How to measure Star Formation Rates and Stellar Masses?

Véronique Buat, LAM, Marseille



Star Formation in Galaxy Clusters - Nice 6-7 june 2011

Outline

Empirical relations to derive SFRs and Mstar:

***SFRs based on the direct emission of young stars**

- Emission lines
- UV continuum

***SFRs based on the dust emission (MIR-FIR)**

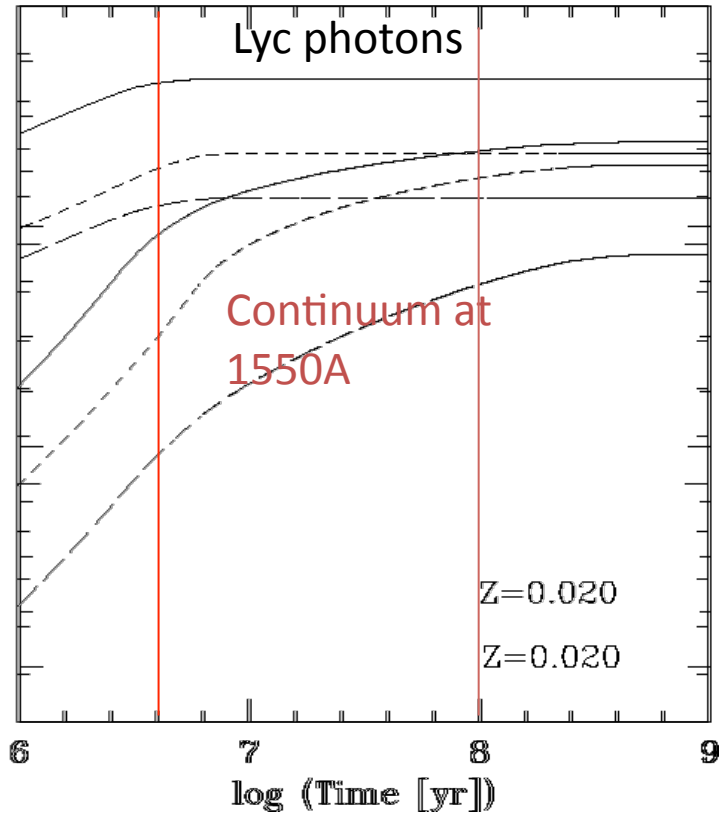
- Monochromatic fluxes
- Global dust emission
- Combination of optical and IR measurements

