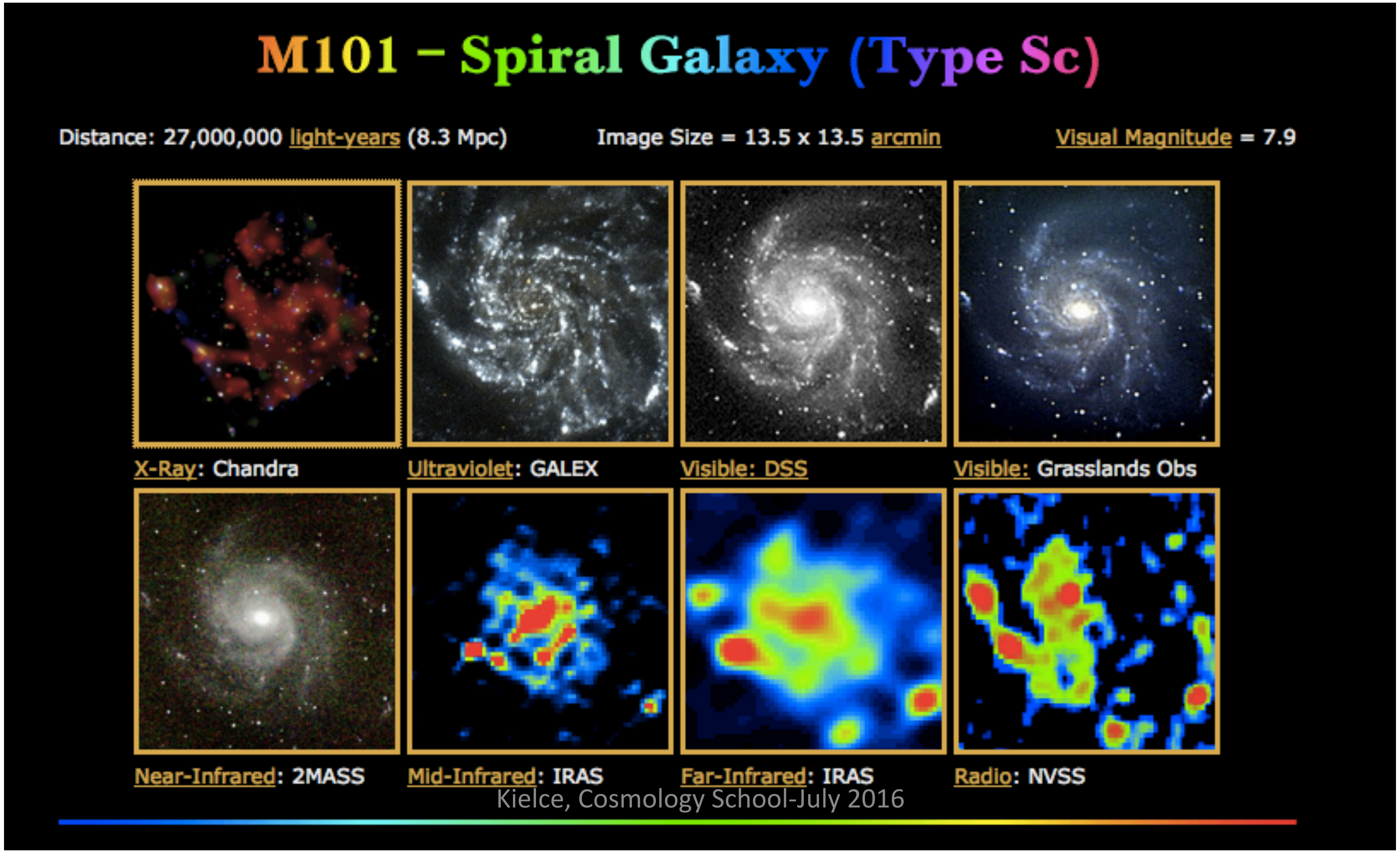
Outline of the lecture

- The « warm » components of a galaxy
- **Photometric observations of galaxies**
  multi-λ data, redshifted SEDs
- Main spectral lines and spectral features
- Dust component

Photometric data:
Galaxies at different wavelengths

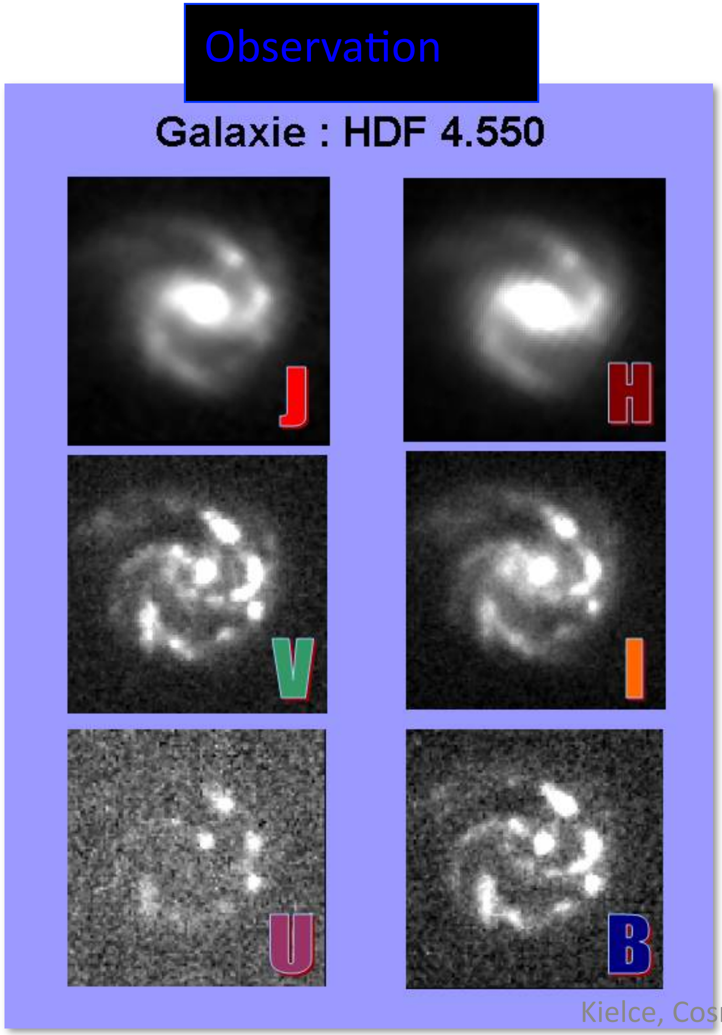
The morphological classification of galaxies was built in visible → may be quite different in other wavelengths, as illustrated with M101

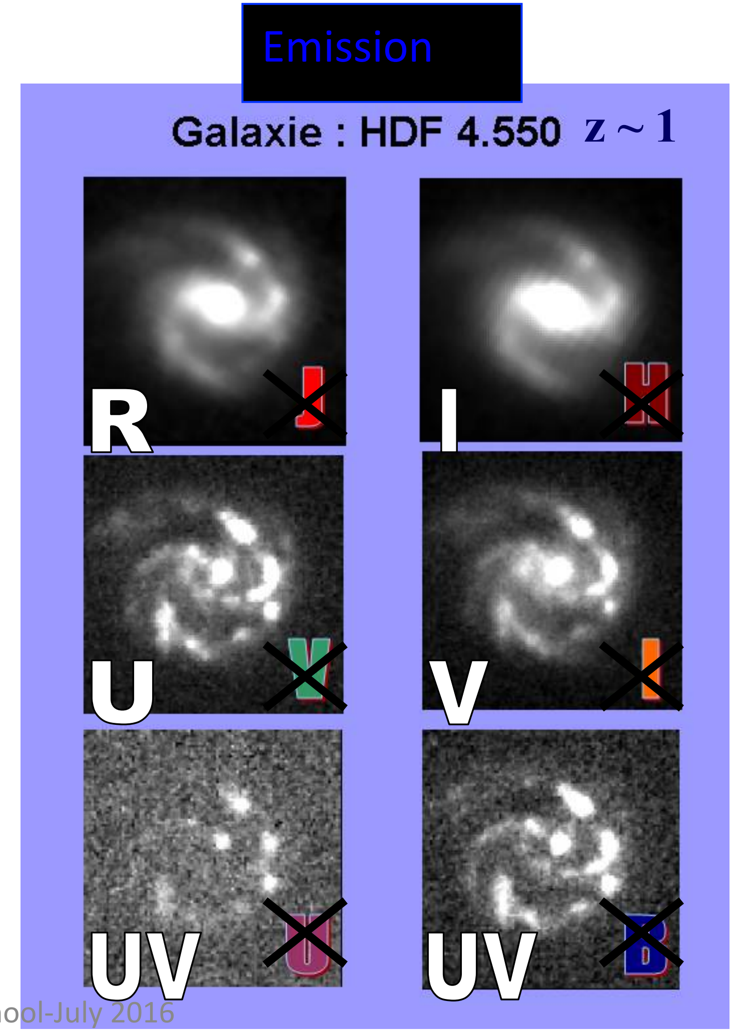
The bulge/disk ratio, arm/interarm contrast are different for the different wavelengths



The situation is getting even more complicated when going to high redshift

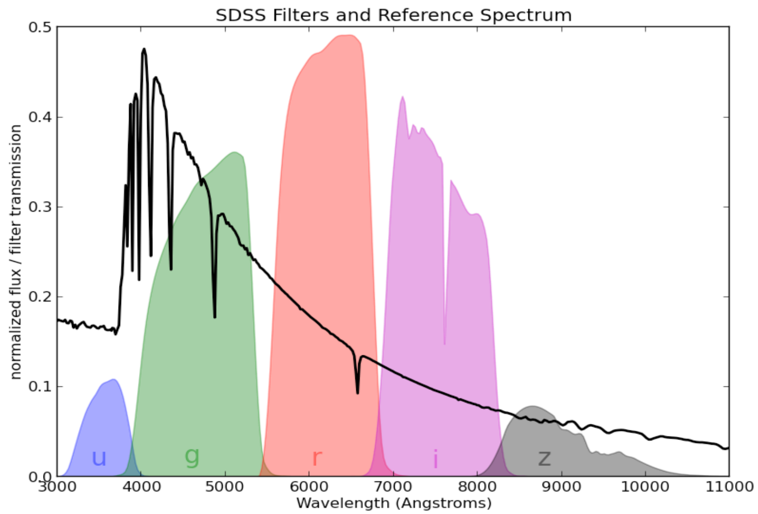
HDF 4.550 at z=1

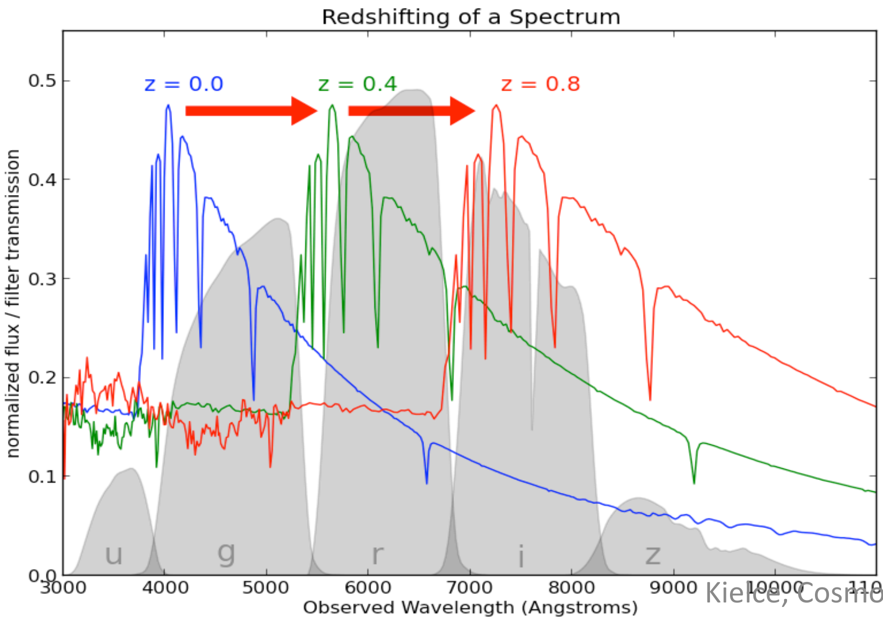




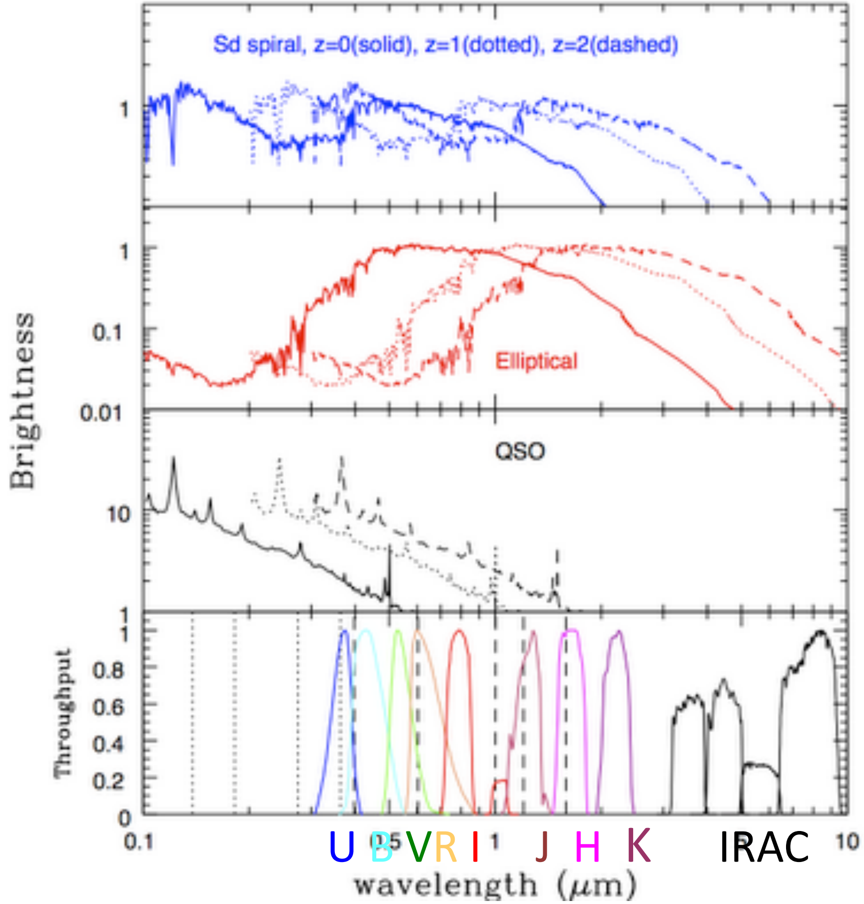
Multi-wavelength photometric observations of galaxies to understand their nature

For a single stellar population





More complex and realistic SEDs, CANDELS project



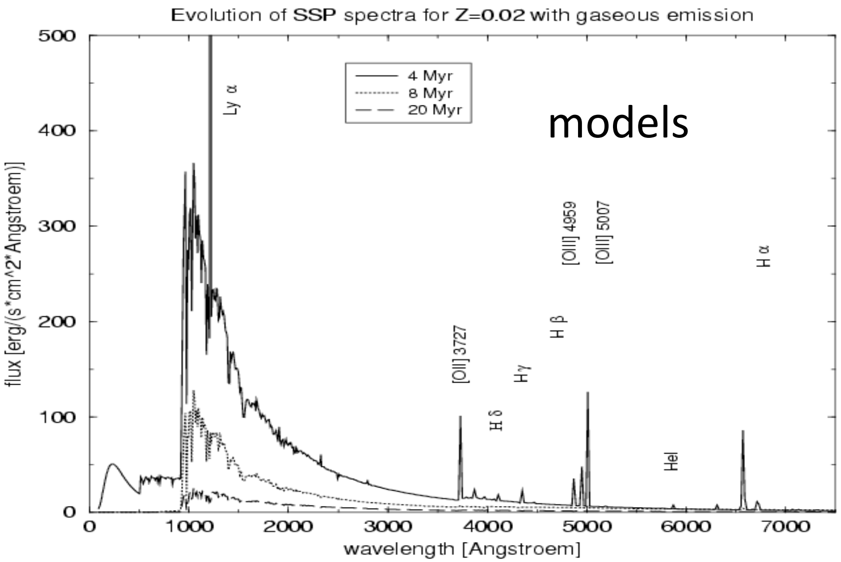
Outline of the lecture

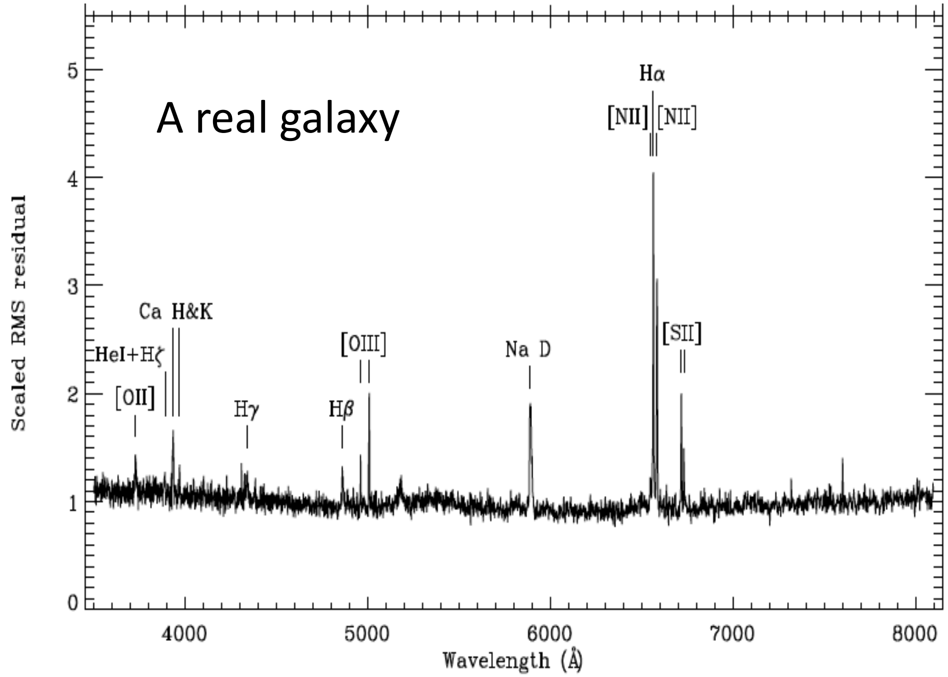
- The « warm » components of a galaxy
- Photometric observations of galaxies
- **Main spectral lines and spectral features**

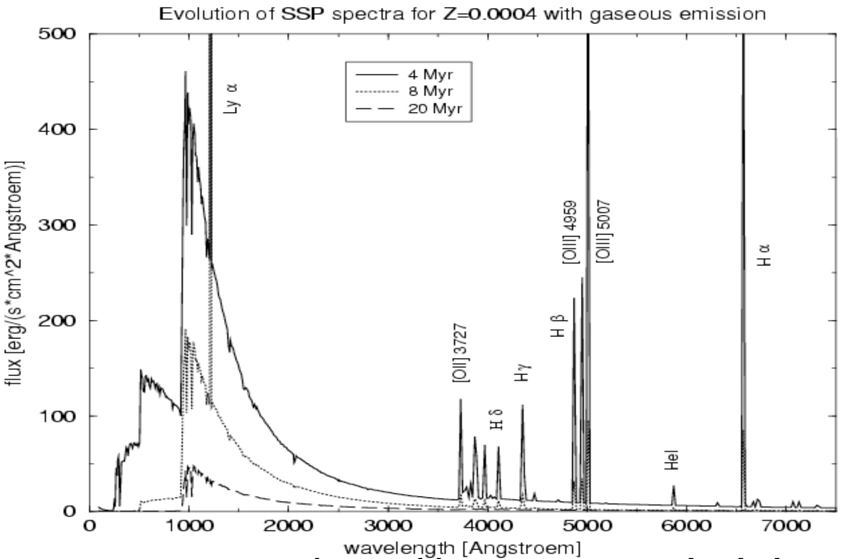
Main emission lines, AGN and normal galaxies, breaks, high redshift galaxies & nearby universe

- Dust component

Spectral lines emission







http://www.astro.virginia.edu/sdc4sb/tableofemissionlines.html

Case B of recombination: optically thick to ionizing photons and Lyman lines

All Lyman line photons are re-absorbed by other hydrogen atoms

Every decay must eventually go to n=2,

→ counting **the Balmer photons** gives access to the number of Lyc photons,

$$F(H_\beta) = 4.757 \times 10^{-13} \cdot N_{Lyc}$$

Ly

decay from n=2 to n=1 with the 2-

		Lower level									
		2 (Balmer)		3 (Paschen)		4 (Brackett)		5 (Pfund)		6 (Humphreys)	
limit		3646.0		8203.6		14584		22788		32814	
Upper level	9	3835.4	0.0734	9229.0	0.0254	18174	0.0126	32961	0.00725	59066	0.00456
	8	3889.1	0.105	9546.0	0.0365	19446	0.0181	37395	0.0104	75005	0.00649
	7	3970.1	0.159	10049.4	0.0553	21655	0.0275	46525	0.0158	123680	0.00927
	6	4101.7	0.260	10938.1	0.0901	26252	0.0447	74578	0.0245		
	5	4340.5	0.469	12818.1	0.162	40512	0.0777				
	4	4861.3	1.00	18751.0	0.332						
	3	6562.8	2.85								

Other lines than H, normalized to Hβ From observations or modeling PHOTO-IONIZATION CODES

Table 1. Non-hydrogen emission lines and their line strengths, normalized to H_β line strength, as a function of metallicity ($Z1 = 0.0004$, $Z2 = 0.004$, $Z3 = 0.008$, $Z4 = 0.02 = Z_\odot$, $Z5 = 0.05$).