***Stellar masses from average M/L**

Outline about SED fitting *to introduce the next talks*

- Main ingredients
- Mock catalogues

Lyc and UV emissions: obvious tracers of star formation

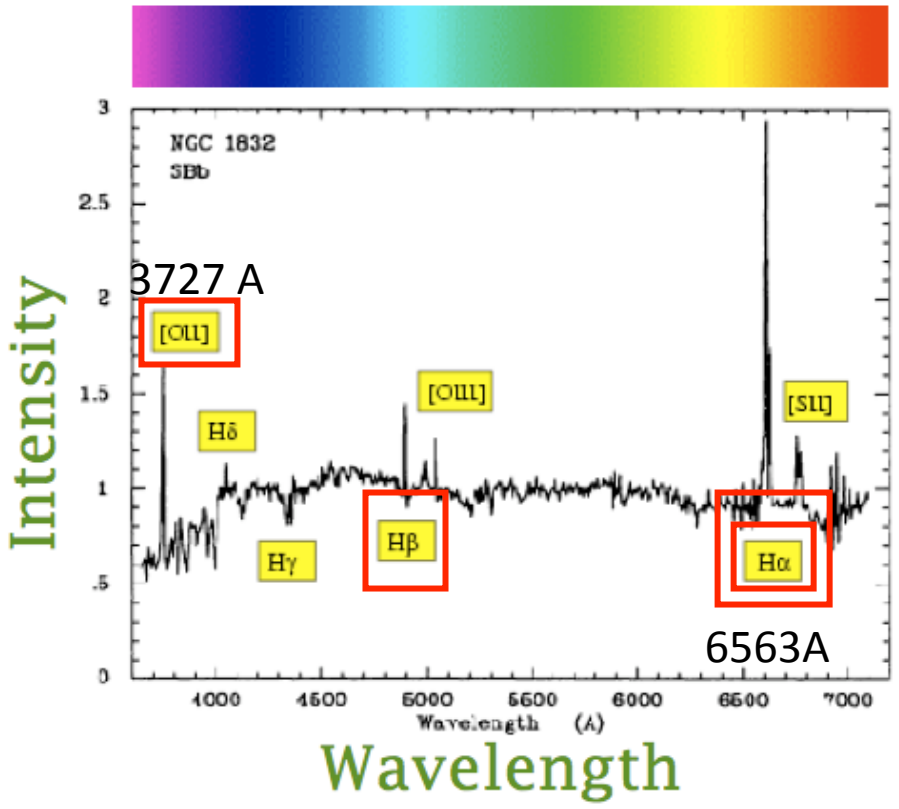


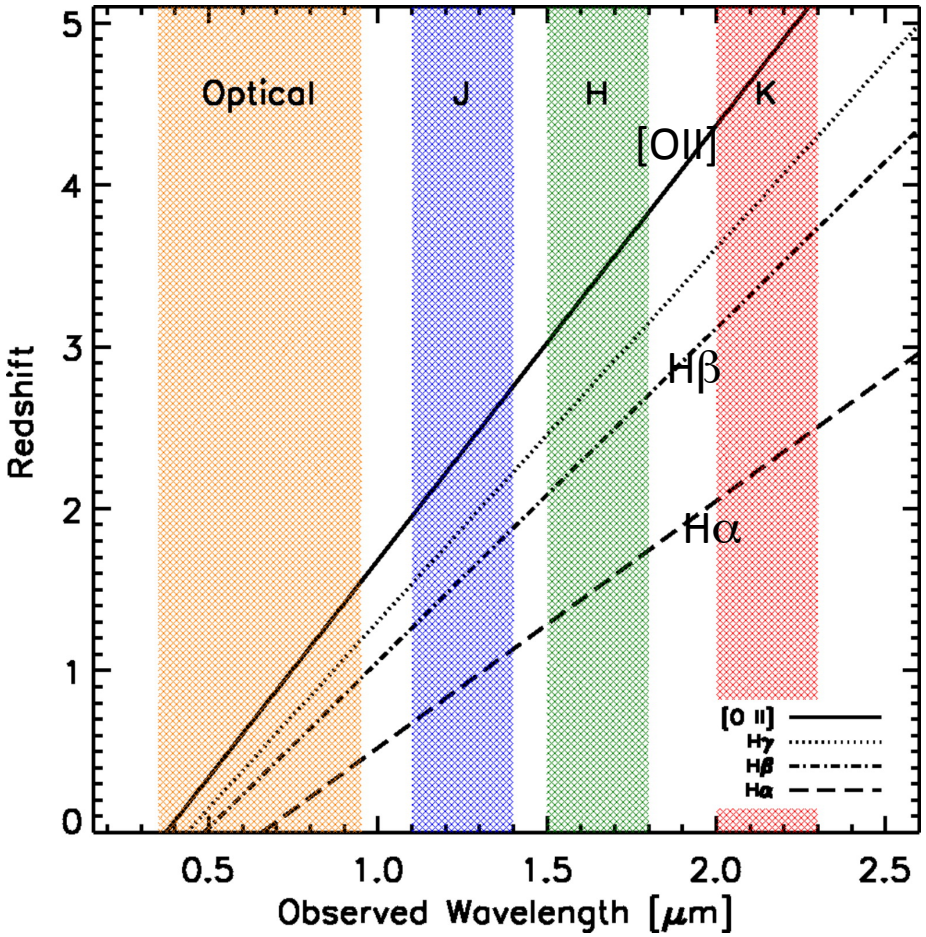
Starburst 99: constant SFR & 3 differents IMF

For a constant SFR over appropriate timescale ,

SFR∝ N(Lyc) and SFR ∝ L(UV)

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





Difficult to observe at z>1

Moustakas et al. 07

SFR(Hα) often taken as a reference

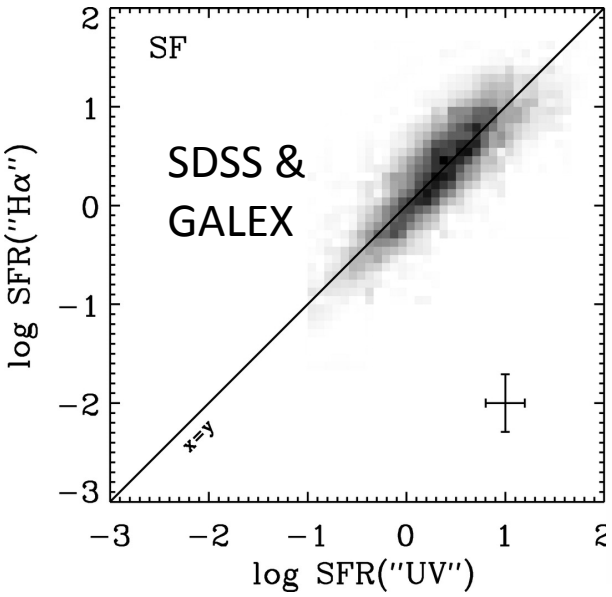
Main inputs:

-A constant SFR over few 10^6 years, a universal IMF

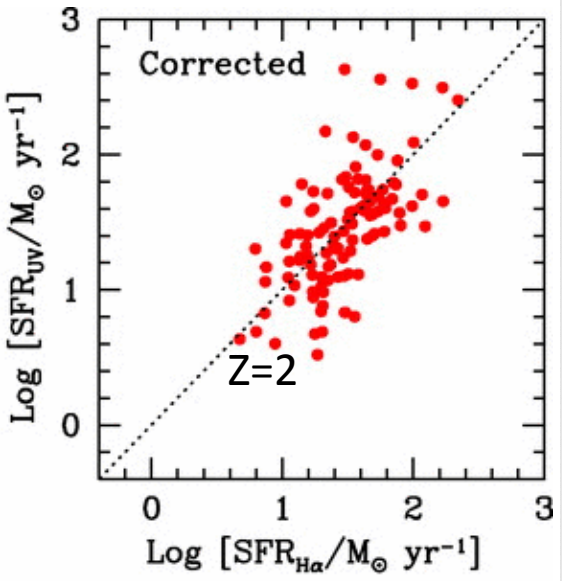
-A correction for dust attenuation (usually based on F(Hα)/F(Hβ))

-A prescription about dust absorption of the Lyc photons, not always considered

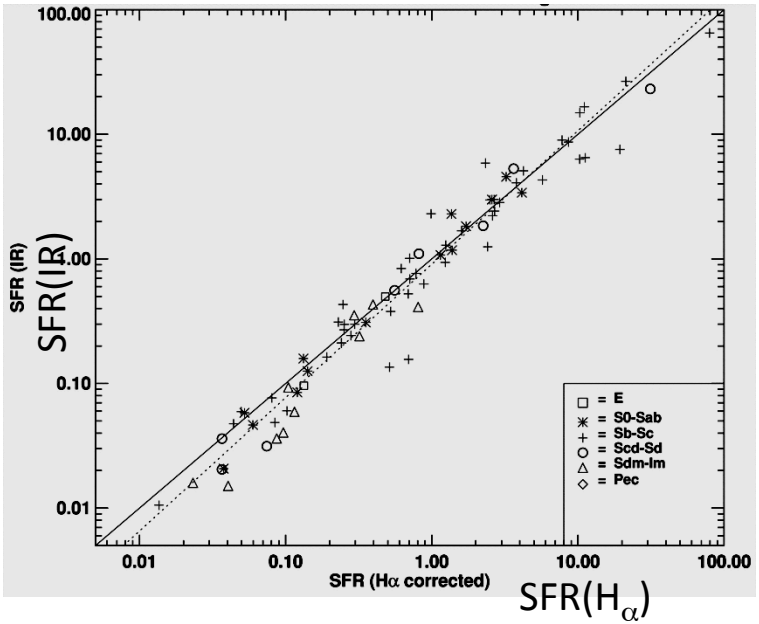
$$\mathbf{SFR_{Msun/yr} = L(H\alpha)_{erg/s} / 1.3\ 10^{41}}\ \ (\textit{Kennicutt 98})$$