Line	λ [Å]	$\frac{F_L}{F_{H_\beta}}$ Z1	$\frac{F_L}{F_{H_\beta}}$ Z2	$\frac{F_L}{F_{H_\beta}}$ Z3–Z5
[CII]	1335.00	0.000	0.000	0.110
[OIII]	1663.00	0.000	0.058	0.010
[CIII]	1909.00	0.000	0.000	0.180
[NII]	2141.00	0.000	0.000	0.010
[CII]	2326.00	0.000	0.000	0.290
[MgII]	2798.00	0.000	0.310	0.070
[OII]	3727.00	0.489	1.791	3.010
[NeIII]	3869.00	0.295	0.416	0.300
H_ζ + [HeI]	3889.00	0.203	0.192	0.107
H_ϵ + [NeIII]	3970.00	0.270	0.283	0.159
[HeI]	4026.00	0.015	0.015	0.015
[SII]	4068.60	0.005	0.017	0.029
[SII]	4076.35	0.002	0.007	0.011
[OIII]	4363.00	0.109	0.066	0.010
[HeI]	4471.00	0.036	0.036	0.050
[ArIV] + [HeI]	4711.00	0.010	0.014	0.000
[OIII]	4958.91	1.097	1.617	1.399
[OIII]	5006.84	3.159	4.752	4.081
[NI]	5199.00	0.003	0.010	0.030
[NII]	5755.00	0.000	0.000	0.010
[HeI]	5876.00	0.096	0.108	0.140
[OI]	6300.00	0.008	0.041	0.130
[SIII]	6312.00	0.009	0.017	0.030
[NII]	6548.05	0.005	0.059	0.136
[NII]	6583.45	0.015	0.175	0.404
[HeI]	6678.00	0.026	0.030	0.030
[SII]	6716.00	0.037	0.188	0.300
[SII]	6730.00	0.029	0.138	0.210
[HeI]	7065.00	0.028	0.023	0.040
[ArIII]	7135.79	0.027	0.071	0.035
[OII]	7319.99	0.012	0.027	0.026
[OII]	7330.73	0.007	0.014	0.014
[ArIII]	7751.11	0.067	0.176	0.086
[SIII]	9068.60	0.000	0.510	0.945
[SIII]	9530.85	0.000	0.000	0.365
[SII]	10286.73	0.000	0.000	0.048
[SII]	10320.49	0.000	0.000	0.058
[SII]	10336.41	0.000	0.000	0.054

The number of Lyc photons is strongly linked to young, hot stars → indicator of the very recent star formation

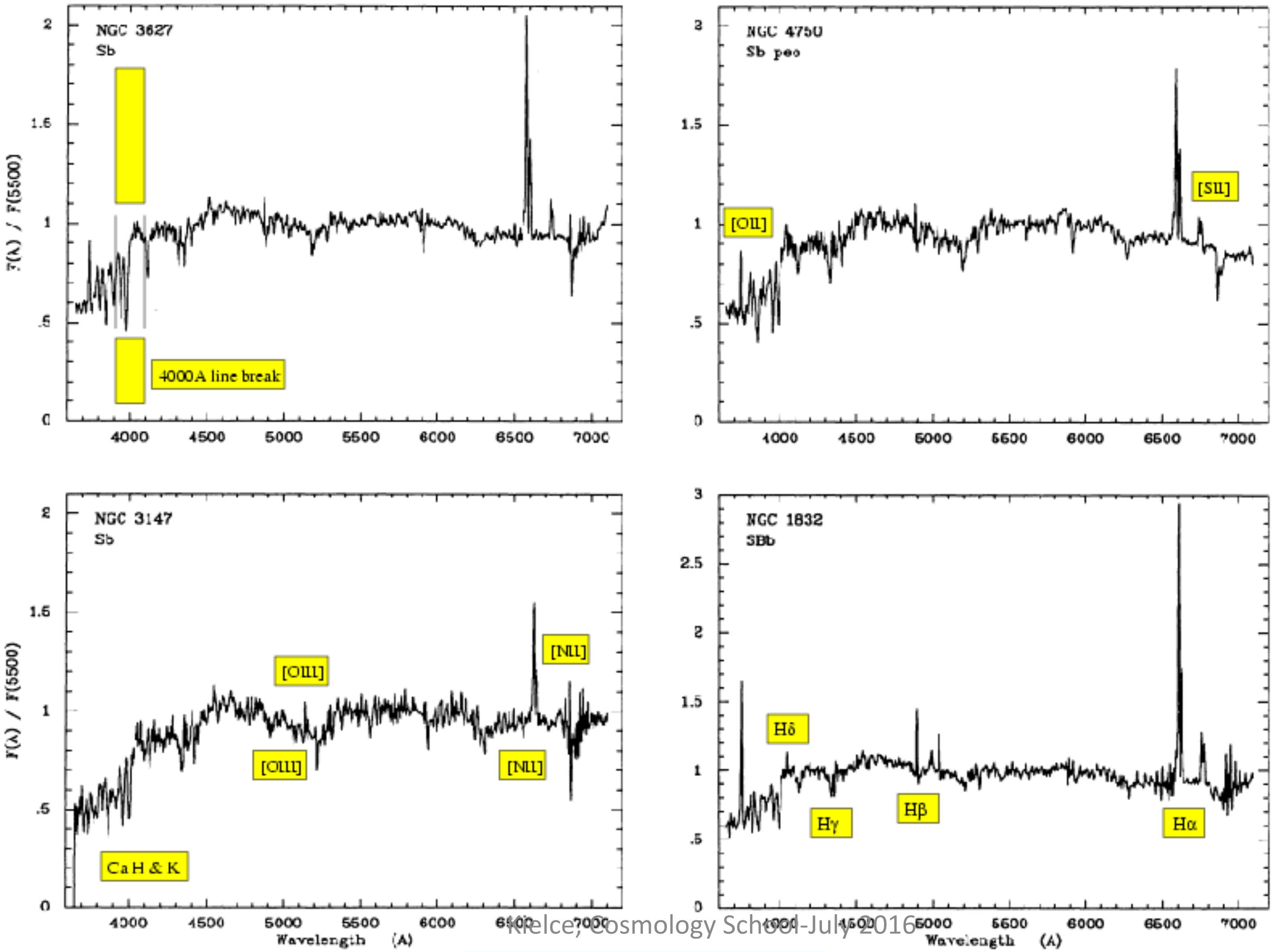
Calculated radii of Strömgren spheres

Spectral type	M_v	$T_*(°K)$	Log $Q(H^0)$ (photons/sec)	Log $N_e N_p r_1^3$ (N in cm^{-3}; r_1 in pc)	r_1 (pc) ($N_e = N_p$ = 1 cm^{-3})
O5	− 5.6	48,000	49.67	6.07	108
O6	− 5.5	40,000	49.23	5.63	74
O7	− 5.4	35,000	48.84	5.24	56
O8	− 5.2	33,500	48.60	5.00	51
O9	− 4.8	32,000	48.24	4.64	34
O9.5	− 4.6	31,000	47.95	4.35	29
B0	− 4.4	30,000	47.67	4.07	23
B0.5	− 4.2	26,200	46.83	3.23	12

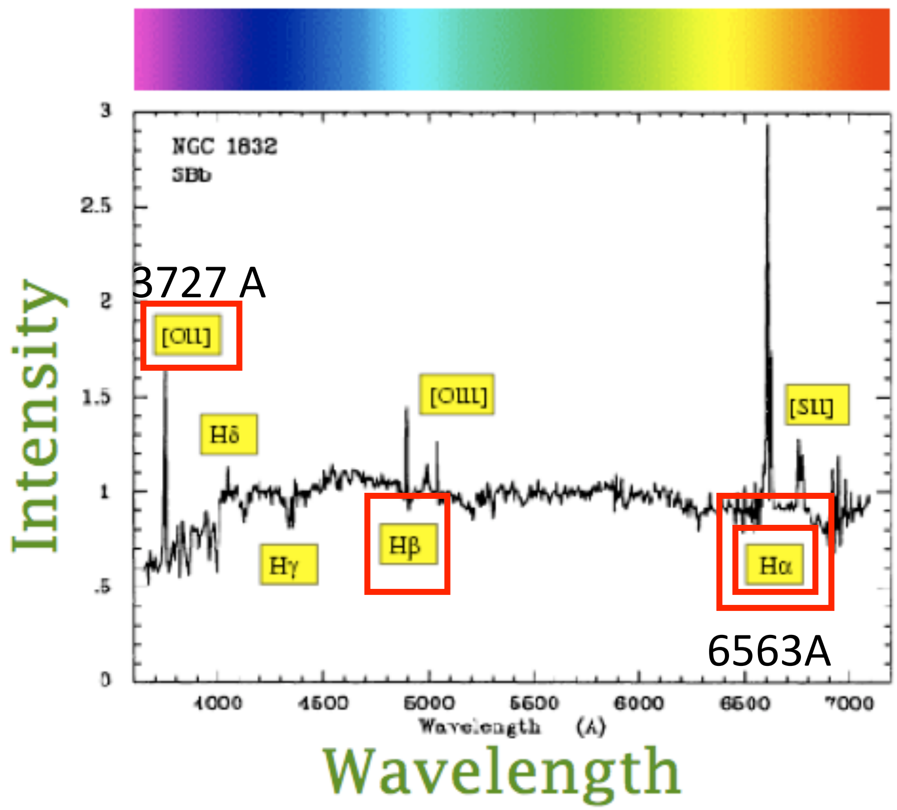
NOTE: $T = 7500°$ K assumed for calculating α_B.

Osterbrock

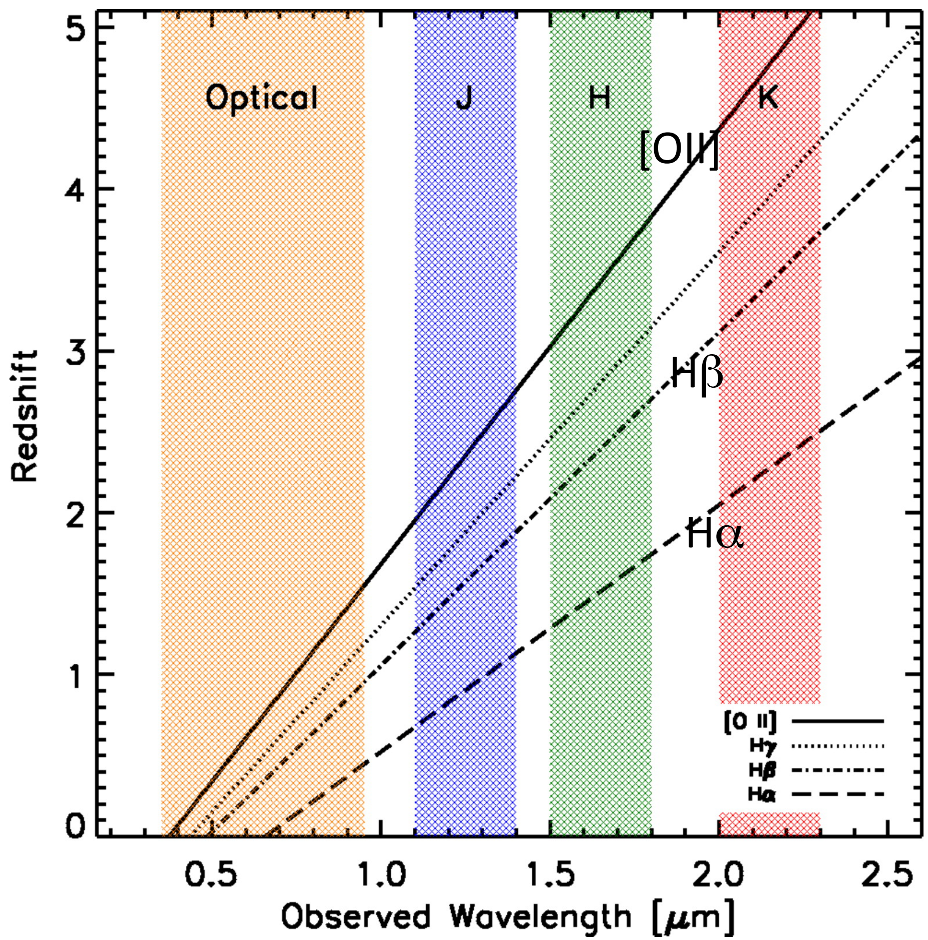
Spectral features differ with morphological type and star formation activity



Hα ([OII], Hß) emission lines used as SFR estimators



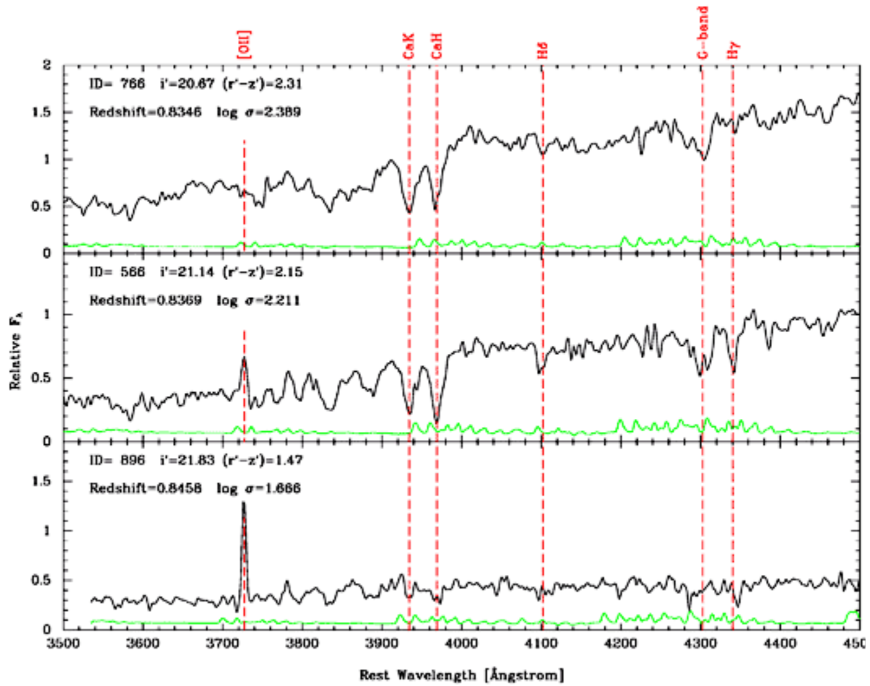
Difficult to observe at z>1



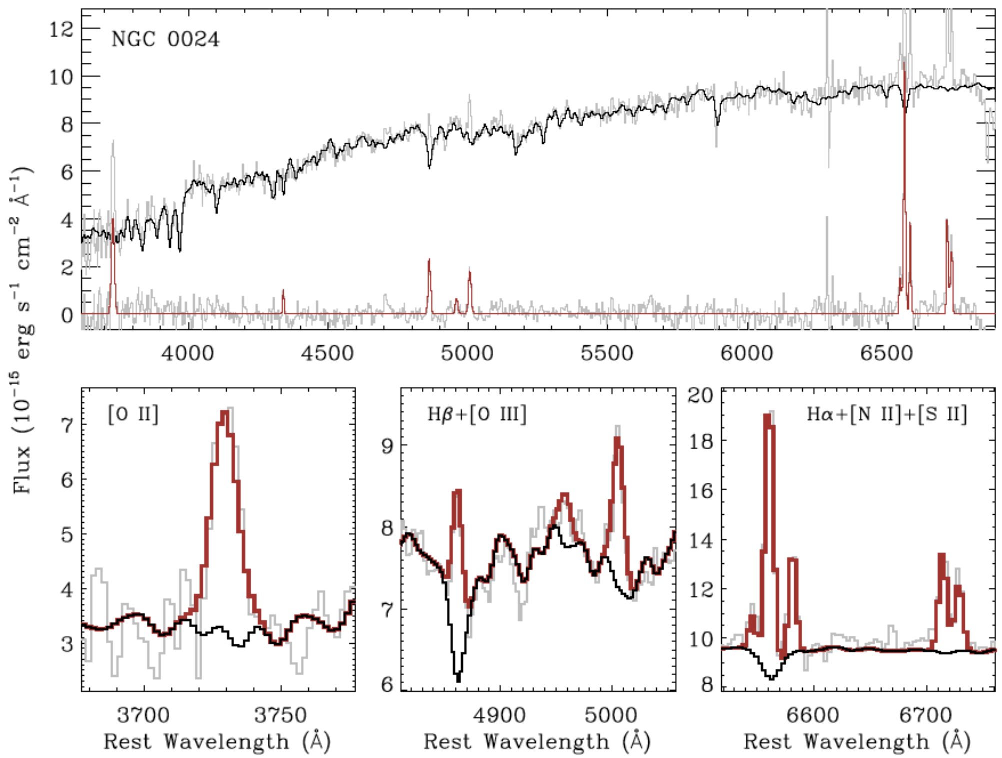
Moustakas et al. 07

Measure of Spectral features in normal galaxies :

- broad absorption lines → stellar content
- Fine emission lines → gas recombination lines



Moustakas+10



Outline of the lecture

- The « warm » components of a galaxy
- Photometric observations of galaxies
- **Main spectral lines and spectral features**

  Main emission lines**, AGN and normal galaxies**, breaks, high redshift galaxies & nearby universe
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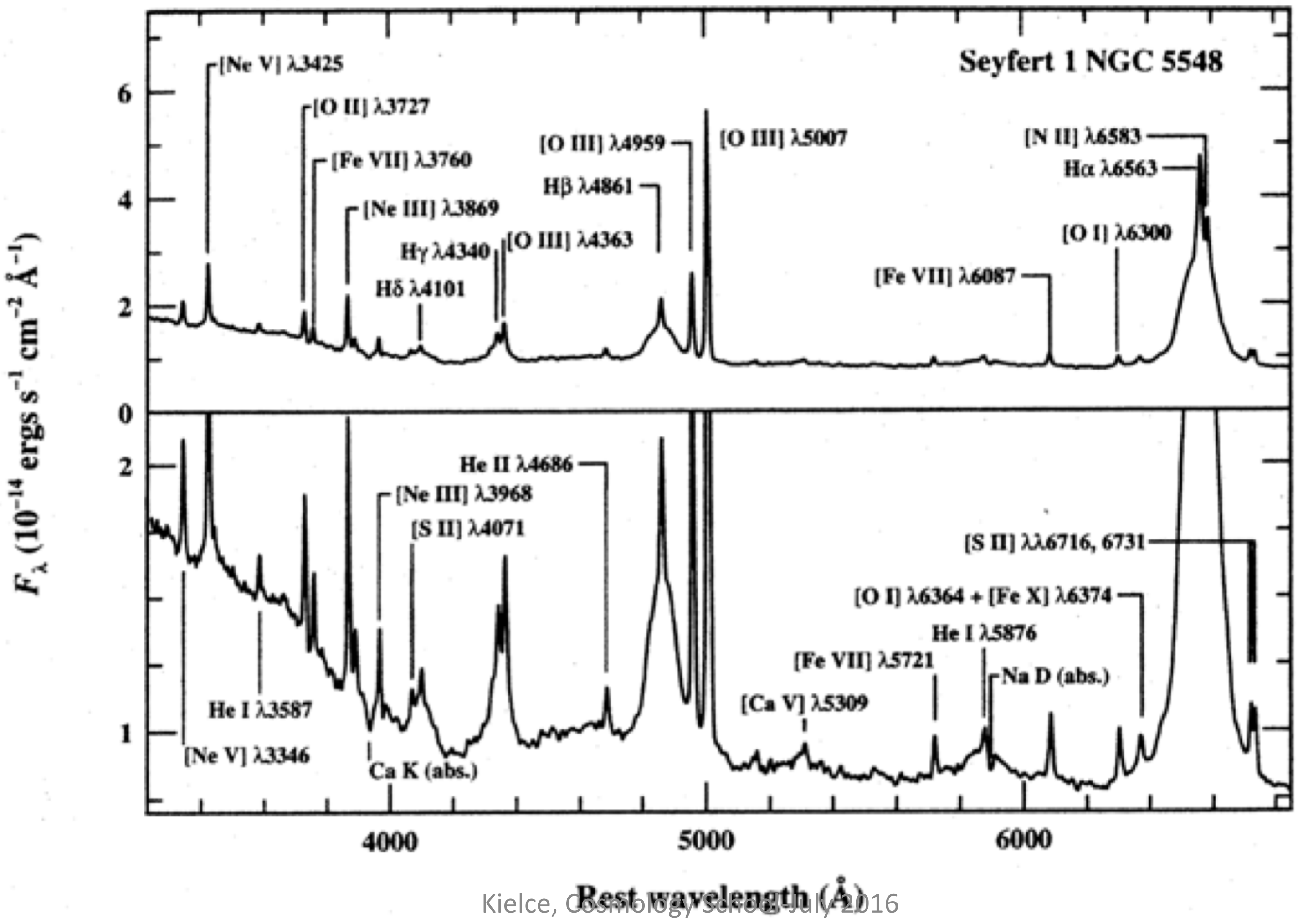
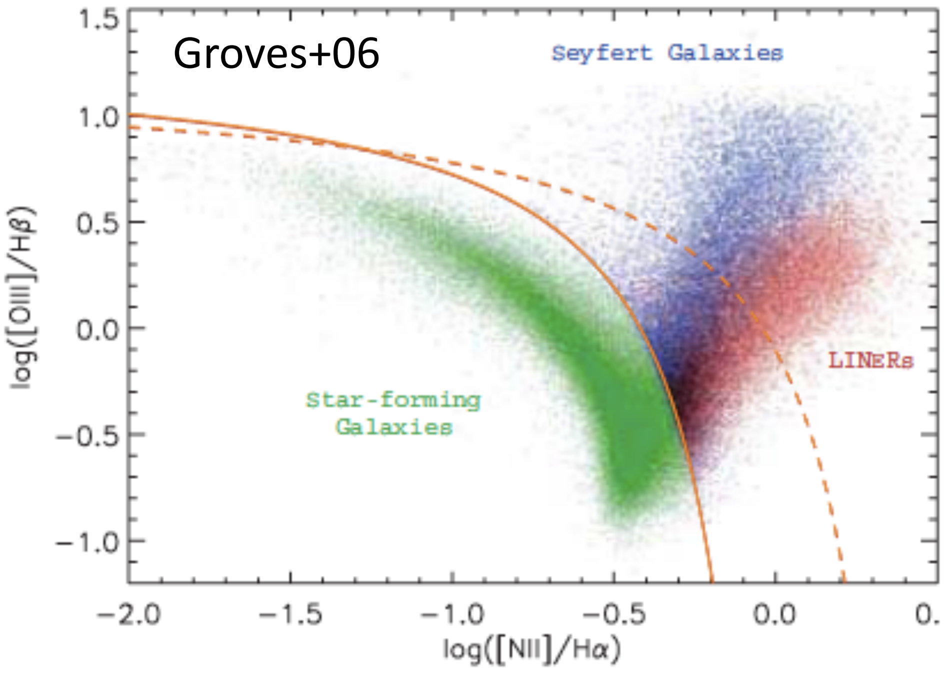
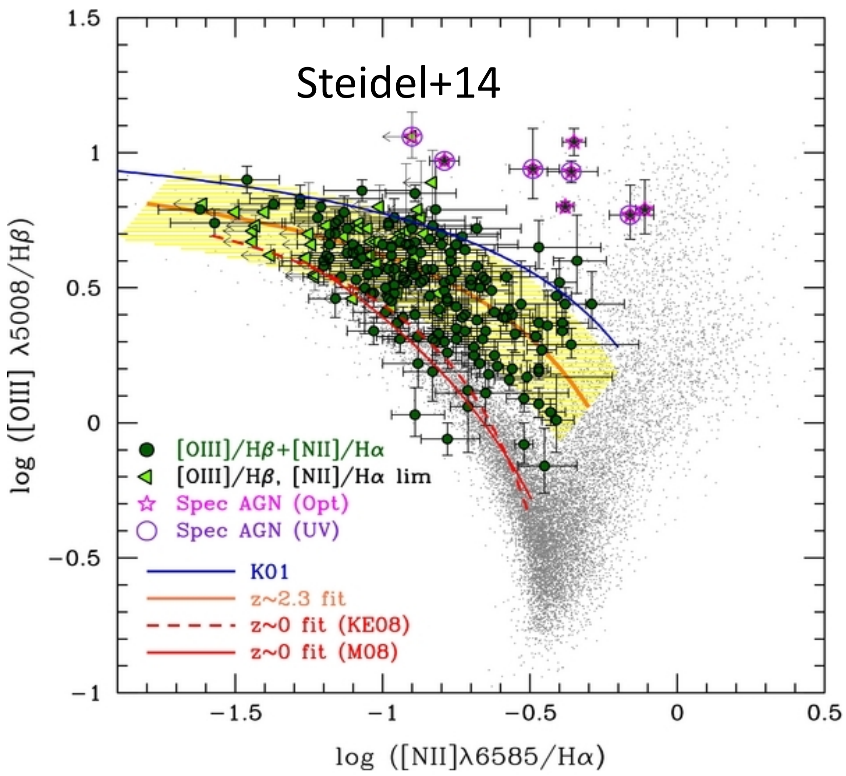
- The spectrum of an active (AGN) galaxy differs with broad and fine emission lines with very high ionisation levels



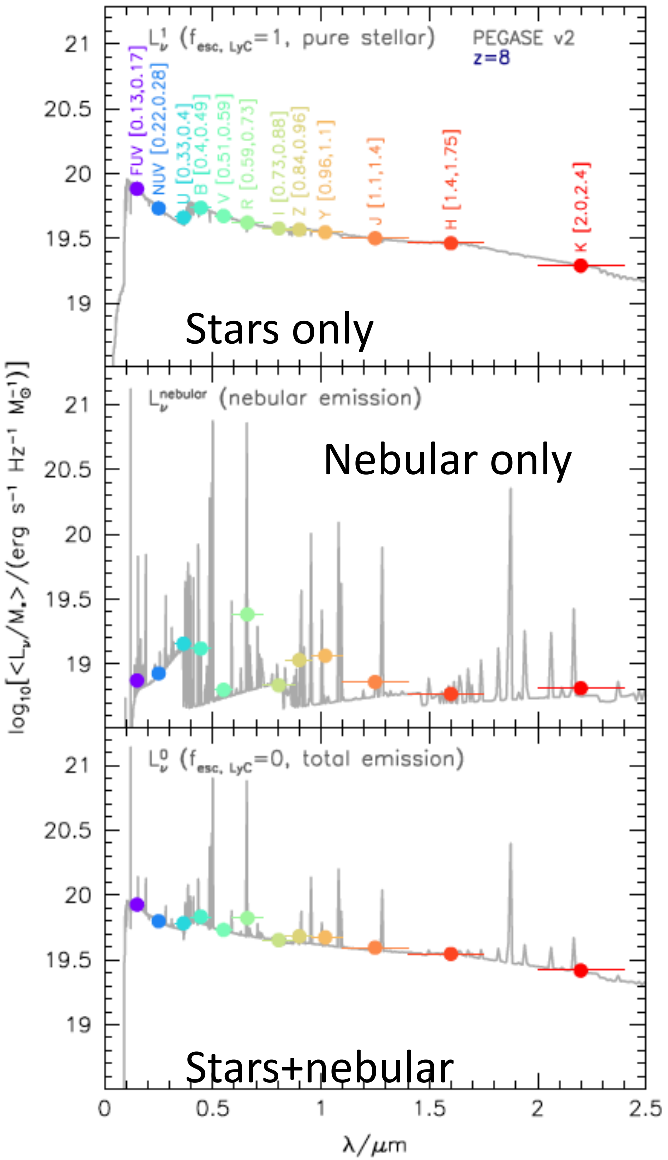
Diagnostics to separate normal and AGN dominated galaxies

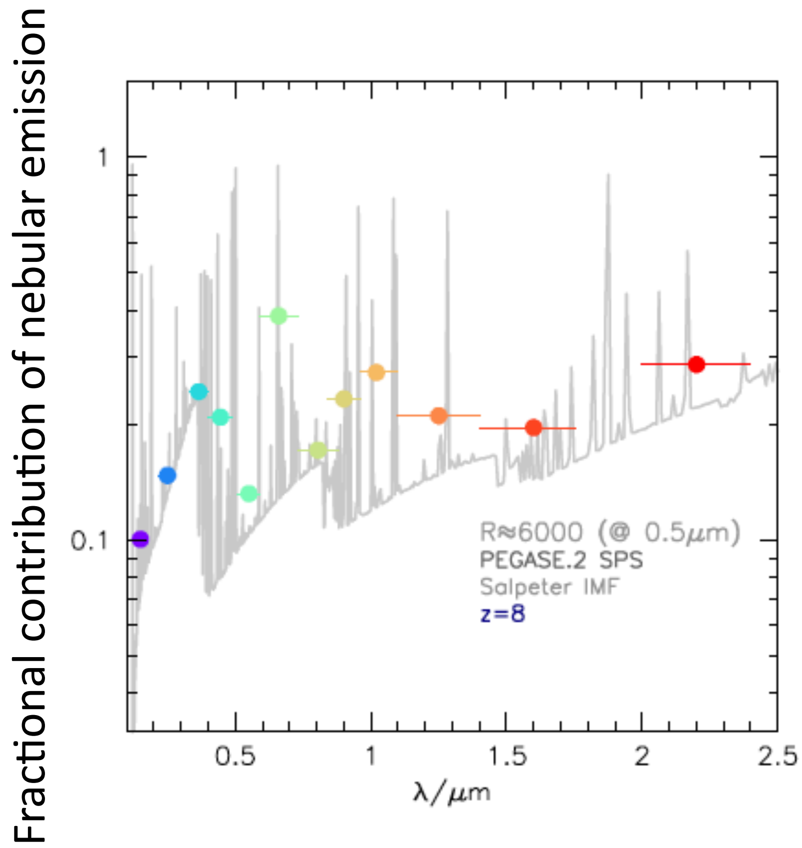




When z increases, harder radiation field, higher ionization

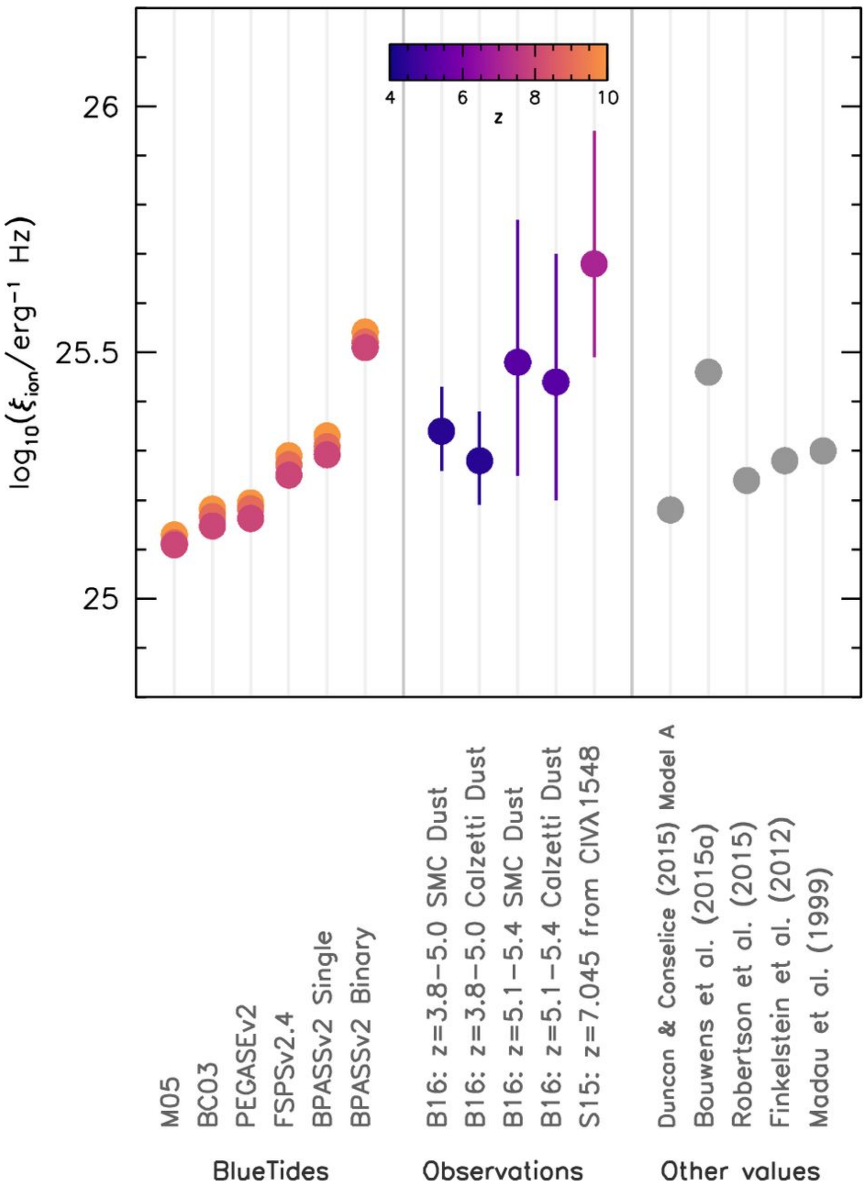
Nebular and line emissions increase at high redshift





Wilkins+16, hydrodynamical simulations, stellar models +cloudy code

Stellar models also predict different production rates of the LyC , especially for binary stars



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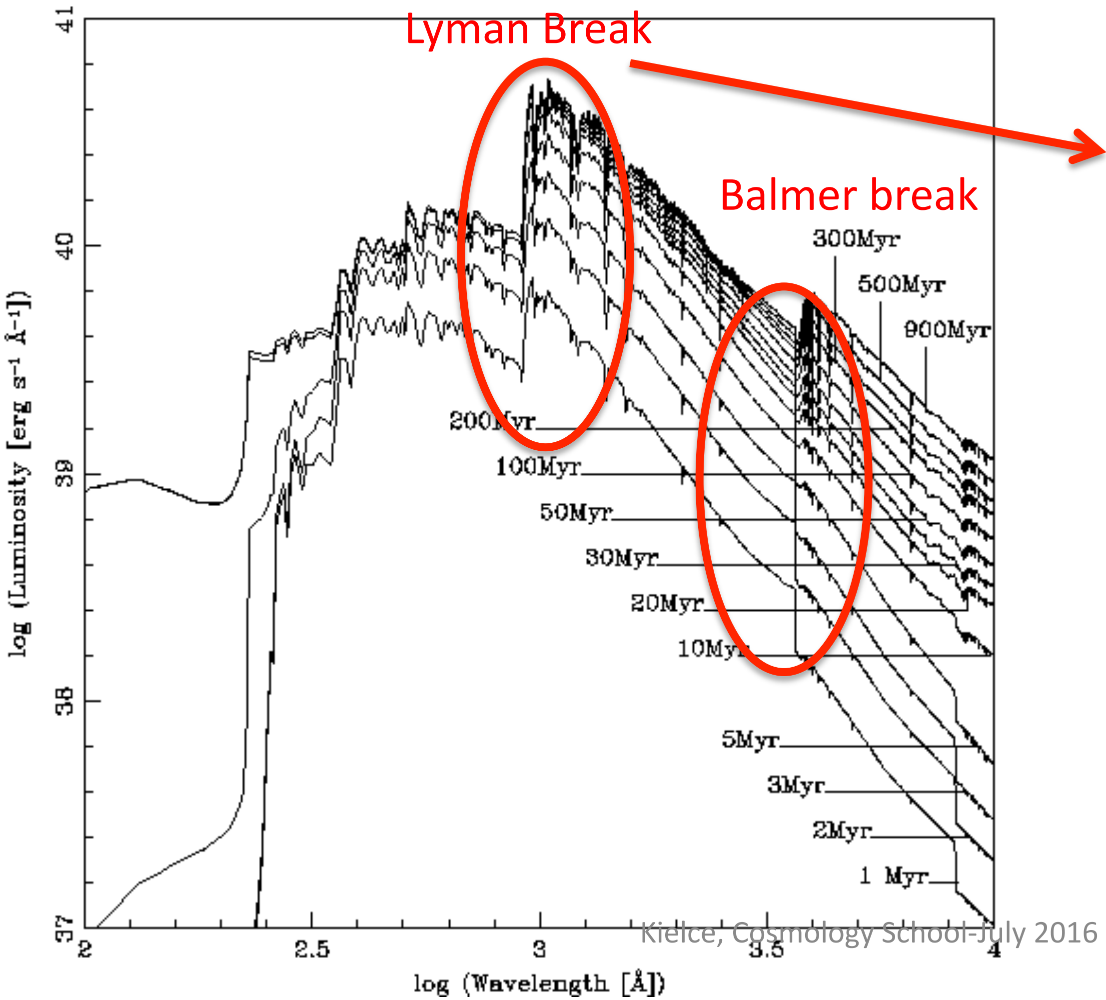
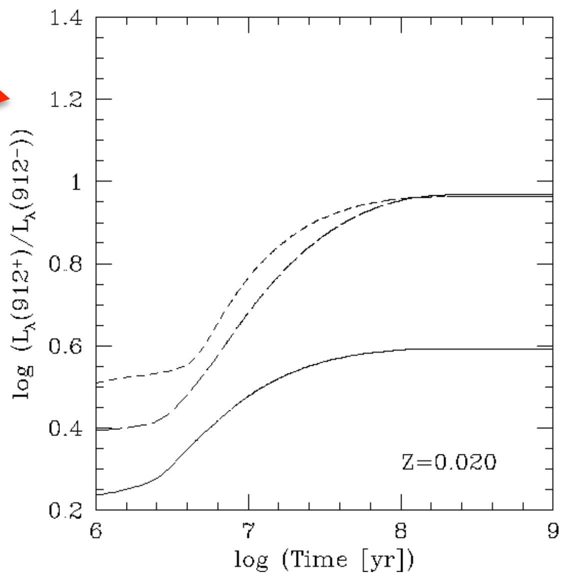
  Main emission lines, AGN and normal galaxies, **Breaks in high redshift galaxies & nearby universe**
- Dust component

Specific spectral features: breaks are particularly useful since they are not very affected by dust extinction

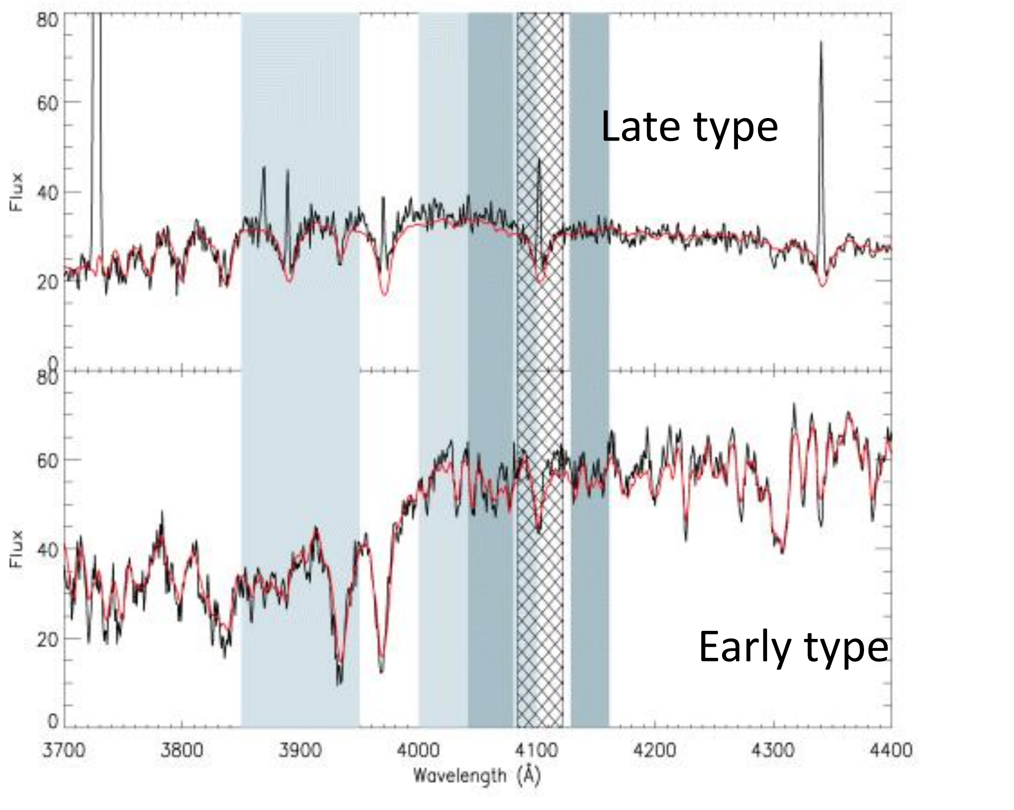




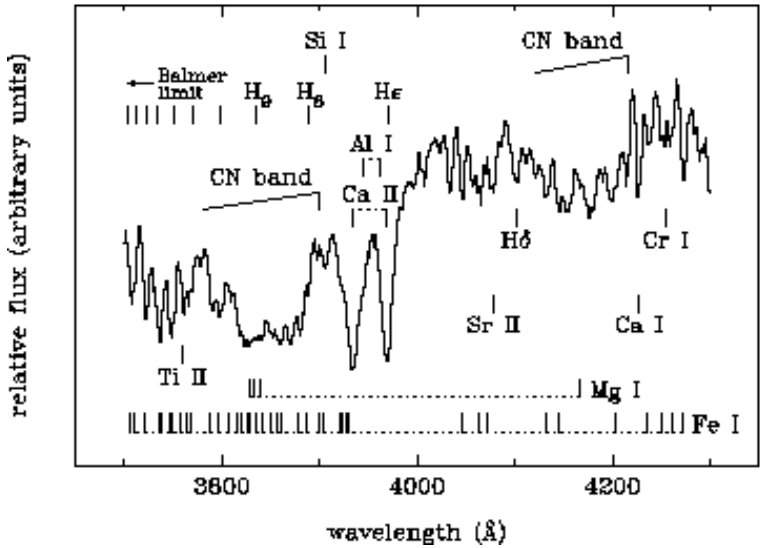
Continuous SFR, different IMFs, solar metallicity, from starburst99

The D4000 break ≠ Balmer break

- Related to old stellar populations, its amplitude increases in early type systems:
- Absorption features bluewards 4000 A for stellar types cooler than G0, line blanketing discontinuity