Salim et al. 07



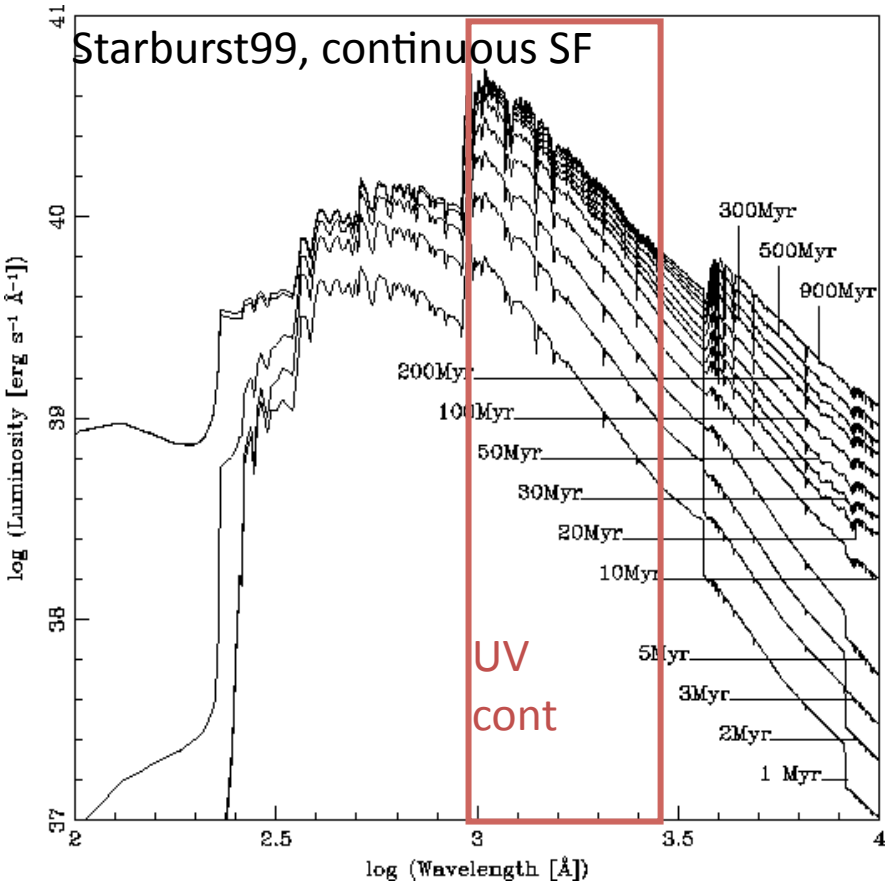
Erb et al. 06



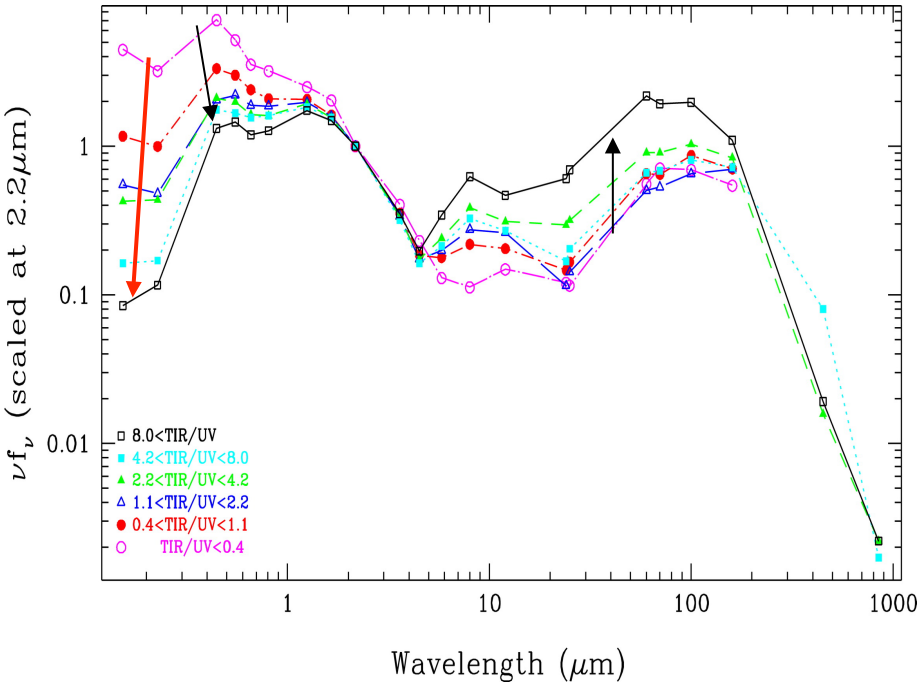
Kewley et al. 02

The UV continuum

a very good intrinsic star formation tracer



BUT….very sensitive to dust attenuation