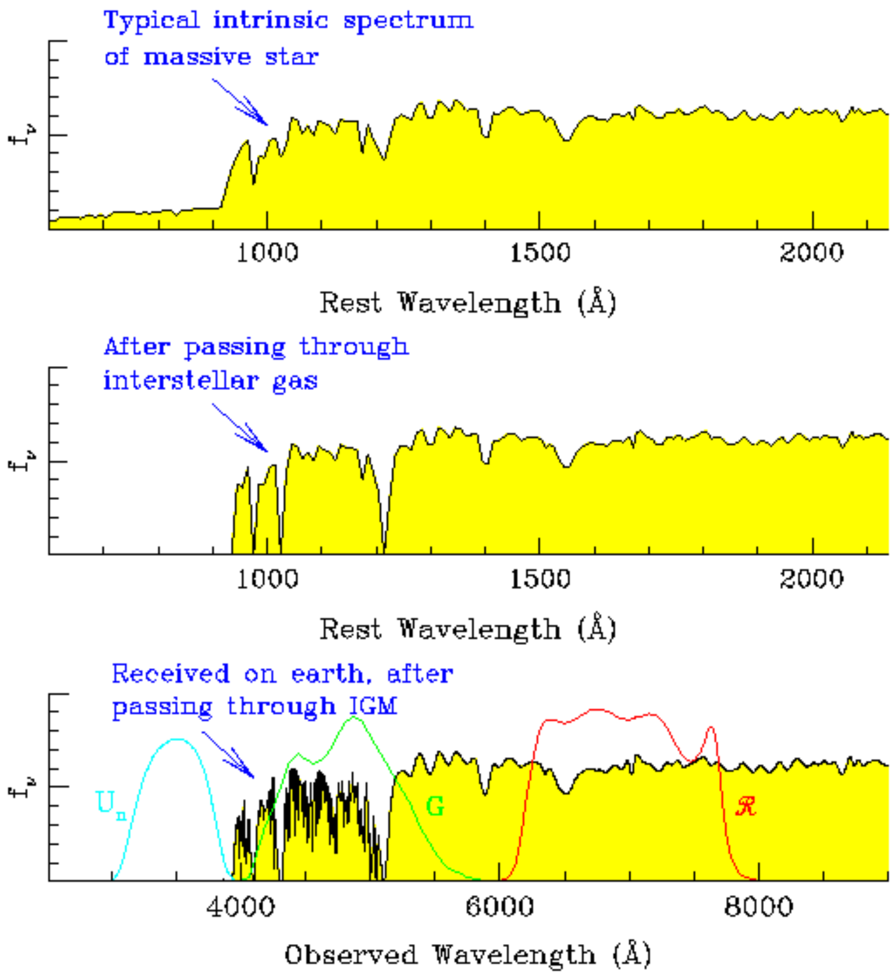


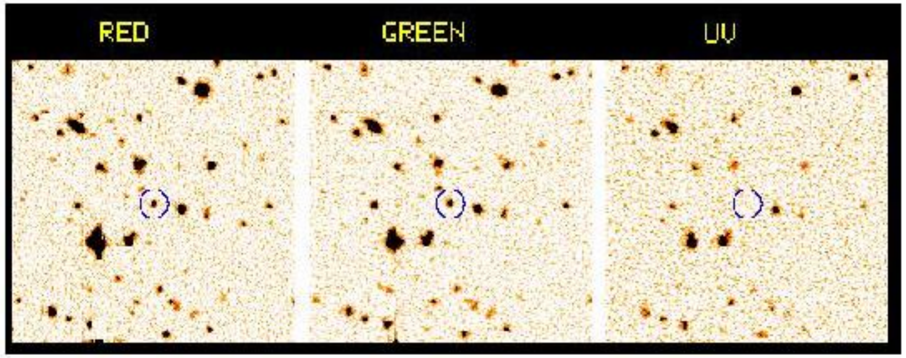
Stellar spectrum



High redshift Lyman Break Galaxies

Effect of neutral hydrogen: below 1216 Å rest frame

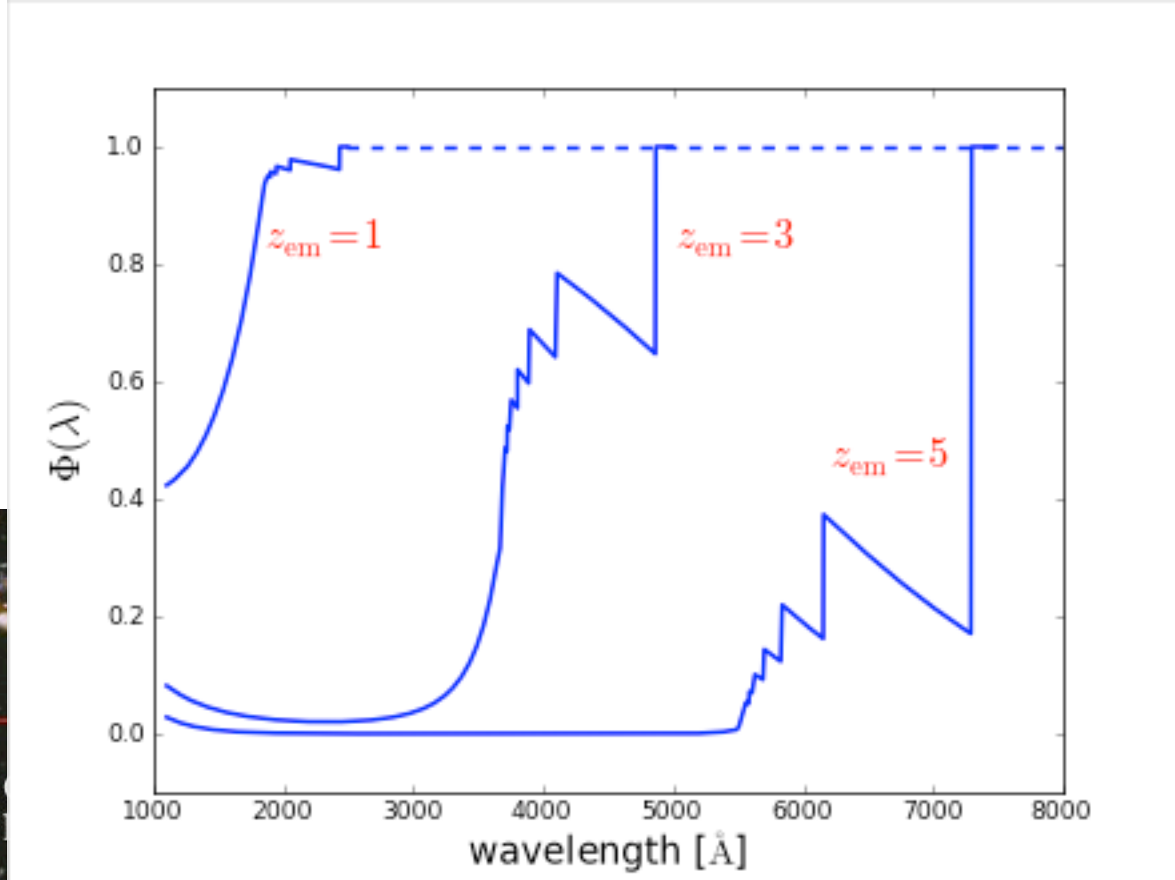


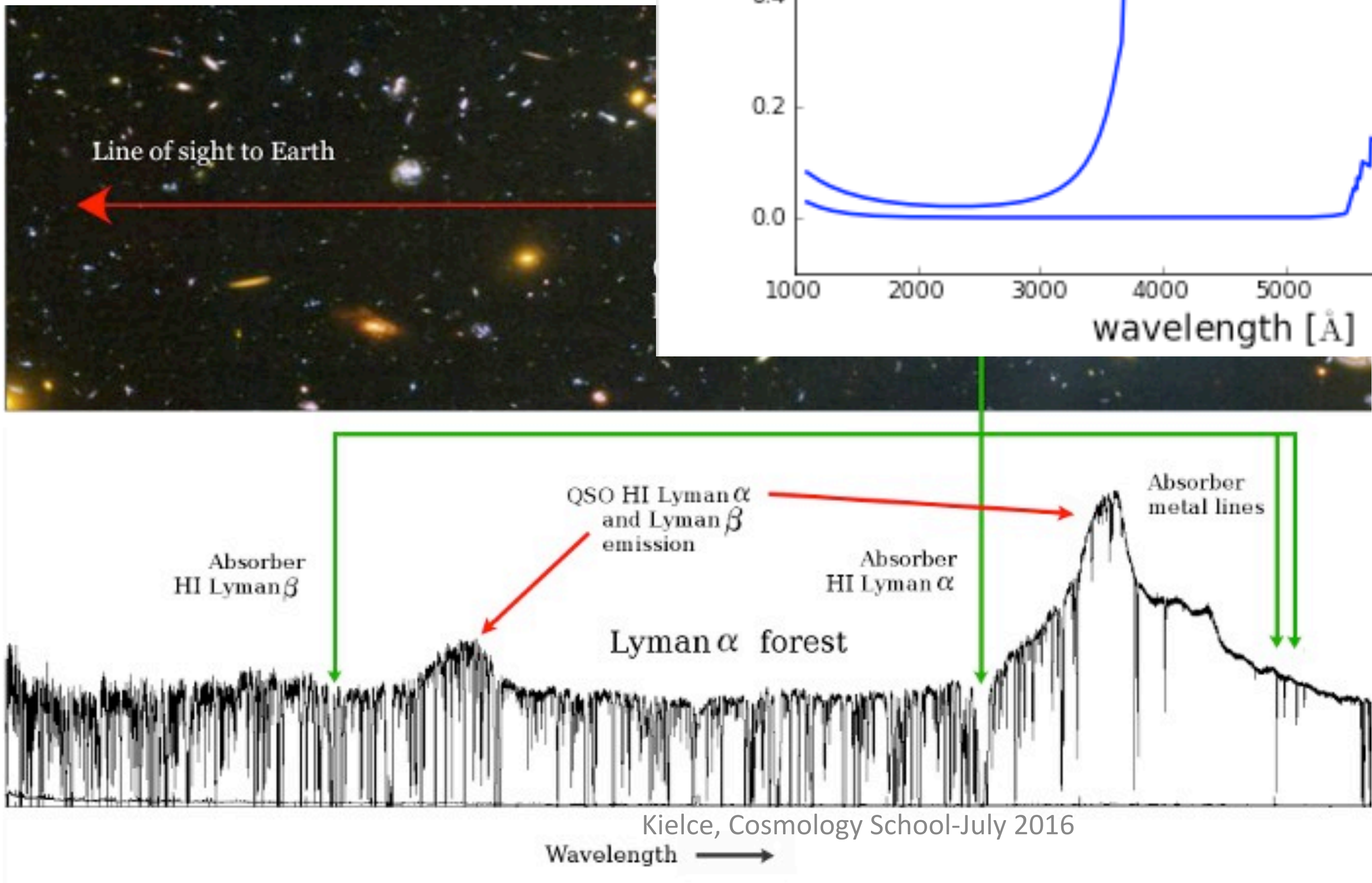


The Lyman continuum discontinuity is particularly powerful for isolating star-forming high redshift galaxies.

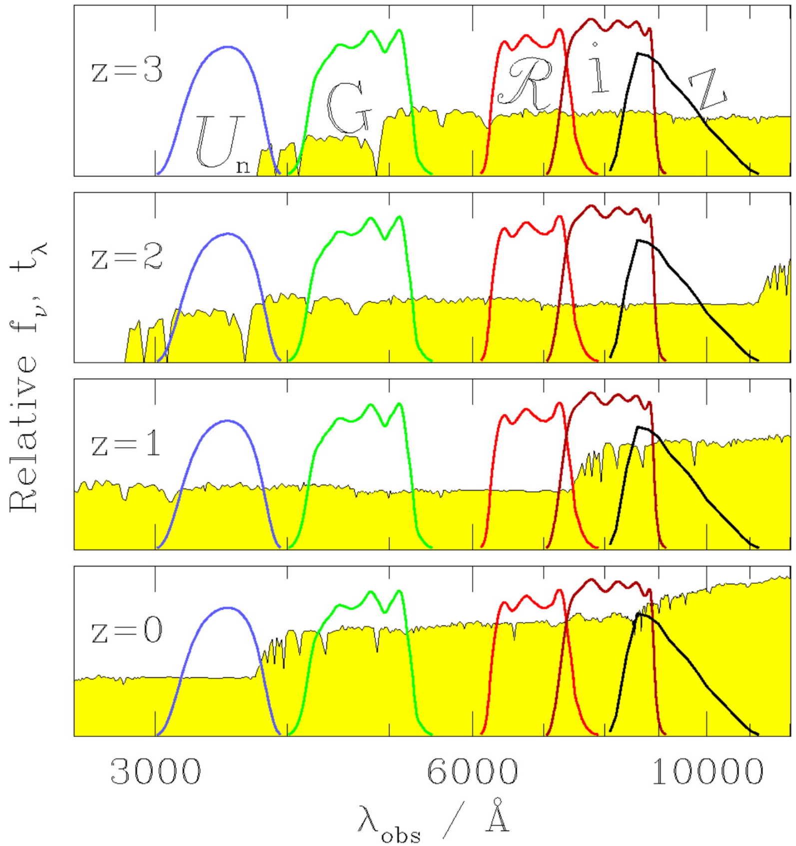
At high z: the break is mostly due to the IGM

About IGM absorption



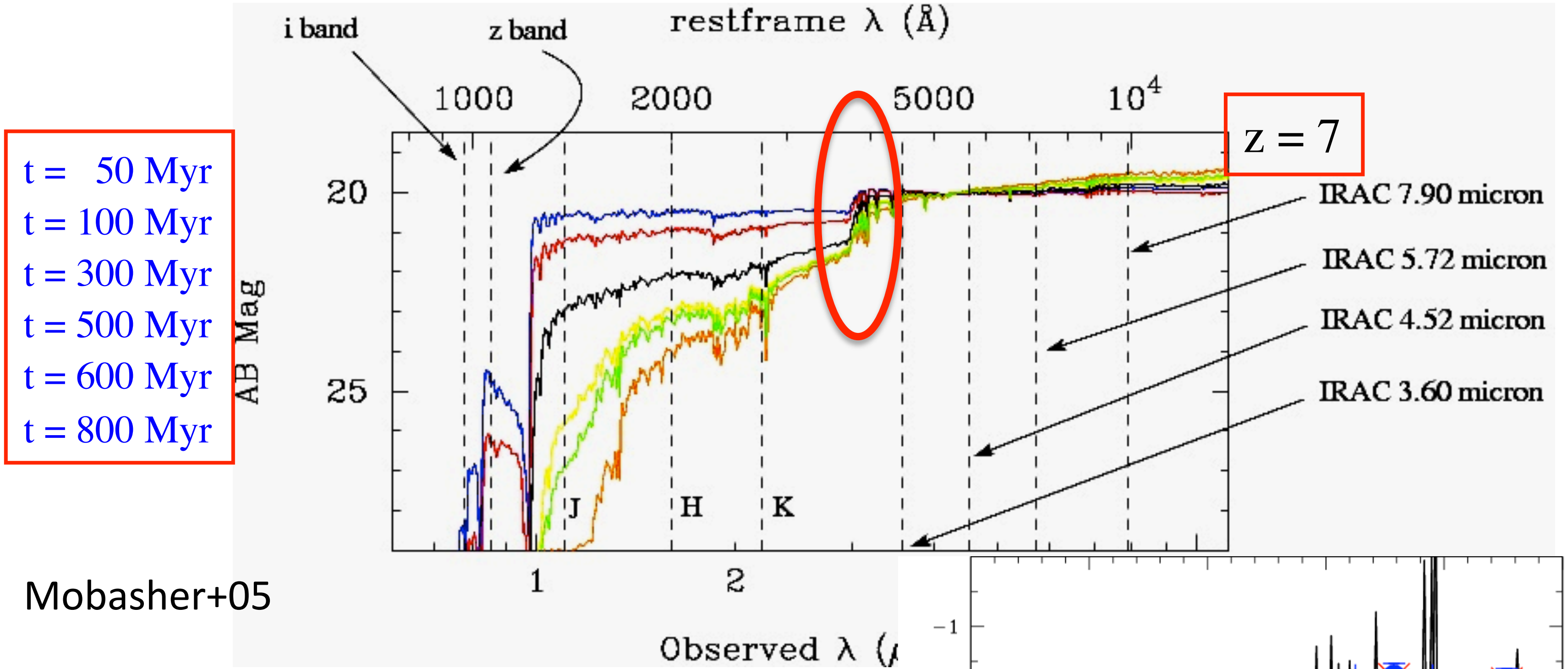


Balmer break: 365 nms



IR observations
For high z galaxies

Balmer Break Galaxies

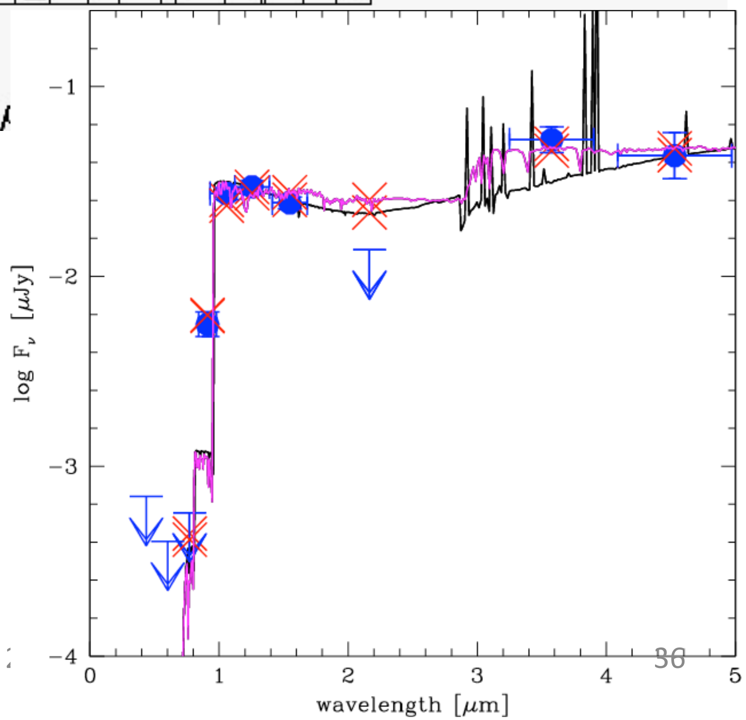


Mobasher+05

Difficult to interpret:

T=700 Myr without nebular emission
T= 4 Myr with nebular emission

Schaerer & de Barros 2010

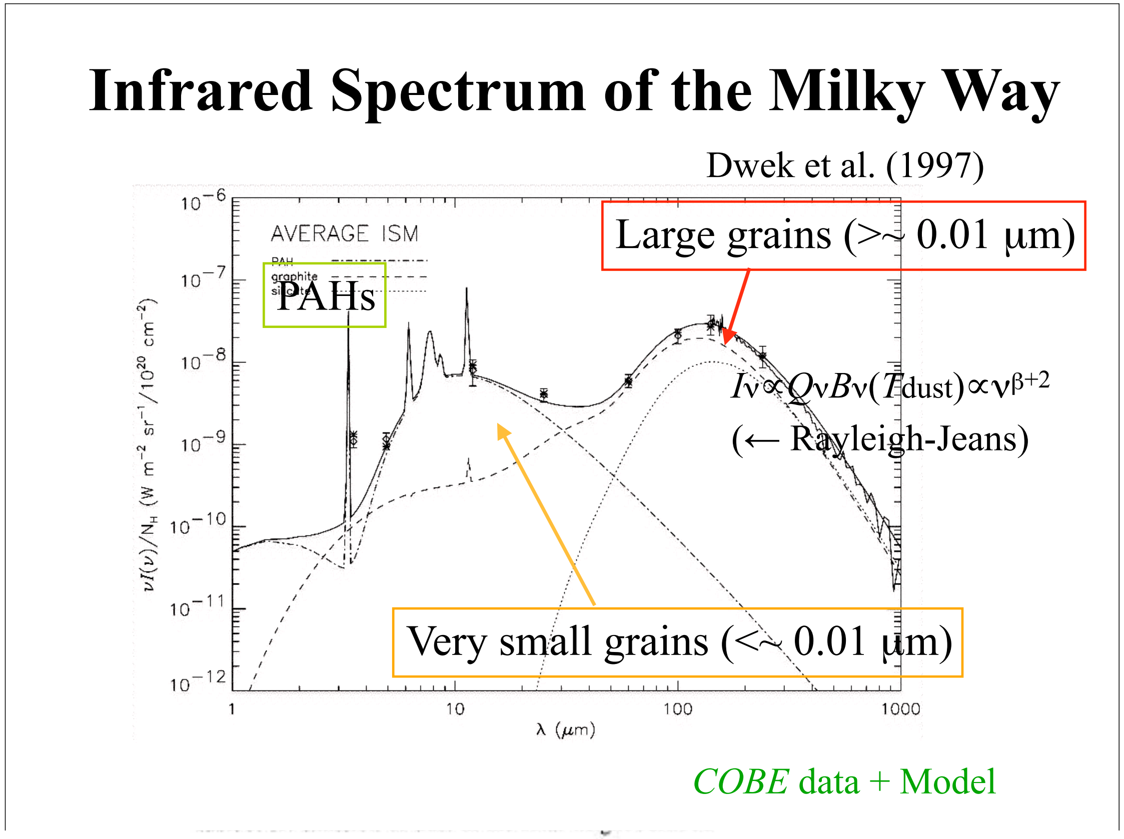


Outline of the lecture

- The « warm » components of a galaxy
- Photometric observations of galaxies
- Main spectral lines and spectral features
- **Dust component**