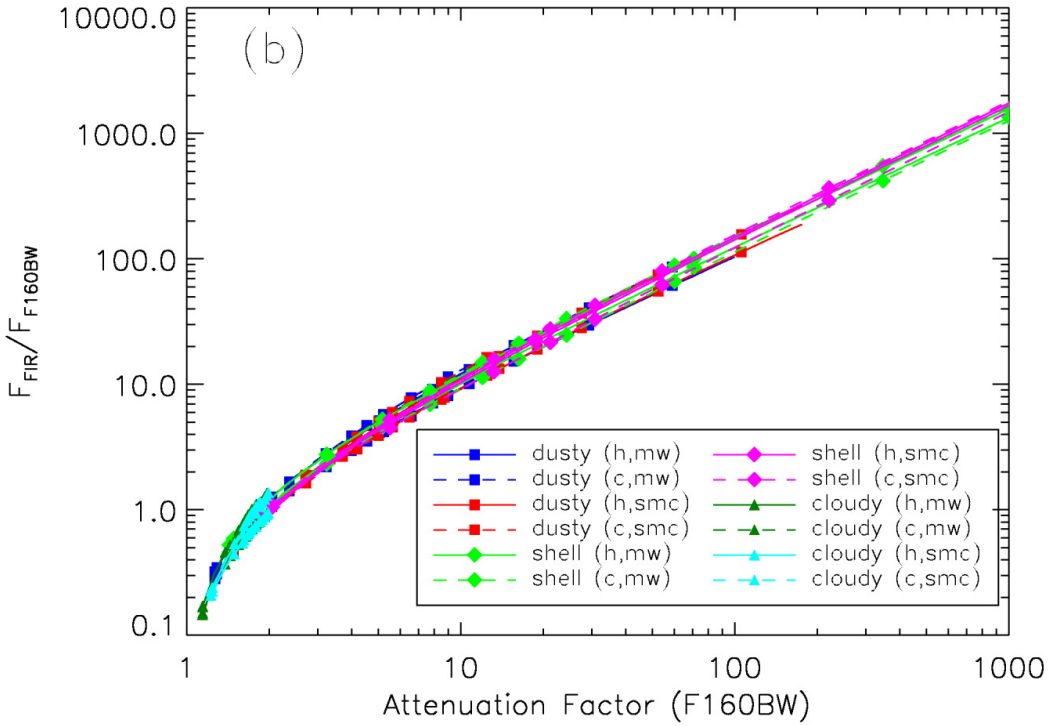


Dale et al. 07

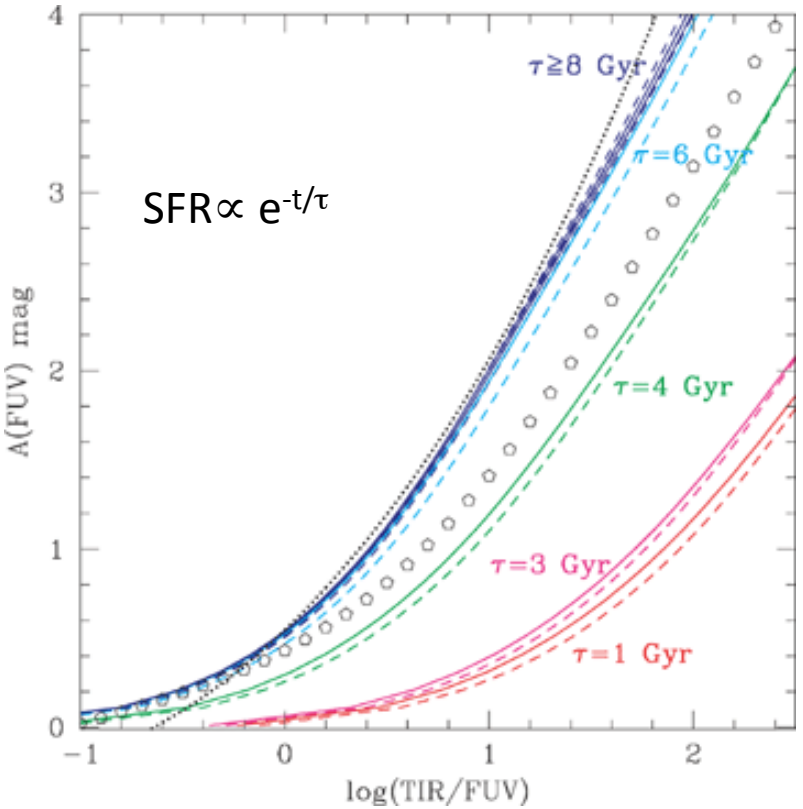
SFR (M_{sun} yr^{-1}) = 1.4 10^{-28} L_{UV}(erg s^{-1} Hz^{-1})

Kennicutt 98

F_{IR}/F_{UV} flux ratio is a robust tracer of the dust attenuation for star forming galaxies only