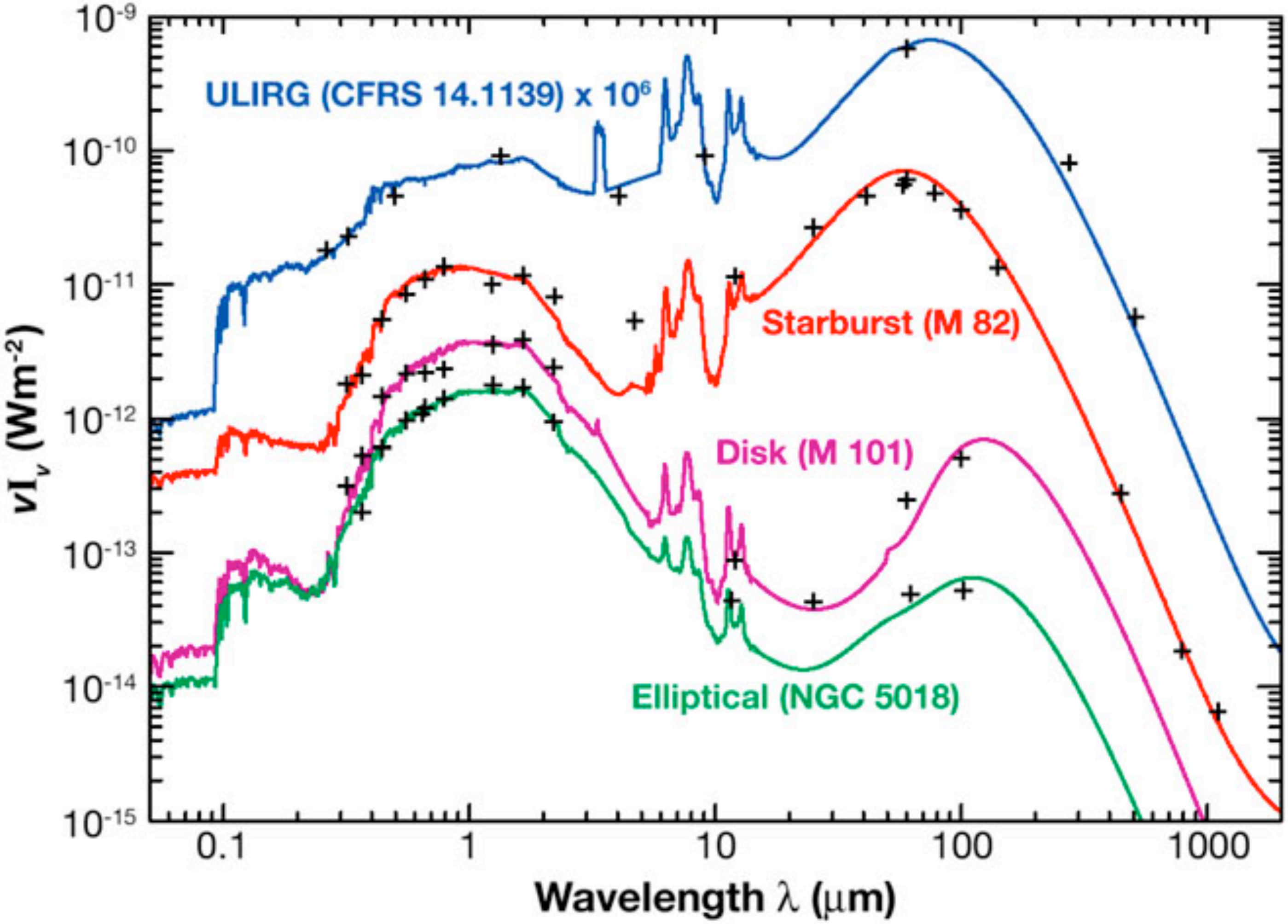
Dust emission, dust mass and temperature, normal & active galaxies, global SED

The main dust components from the Milky Way



λ µm Band#	12 1	25 2	60 3	100 4	200 5	400 6	800
PAH	3.12(-2)	1.90(-2)	4.23(-3)	1.11(-3)	1.49(-4)	1.43(-4)	3.06(-4)
VSG	1.77(-3)	2.06(-2)	1.06(-1)	1.22(-1)	5.88(-2)	1.61(-2)	7.19(-3)
BG	0.00(0)	2.11(-7)	6.62(-2)	7.45(-1)	1.48(0)	3.98(-1)	5.36(-2)
Total	3.30(-2)	3.96(-2)	1.76(-1)	8.68(-1)	1.54(0)	4.14(-1)	6.11(-2)

Desert+90



ULIRG (CFRS 14.1139) x 10^6
Starburst (M 82)
Disk (M 101)
Elliptical (NGC 5018)
νI_ν (Wm^{-2})
Wavelength λ (μm)
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
0.1
1
10
100
1000

Lagache+05

Global emission of galaxies: observe the different fractions of energy in UV-optical and mid-farIR

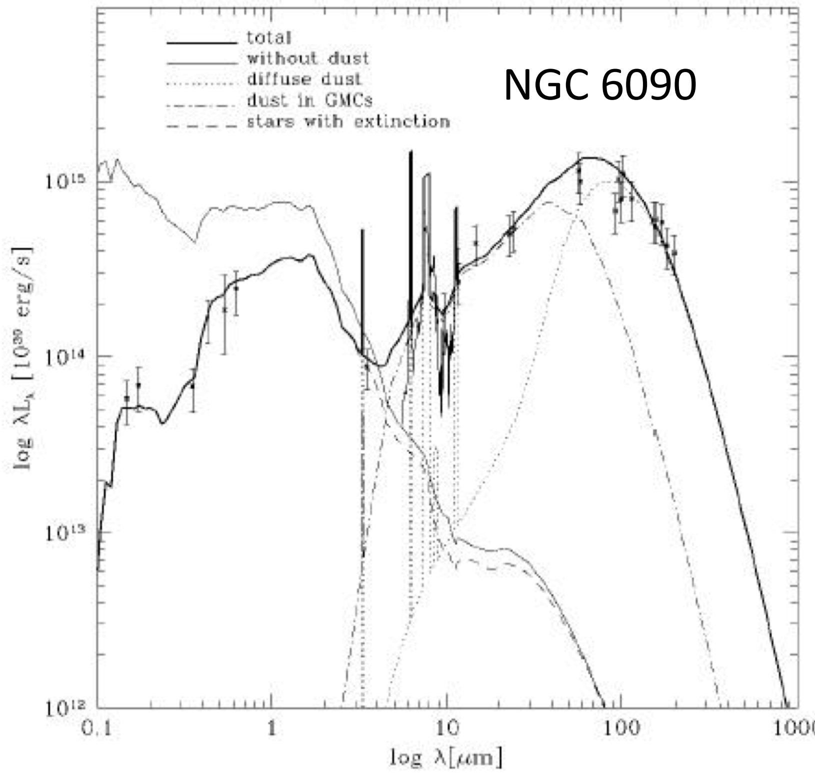
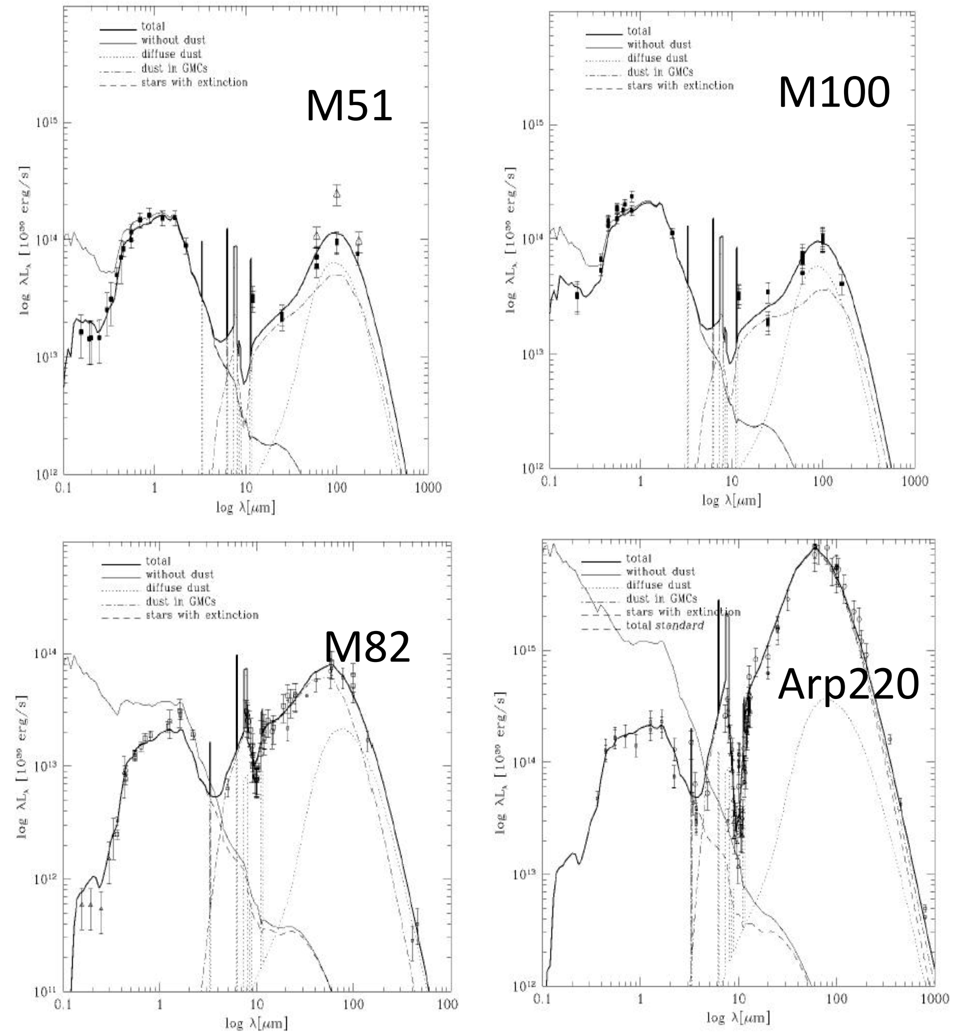


FIG. 8.—Fit to the SED of NGC 6090. Data are from Mazzarella Boroson (1993), Acosta-Pulido et al. (1996), Gordon et al. (1997).

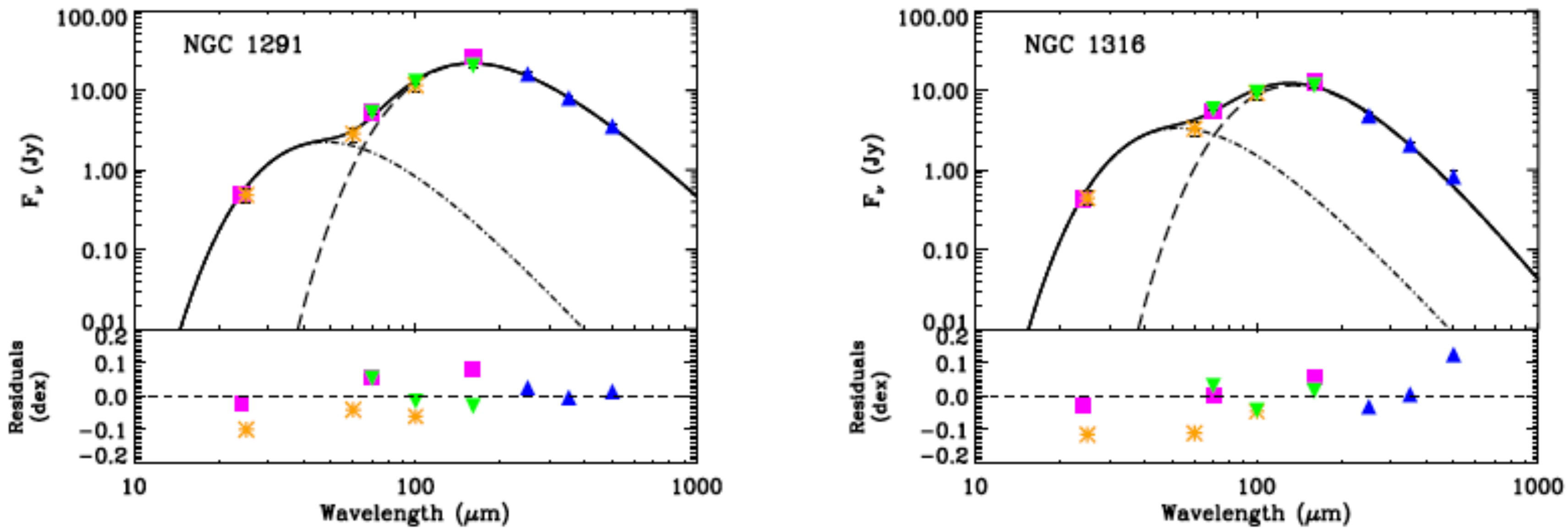


Modeling: Silva et al. 1998

Dust temperature

Routinely measured in external galaxies BUT may strongly depend on the adopted model

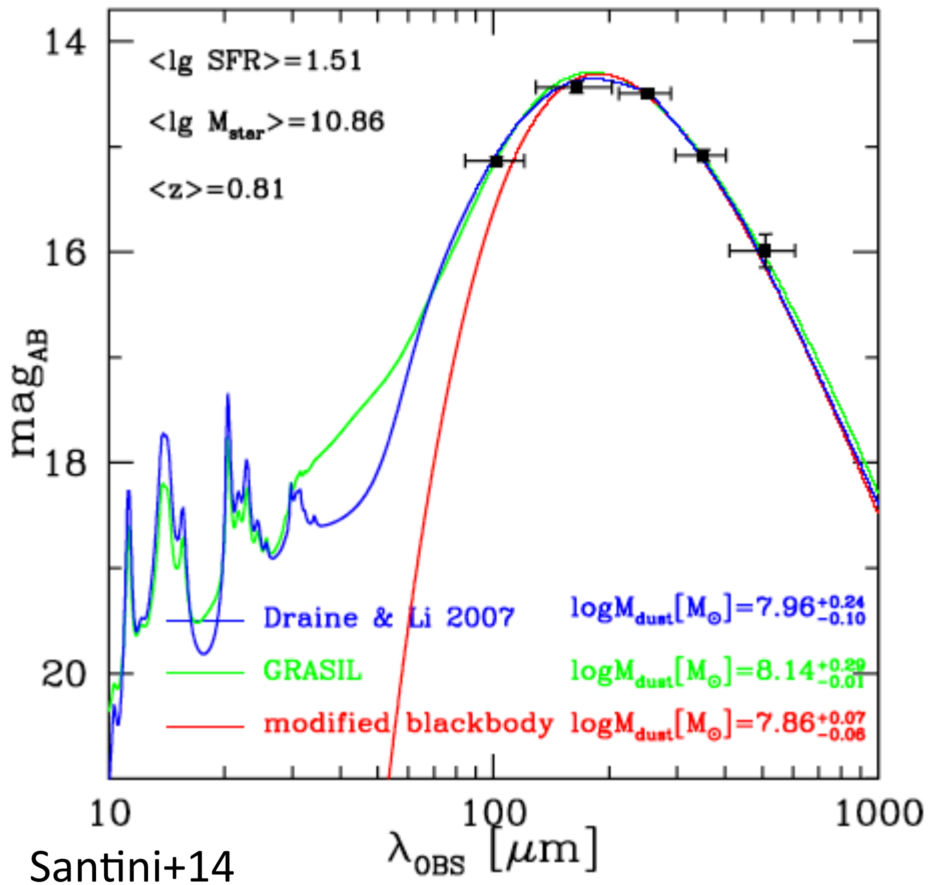
•Dust temperature: assuming one or several modified Black Bodies→ oversimplification



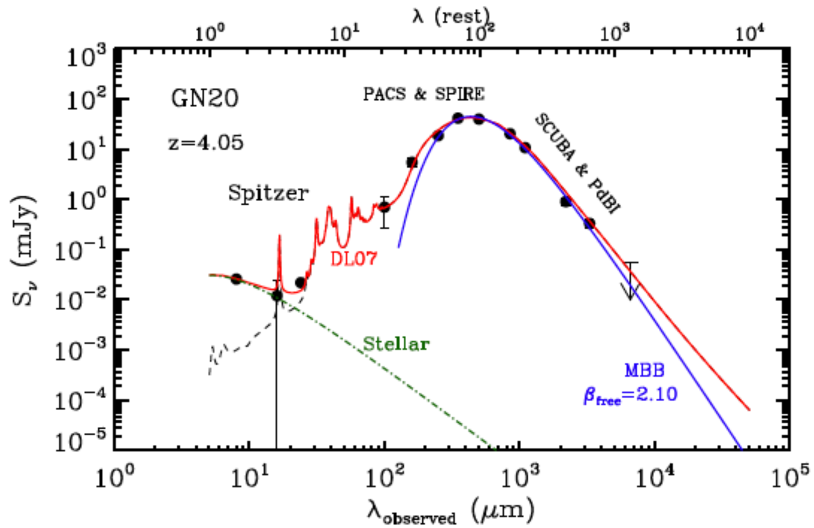
Galametz+12

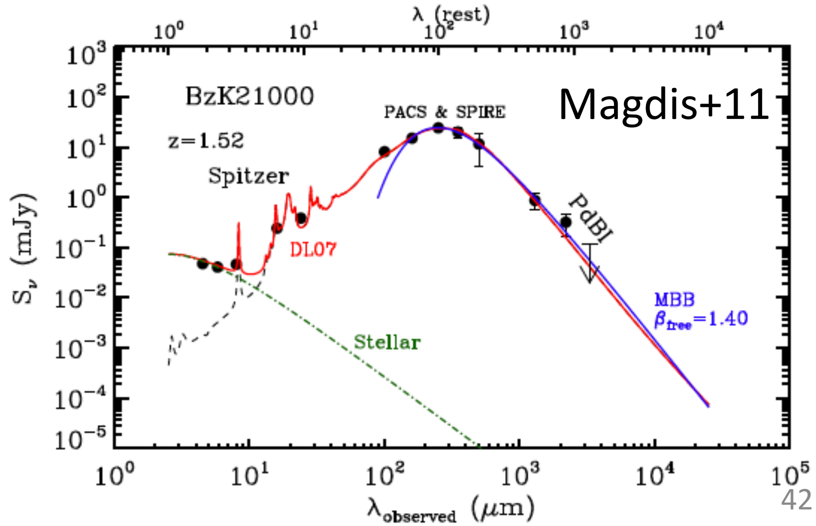
Dust mass

Estimated with either a modified BB model or more complex model of dust emission such that of Draine & Li 2007