Star forming galaxies and various geometries/dust properties
Gordon et al. 2000

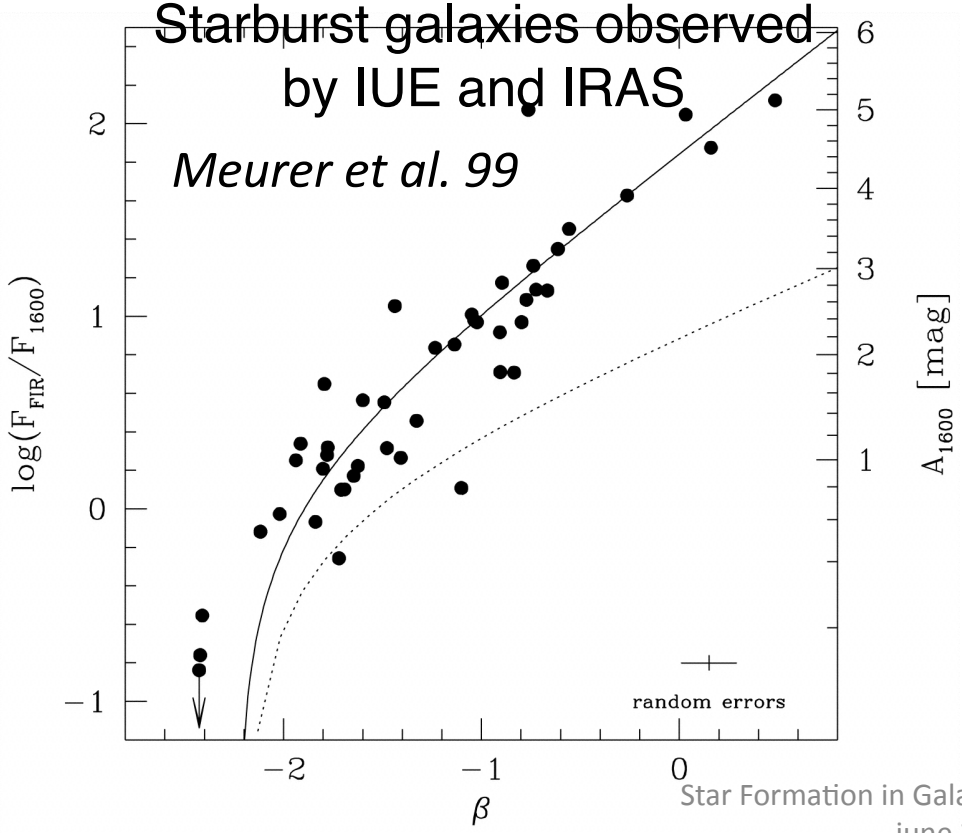


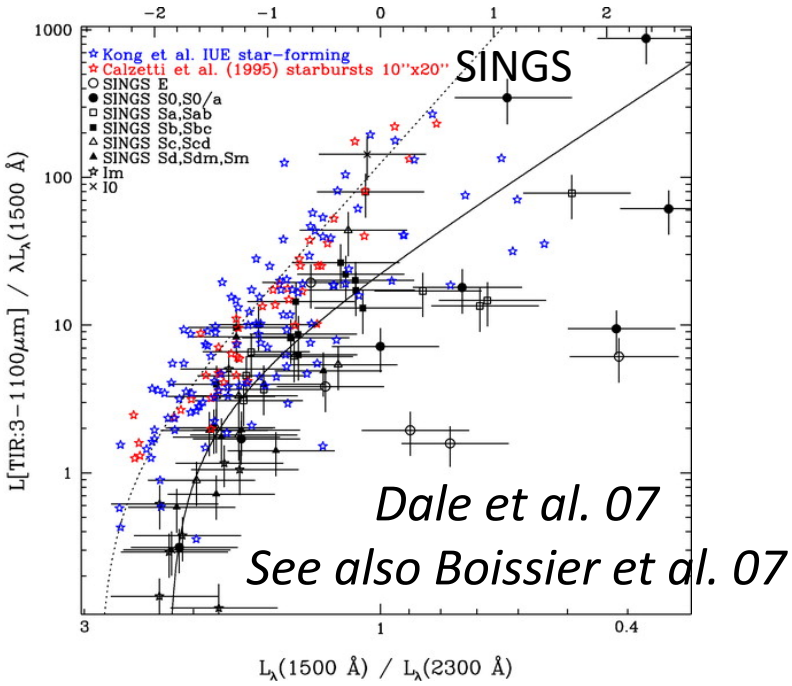
Cortese et al. 08