Santini+14



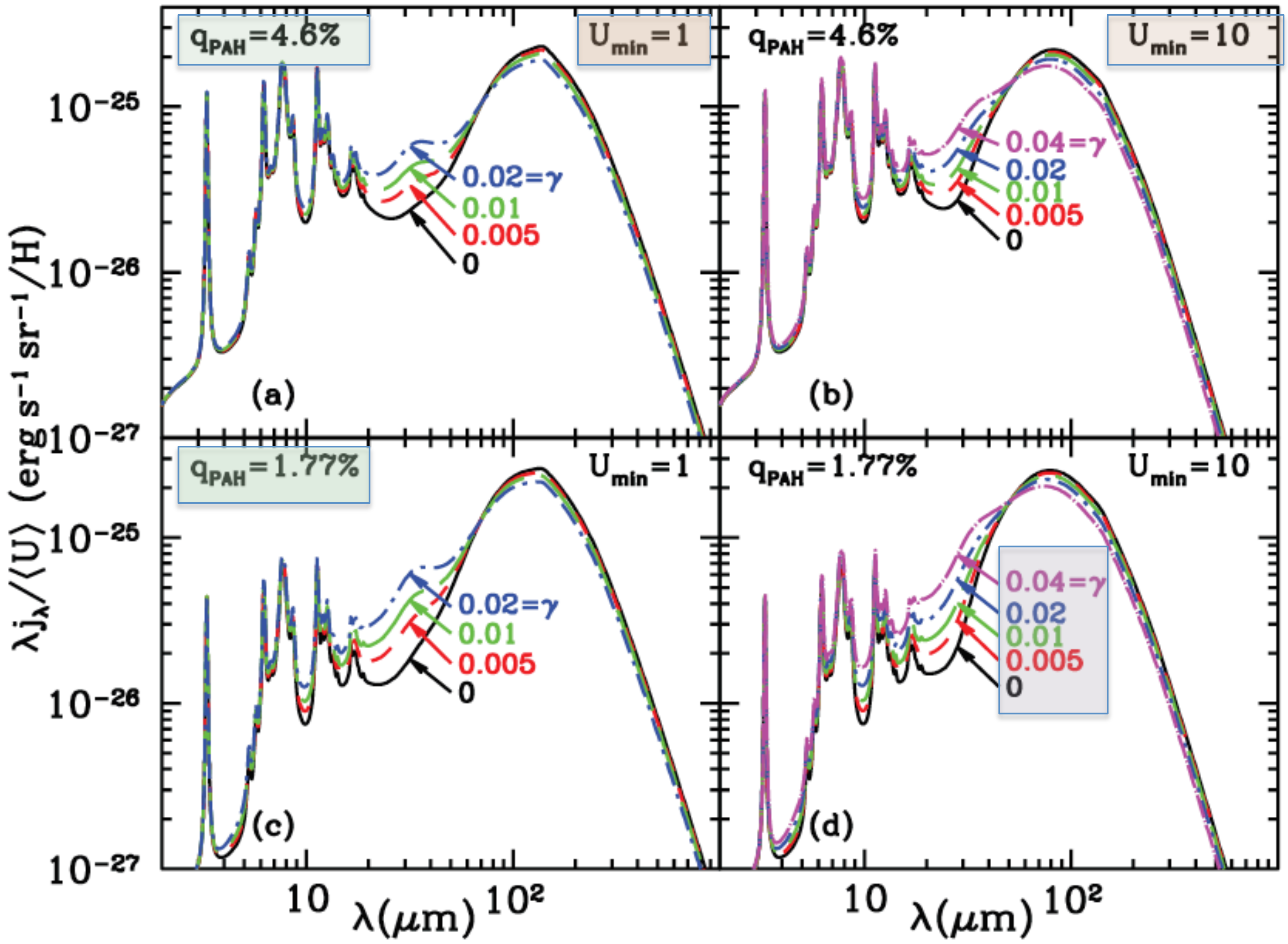


Magdis+11

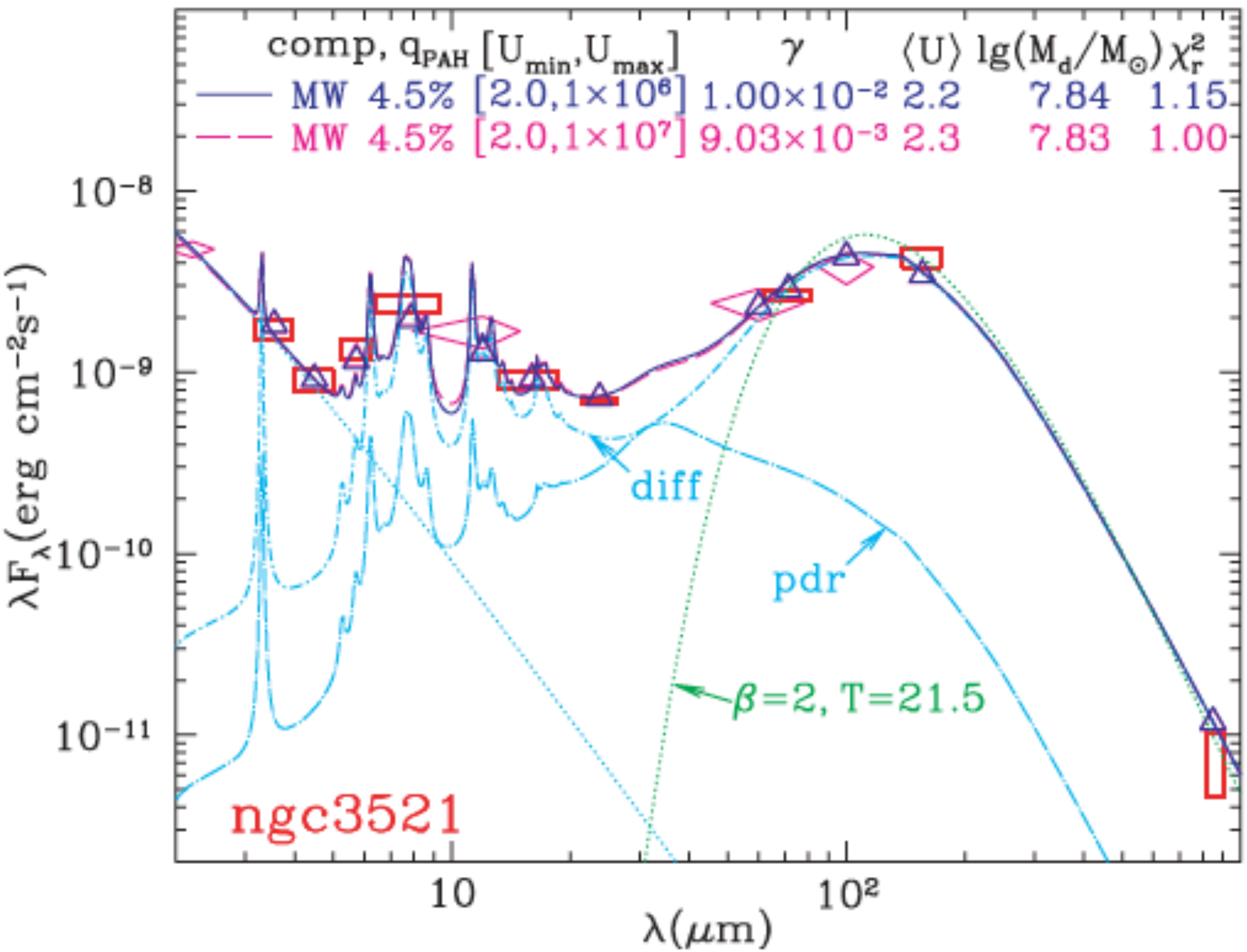
Draine & Li (07) model

- Dust: carboneceous +amorphous silicate grains, mainly heated by the **ISM** (U_{min})
- Intensity of the ISRF U_{min}<U<U_{max} (U=1 for ISRF(MW)) **PDR**
- q_{PAH}: fraction of dust mass in **PAH**
- γ: fraction of dust heated by **intense starlight** (U>U_{min})

Typical values: **q_{PAH}**<~5%, **γ**~<10%, **U_{max}**=10^6 (MW), **U_{min}**<~10 *(Ciesla+14, Draine+07)*



q_{PAH}=4.6%
U_{min}=1
q_{PAH}=4.6%
U_{min}=10
0.02=γ
0.01
0.005
0
0.04=γ
0.02
0.01
0.005
0
(a)
(b)
q_{PAH}=1.77%
U_{min}=1
q_{PAH}=1.77%
U_{min}=10
0.02=γ
0.01
0.005
0
0.04=γ
0.02
0.01
0.005
0
(c)
(d)
$\lambda j_\lambda/\langle U \rangle$ (erg s^{-1} sr^{-1}/H)
10^{-25}
10^{-26}
10^{-27}
10
10^2
$\lambda(\mu m)$



comp, q_{PAH} [U_{min},U_{max}] γ ⟨U⟩ lg($M_d/M_\odot$) χ^2_r
MW 4.5% [2.0,1×10^6] 1.00×10^-2 2.2 7.84 1.15
MW 4.5% [2.0,1×10^7] 9.03×10^-3 2.3 7.83 1.00
diff
pdr
β=2, T=21.5
ngc3521
λF_λ(erg cm^{-2}s^{-1})
λ(μm)

Draine+07

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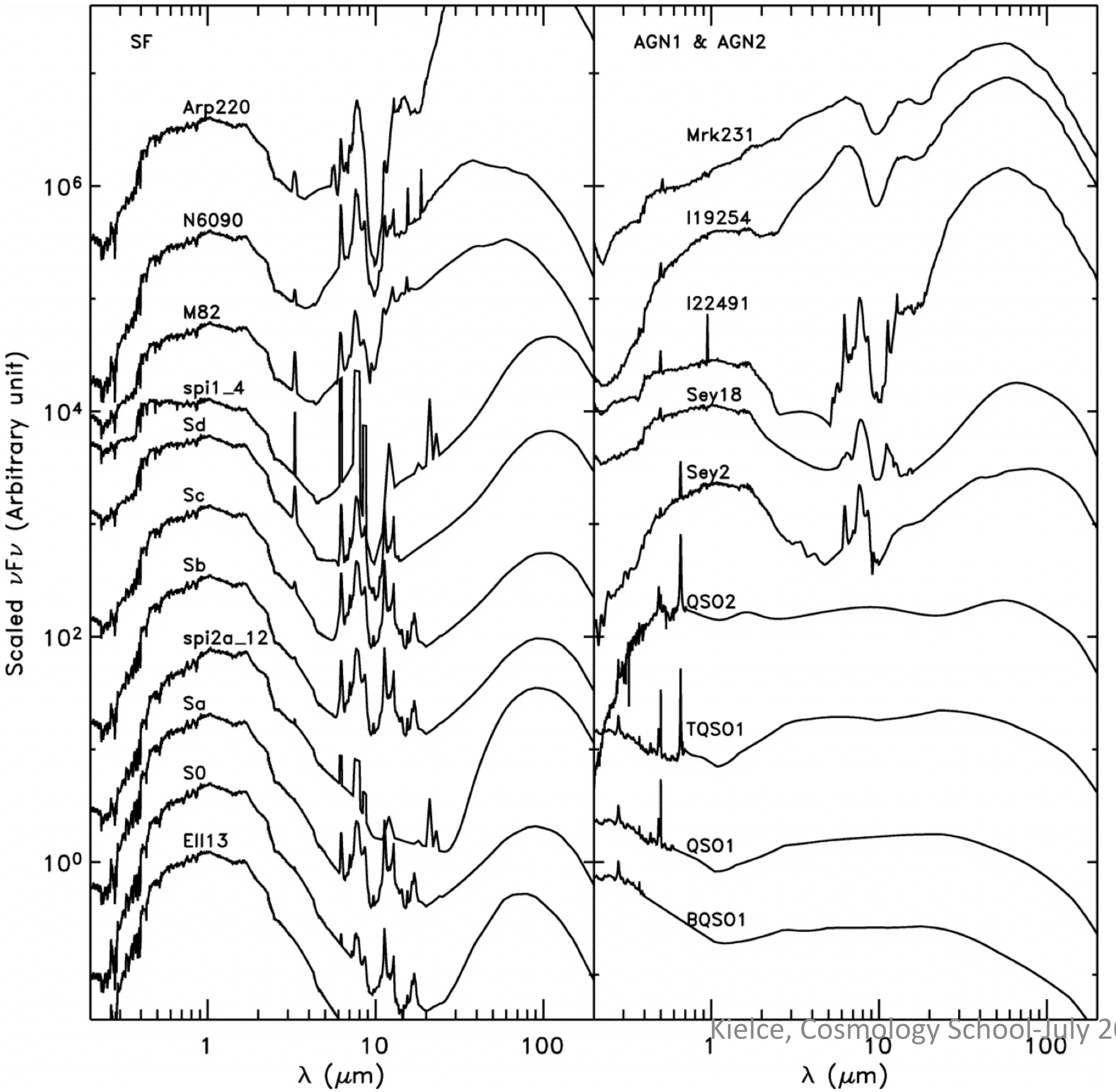
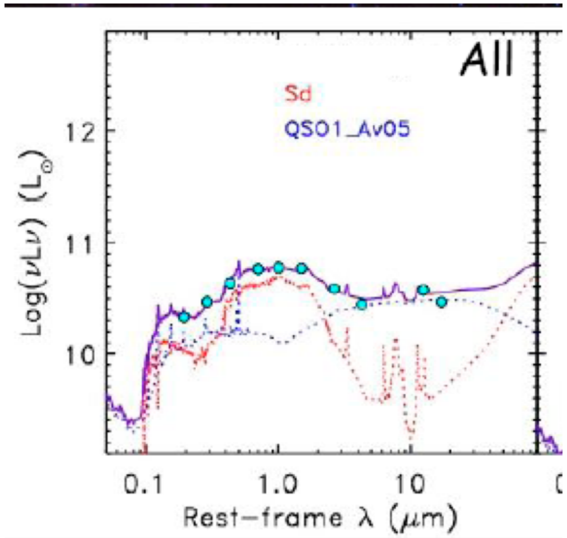
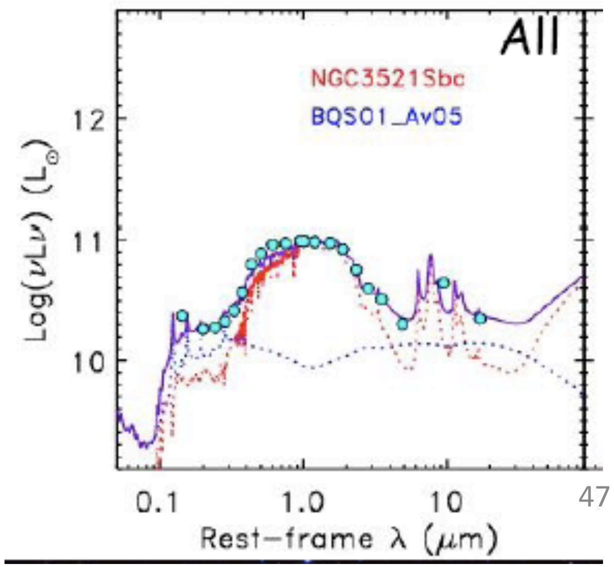
  Dust emission, dust mass & temperature, **normal & active galaxies**, global SED

SEDs of normal and active galaxies

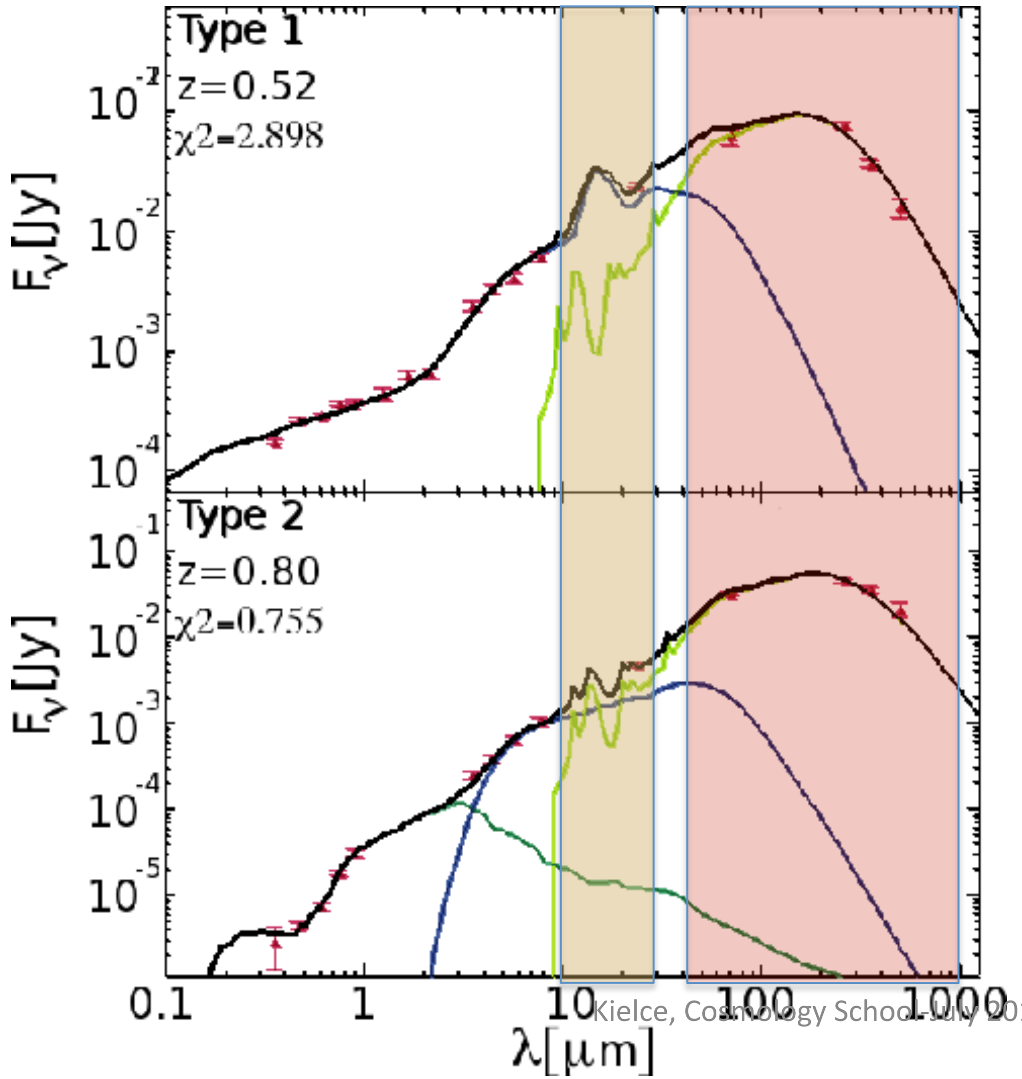
Star forming galaxies AGN & QSO Polletta+08







The far-IR range is not sensitive to non thermal (AGN) dust emission

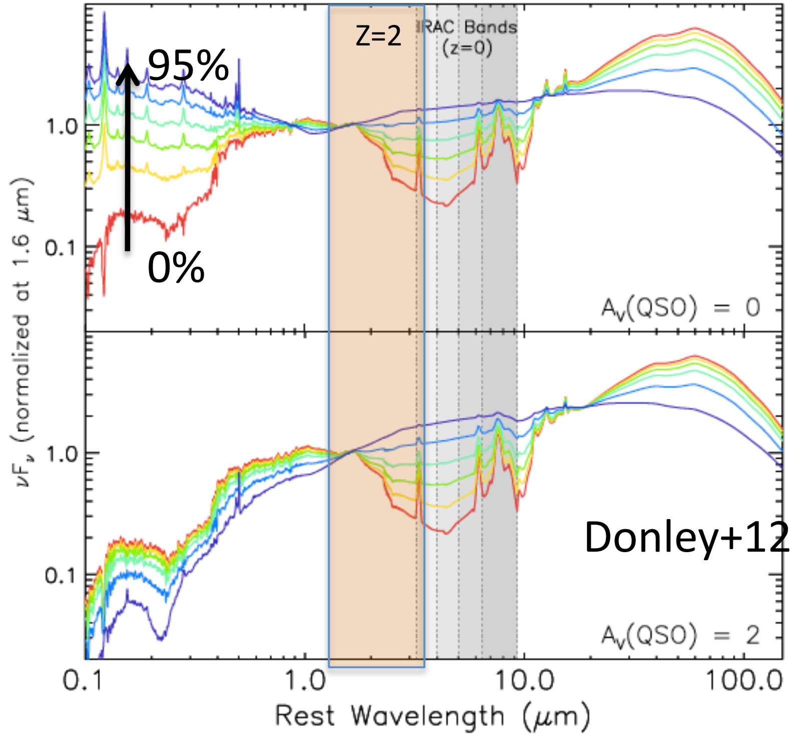


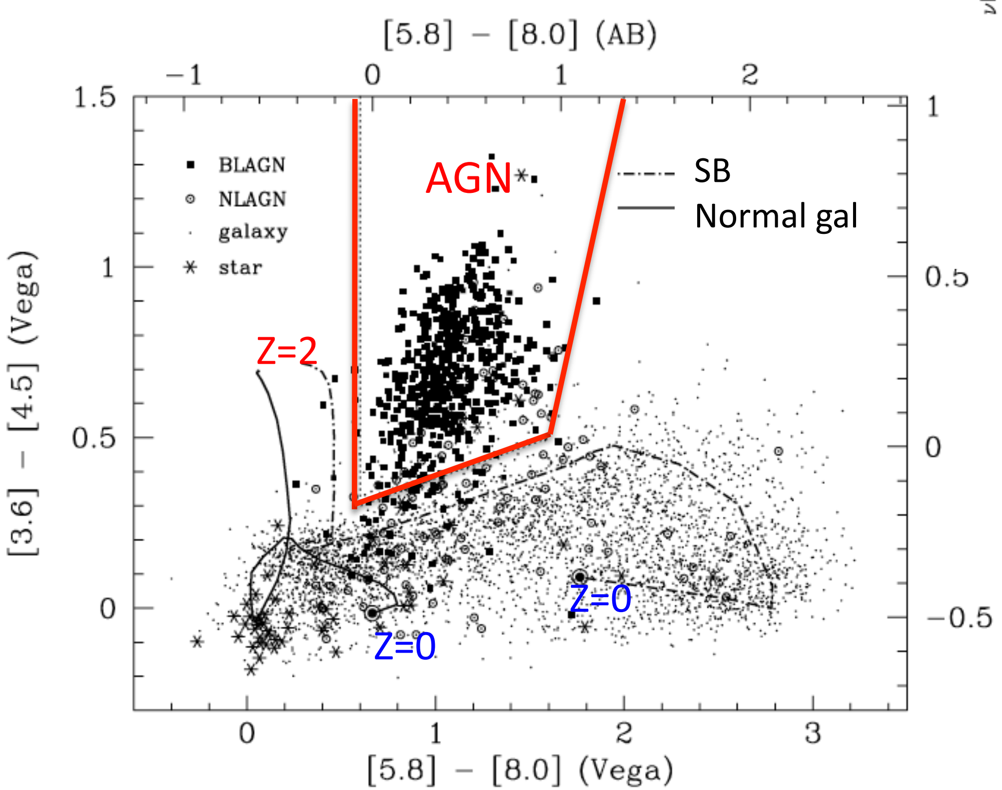
Hatziminaoglou+10

Blue: AGN-torus model
Green: IR starburst
Dark green: stellar component
Black:total SED

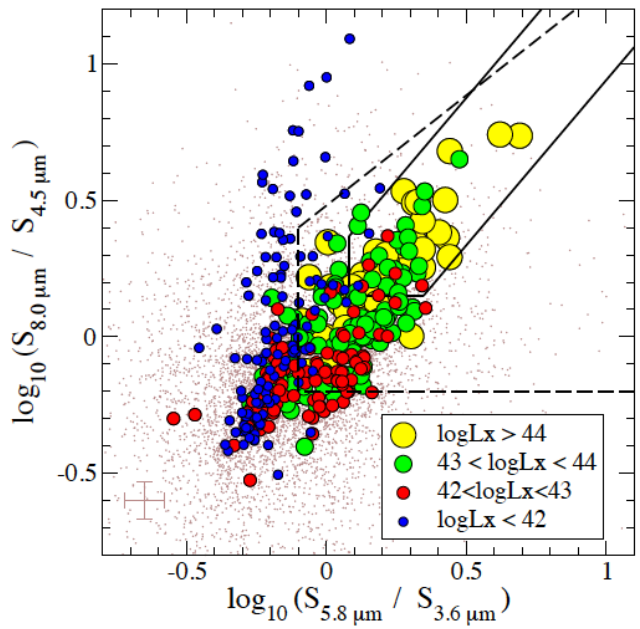
•mid-IR sensitive to AGN contribution
•Far-IR dominated by star formation, secure measure of the (obscured) SFR

Colour-colour diagrams to check the global shape of the IR SED of AGN/SF systems
IRAC data

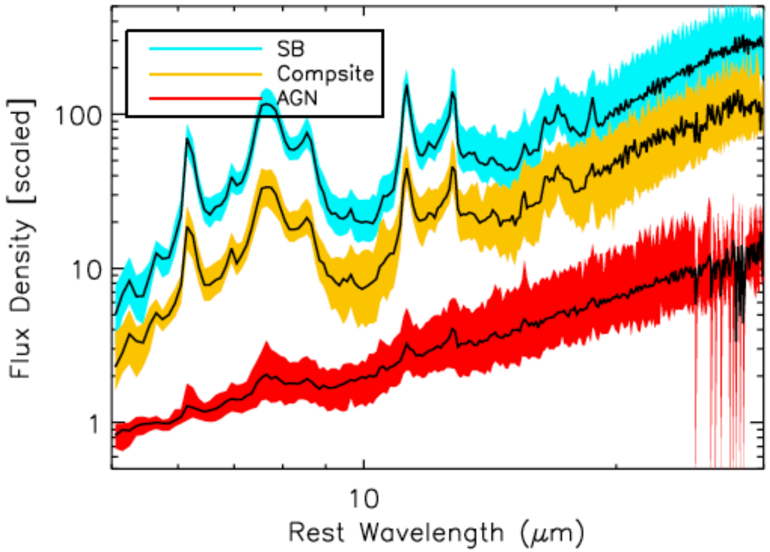




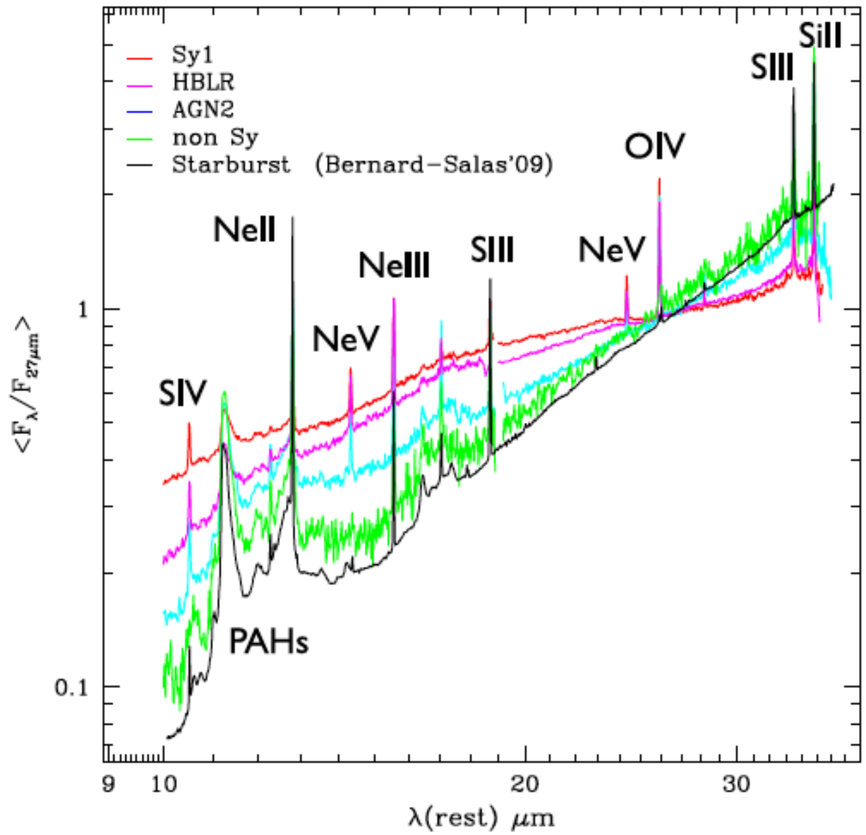
Stern+05



Mid-IR features and high ionisation lines AGN/Starburst galaxies



PAH in the mid-IR: weaker in AGN hosts than in SF galaxies
the reality is more complicated…..



High ionisation lines from IR spectroscopy, more secure AGN indicators

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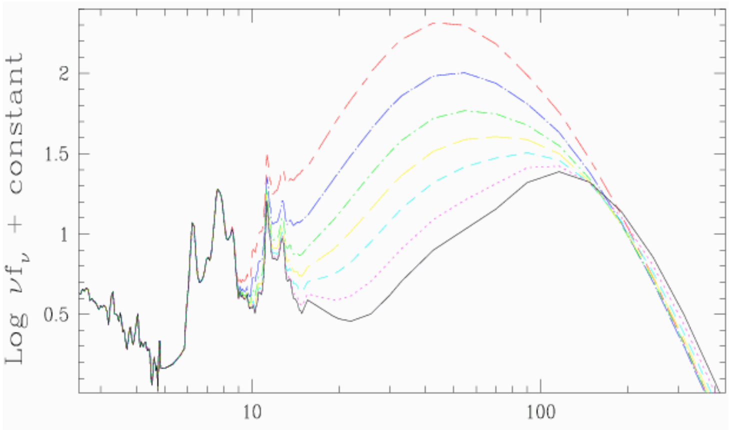
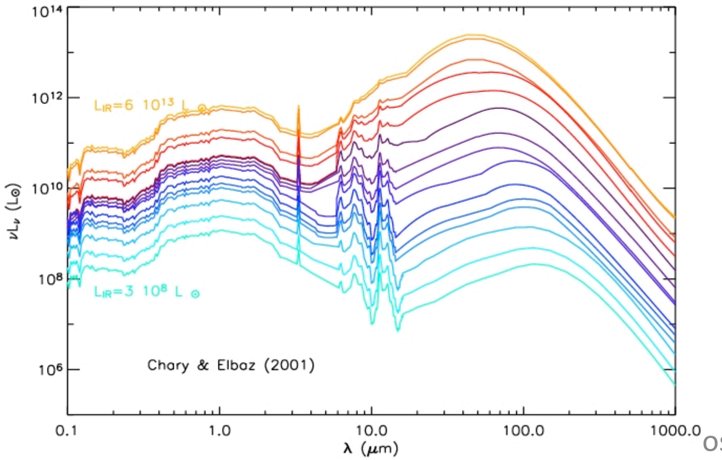
How to measure L_{IR} from ~5 to 1000 µm? From Templates…

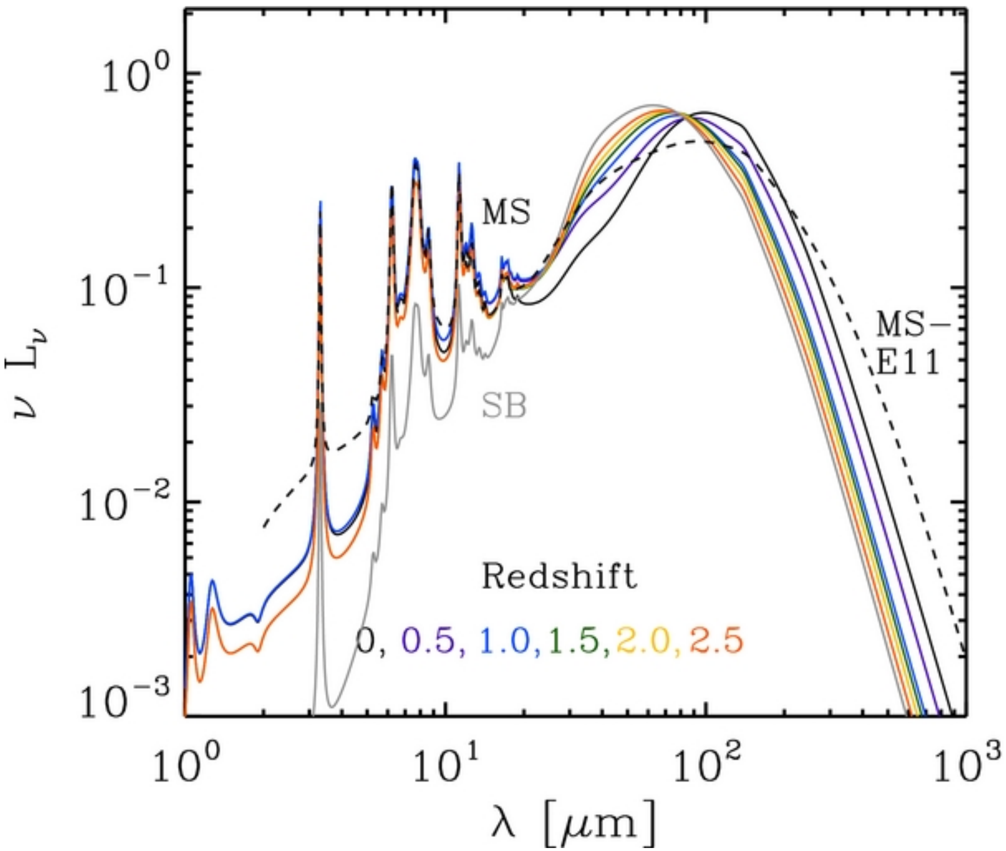
Dale & Helou (2002)
64 semi-empirical templates



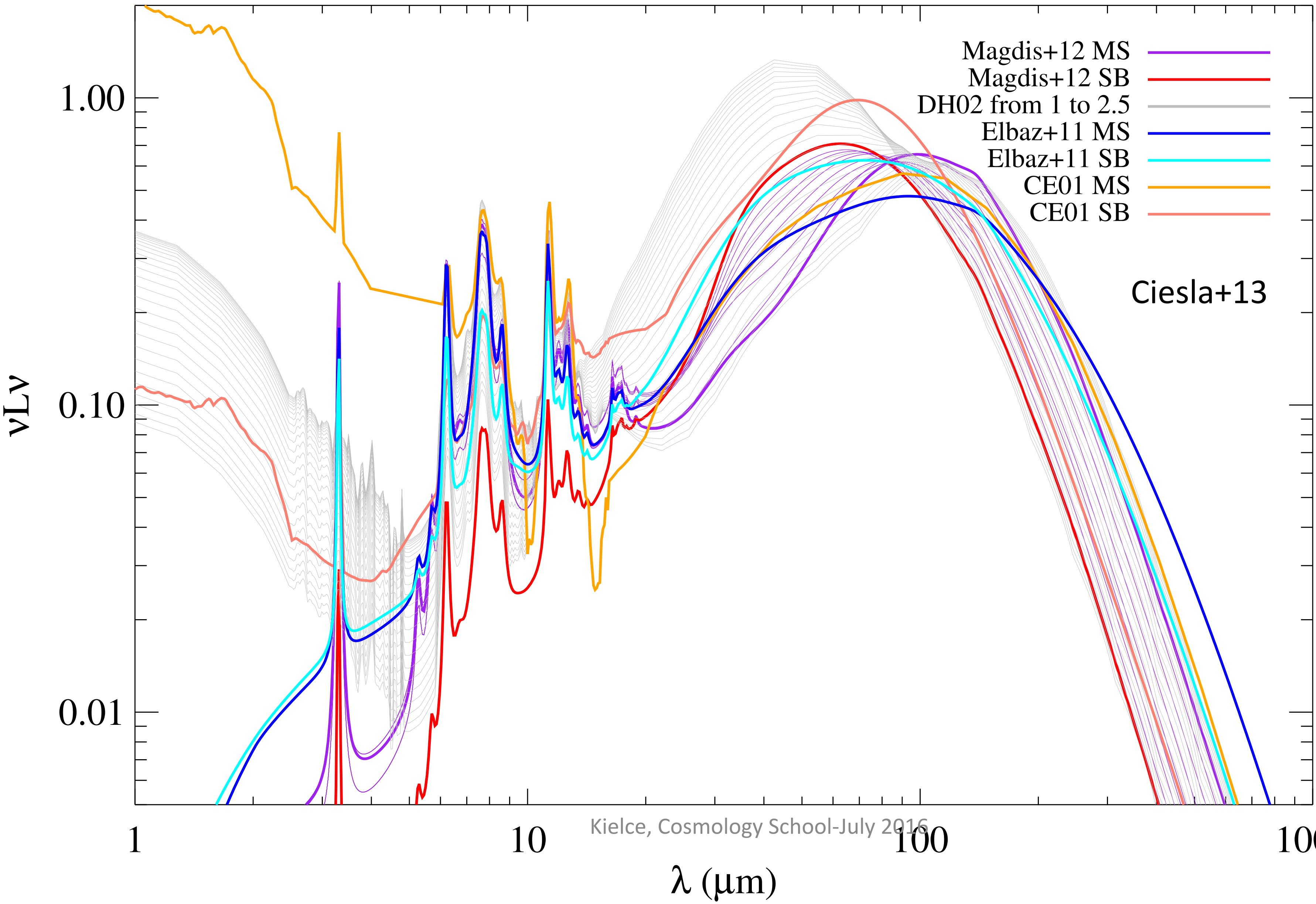
Chary & Elbaz (2001)
105 empirical templates



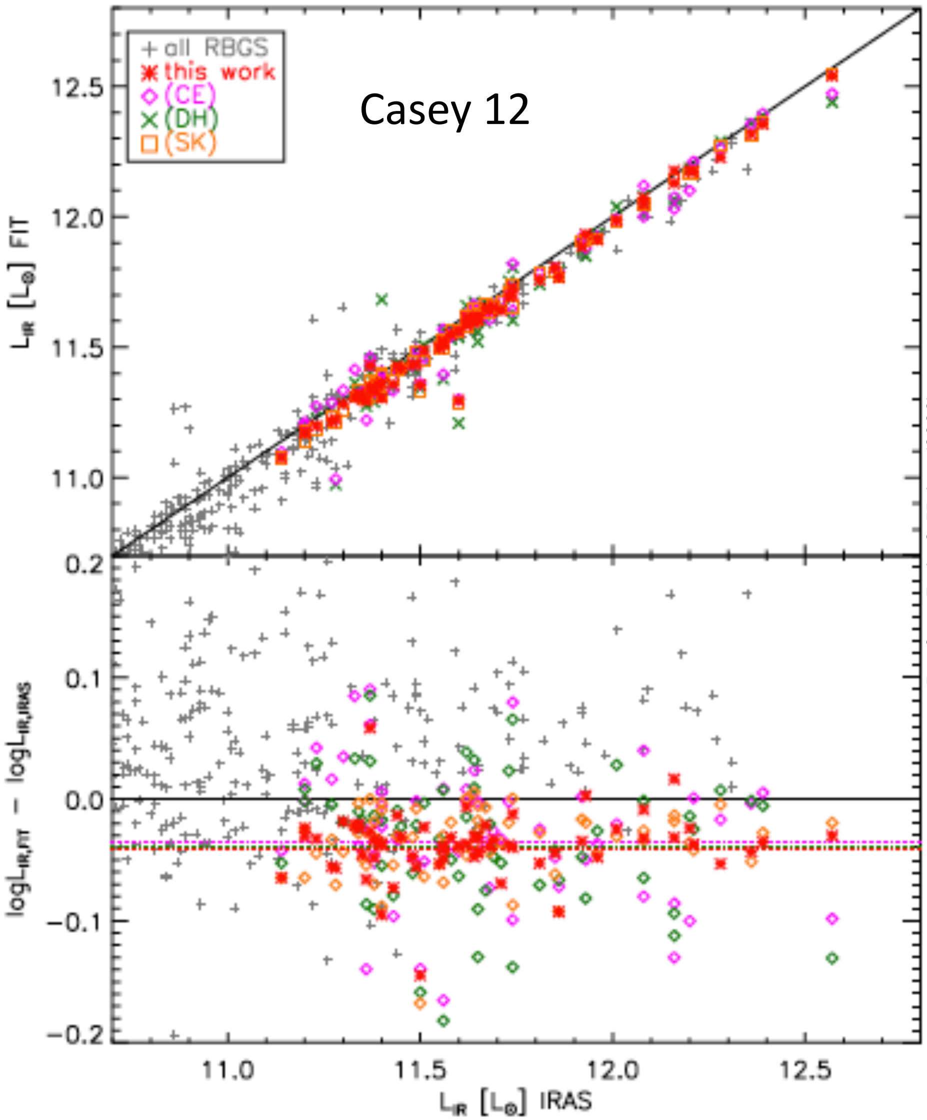
-Draine & Li (2007) models (Draine+07): very useful with Herschel data
Magdis+12 templates at different z



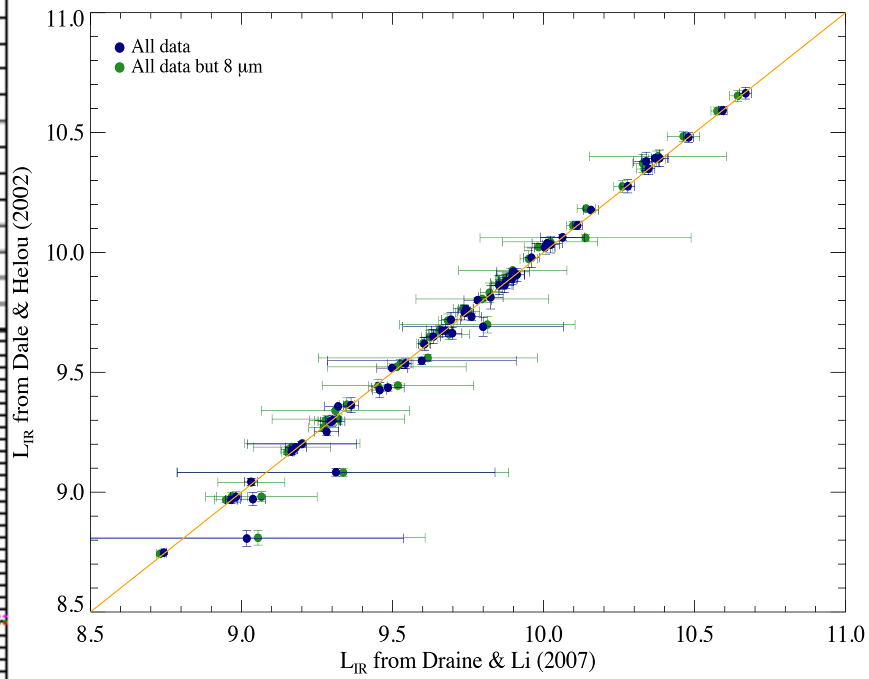
the situation remains complicated....



To be optimistic: L_{ir} estimates do not strongly depend on the adopted template when several bands are available



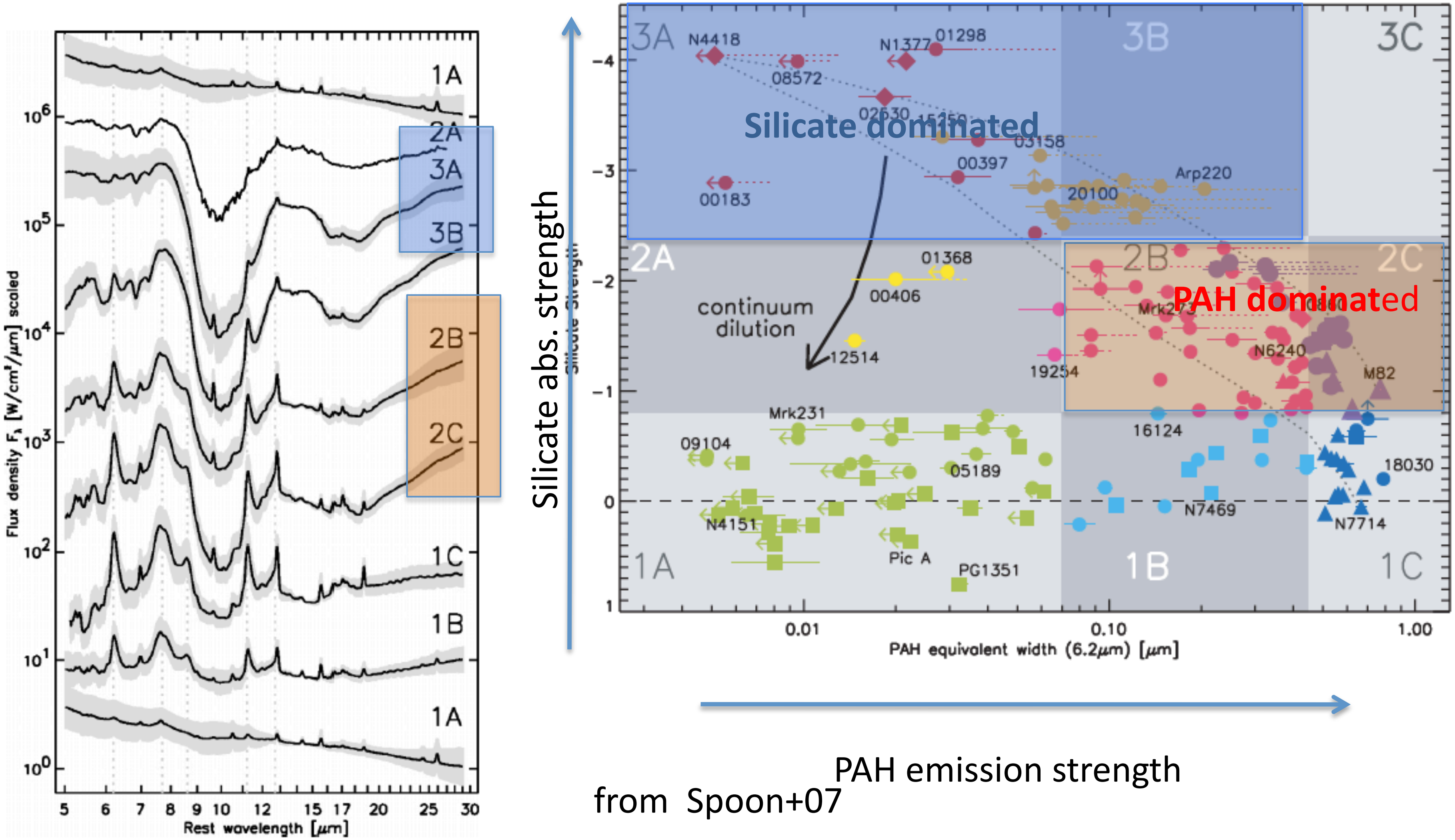
Ciesla, 12, PhD thesis
Herschel Reference Sample,
SPITZER+ SPIRE data



References

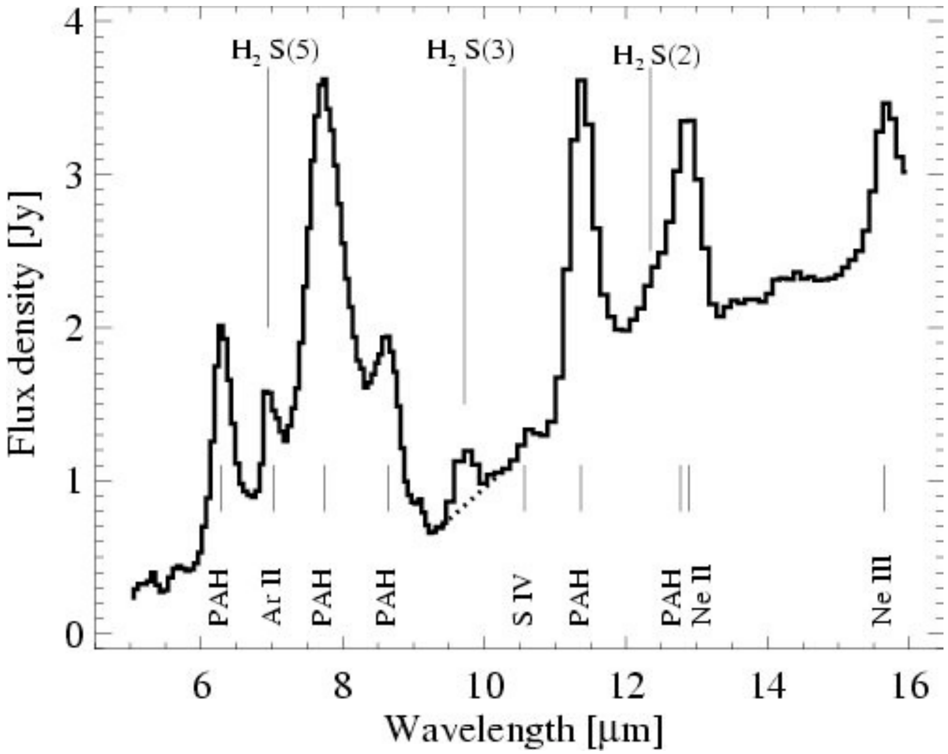
- Boselli,A: A panchromatic view of galaxies, Wiley
- Phillips, the structure & evolution of galaxies,Wiley
- NED-Level 5, knowledgebase for extragalacitc astronomy and cosmology : http://ned.ipac.caltech.edu/level5/
- http://www.astr.ua.edu/keel/galaxies/
- http://www.stsci.edu/science/starburst99/docs/
- Caputi, K: JMPD 2014, vol23, issue 7

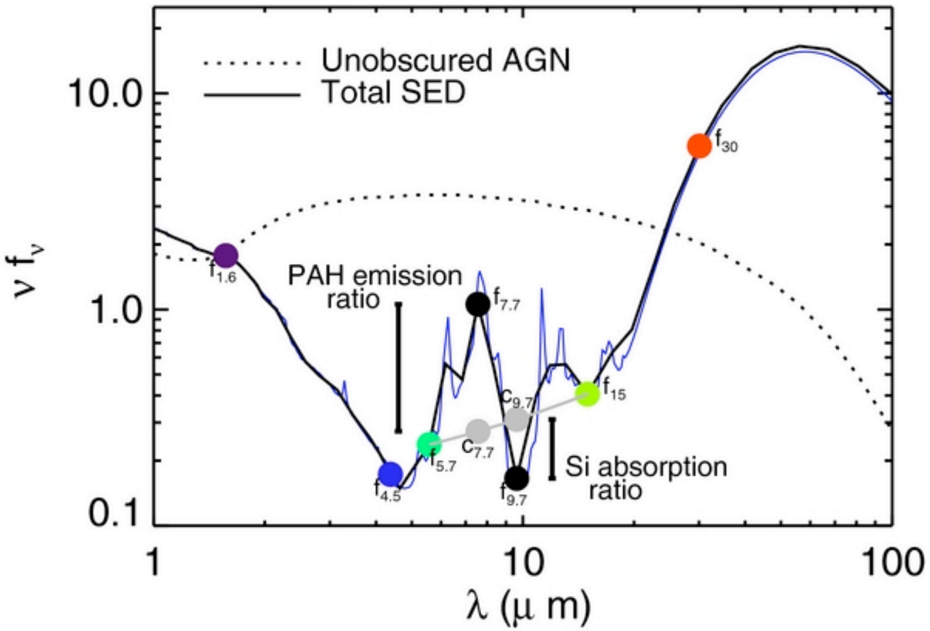
A large variety of mid-IR spectra



from Spoon+07

Mid-IR range :
PAH and silicate features in AGN 2 (obscured)





- PAH emission and silicate absorption often used to characterize the spectrum
- Ionized Neon lines, H_2 lines

How to measure dust masses?

The classical measure is based **on a modified Black Body distribution** (Hildebrand, 1983)

Considering a cloud (distance D) formed by N spherical particules of section s (radius a), temperature **T** and emissivity **Q(ν)**, the flux is given by:

$F(\nu) = N\,(s/\,4\pi\,D^2)\,Q(\nu)\;\;4\,\pi\,B(\nu,T)\;(W\,m^{-2}Hz^{-1})$

Soit $F(\nu) = N\,(s/\,D^2)\,Q(\nu)\,B(\nu,T)$ et $N = F(\nu)\,D^2/(B(\nu,T)\,Q(\nu)\,s$

$B(\nu,T)$ expressed in $W\,m^{-2}sr^{-1}Hz^{-1}$

Le total volume is V = N v

$V = N\,v = (F(\nu)\,D^2/B(\nu,T)\,Q(\nu))\,(v/s)$

With $v=4/3\,\pi\,a^3$ et $s = \pi\,a^2$

→ $M_{dust} = V\,\rho$ → $M_{dust} = (F(\nu)\,D^2/B(\nu,T))\,(4a\rho/3)/Q(\nu))$

Q(ν) prop. to $\nu^{-\beta}$ with β=1, 2

- Temperatures and dust grain emissivities estimated by combining data at different wavelengths (IRAS, ISO , Spitzer, Scuba, Herschel)
- K = 3Q/4aρ, grain opacity, depends on λ and dust grains characteristics (graphite/silicate)
- If several dust components (several BB) are fitted, one adds the corresponding dust masses
- More sophisticated models of dust emission accounting for the properties of yje dust components (Draine & Li 2007) are also used to fit the multi-wavelength data, and dust masses are a by product (Munoz-Mateos+09, Cortese+12, Magdis+12)

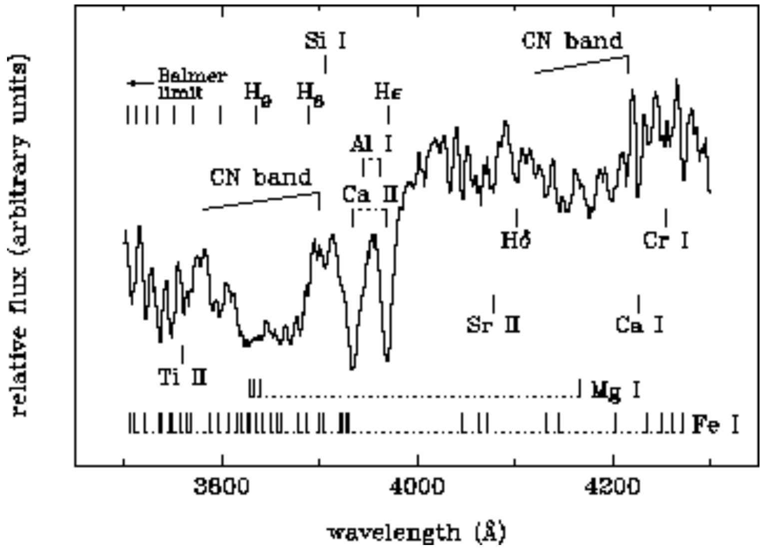
About the D4000 break

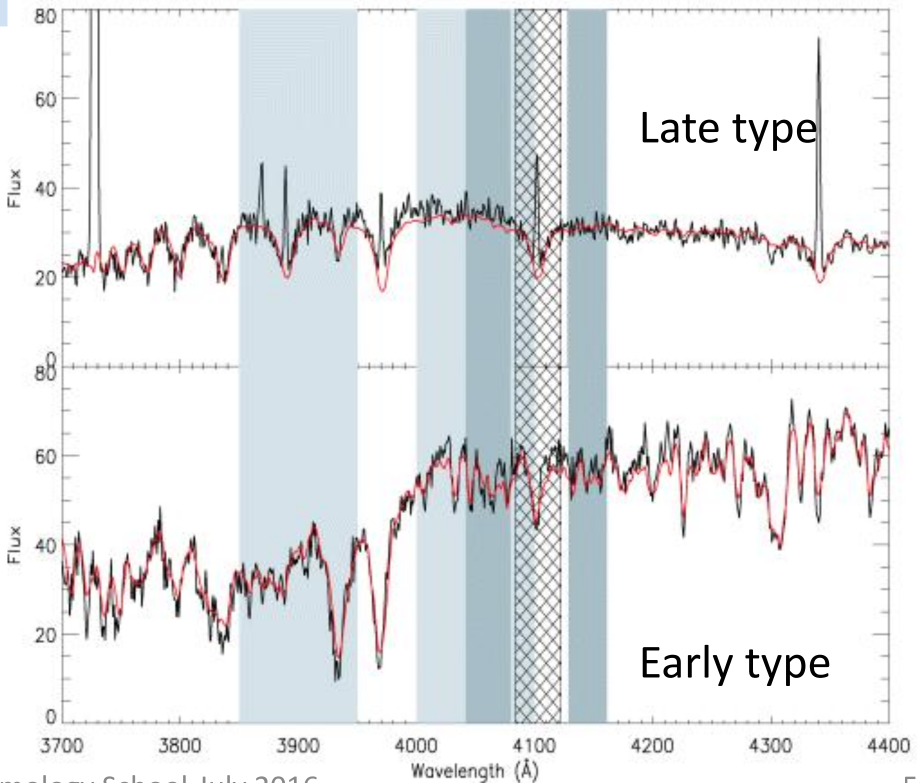
- Related to old stellar populations, its amplitude increases in early type systems:
- Absorption features bluewards 4000 A for stellar types cooler than G0, line blanketing discontinuity

$$D_{4000} = \frac{(\lambda_2^- - \lambda_1^-)\int_{\lambda_1^+}^{\lambda_2^+} F_\nu \, d\lambda}{(\lambda_2^+ - \lambda_1^+)\int_{\lambda_1^-}^{\lambda_2^-} F_\nu \, d\lambda}, \qquad (1)$$

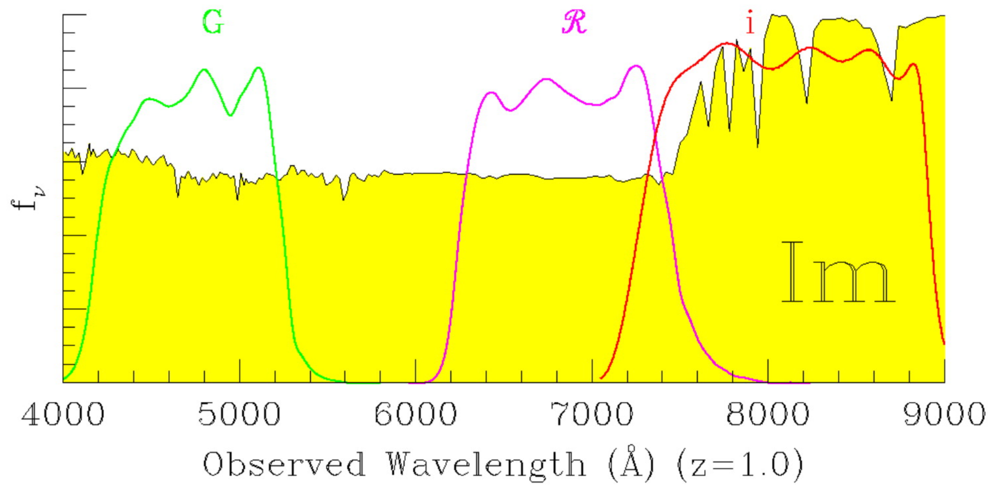
where $(\lambda_1^-, \lambda_2^-, \lambda_1^+, \lambda_2^+) = (3750,\ 3950,\ 4050,\ 4250)$ Å.

Stellar spectrum

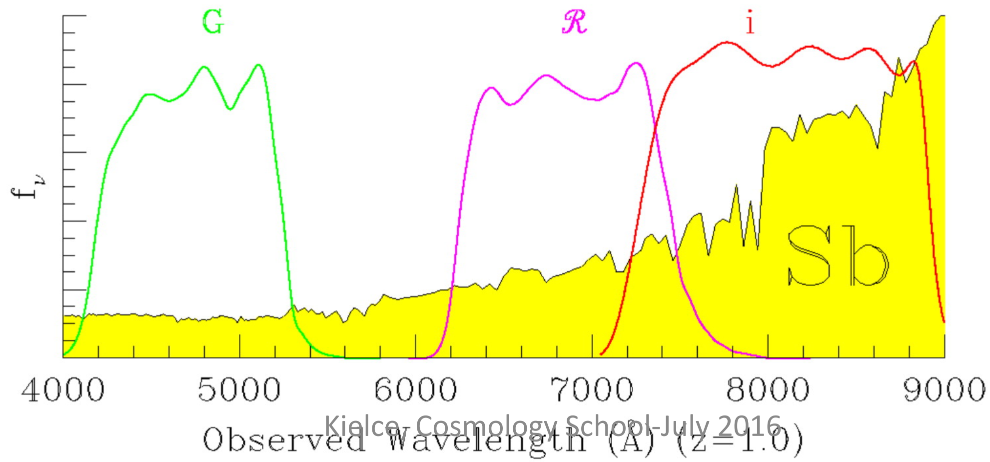




Balmer and D4000 breaks are often used as a single feature to detect high redshifted « quiescent » galaxies



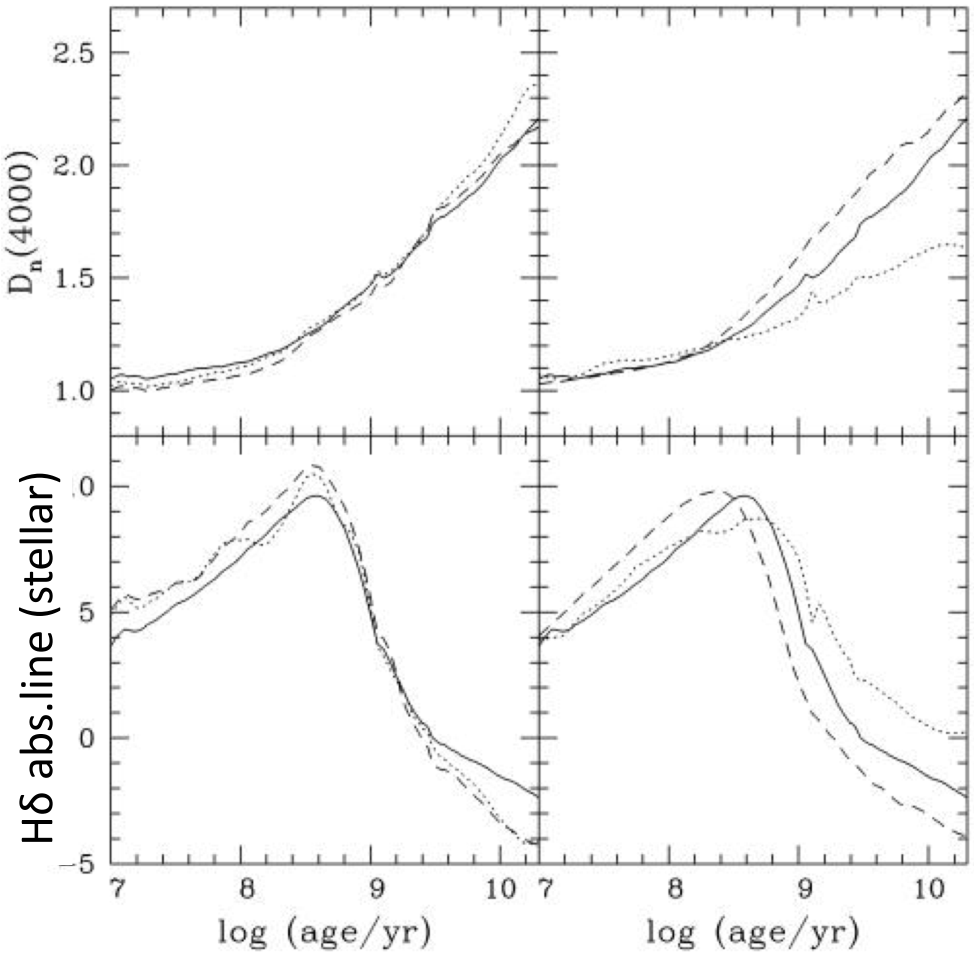
Balmer Break



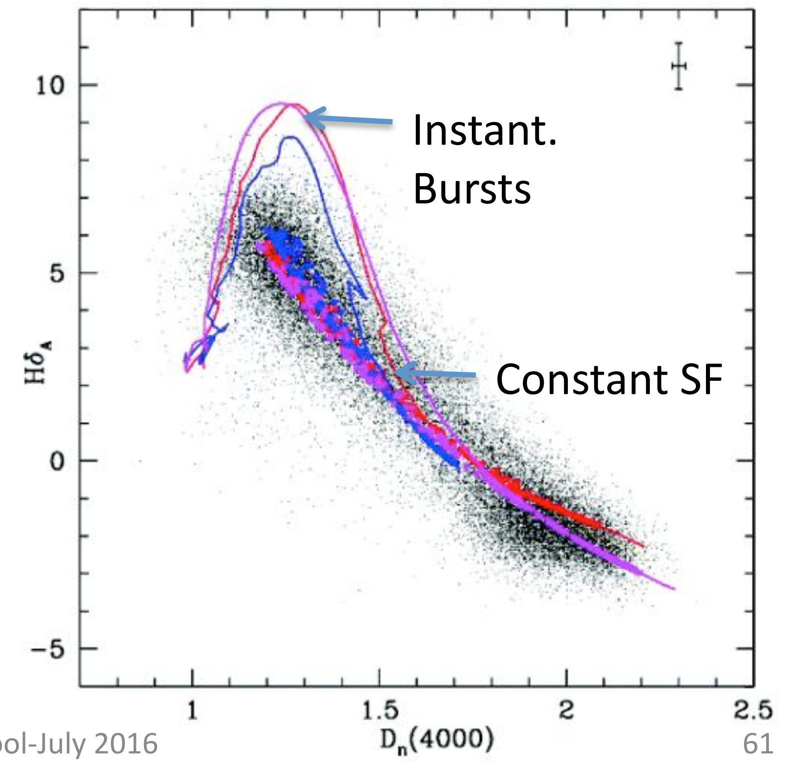
D4000 break

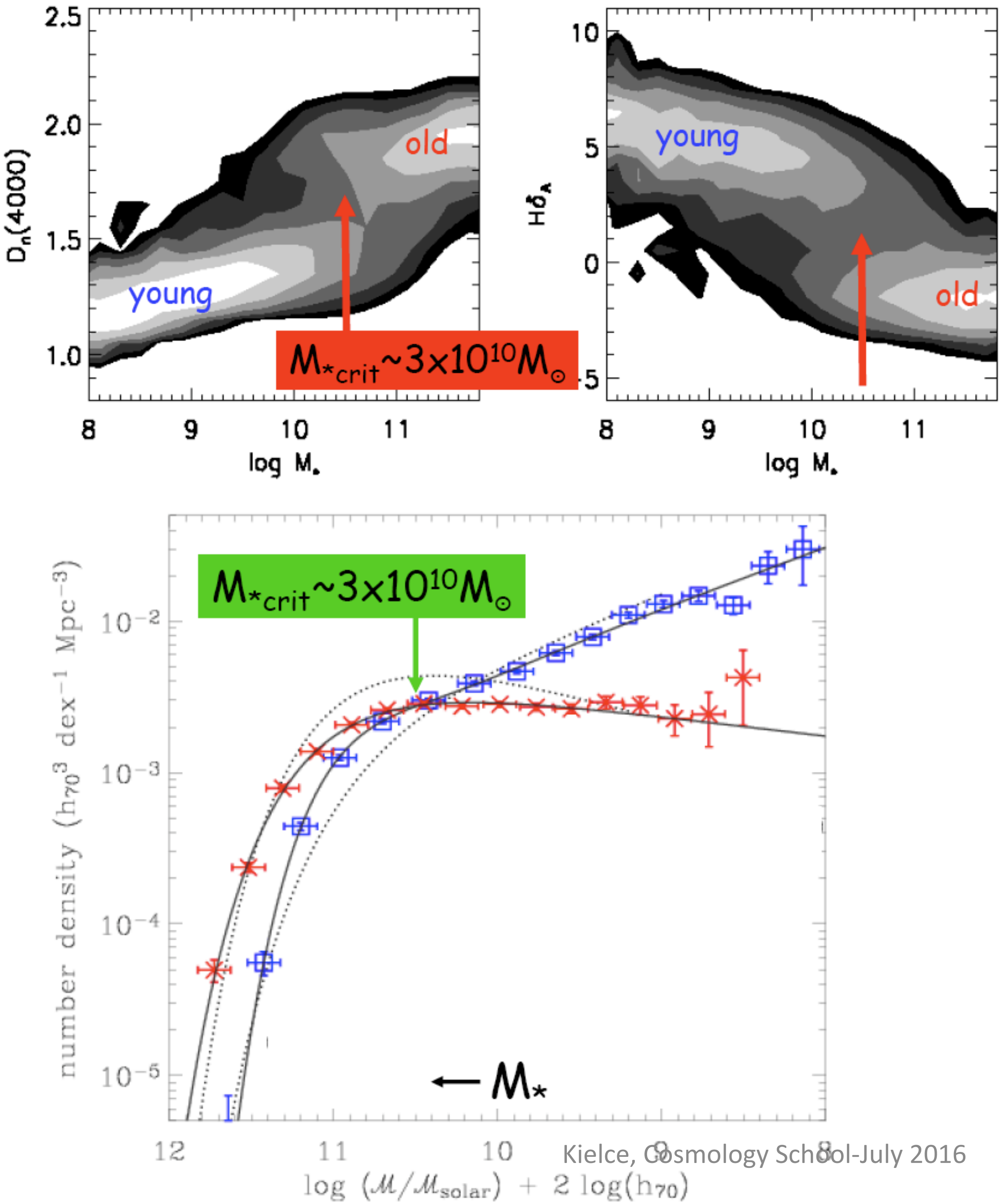
Features in the nearby universe: The SDSS legacy

Instantaneous Burst



In the nearby universe the Balmer features and D4000 breaks are distinct indicators of stellar age Kauffmann+03





Blue and red clouds

Young and old stellar populations