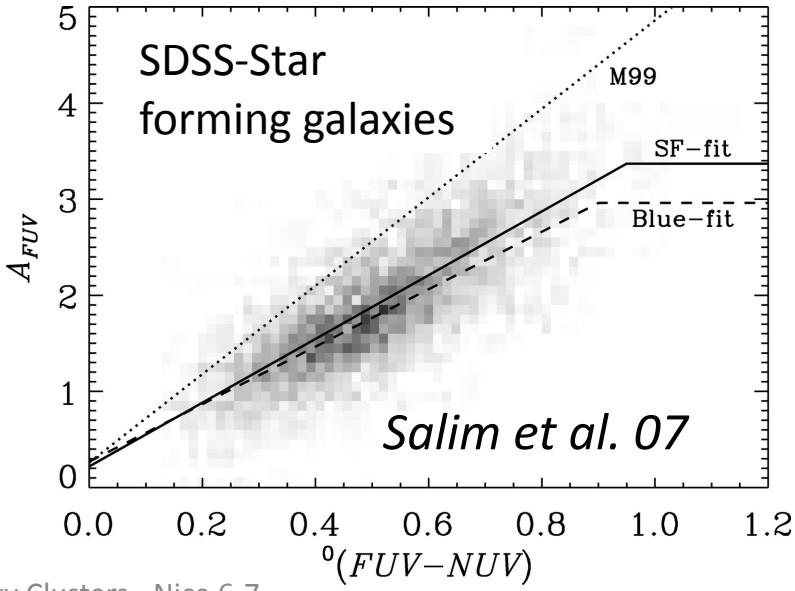
The calibration depends on the star formation history

More controversed: the slope of the UV continuum to measure dust attenuation

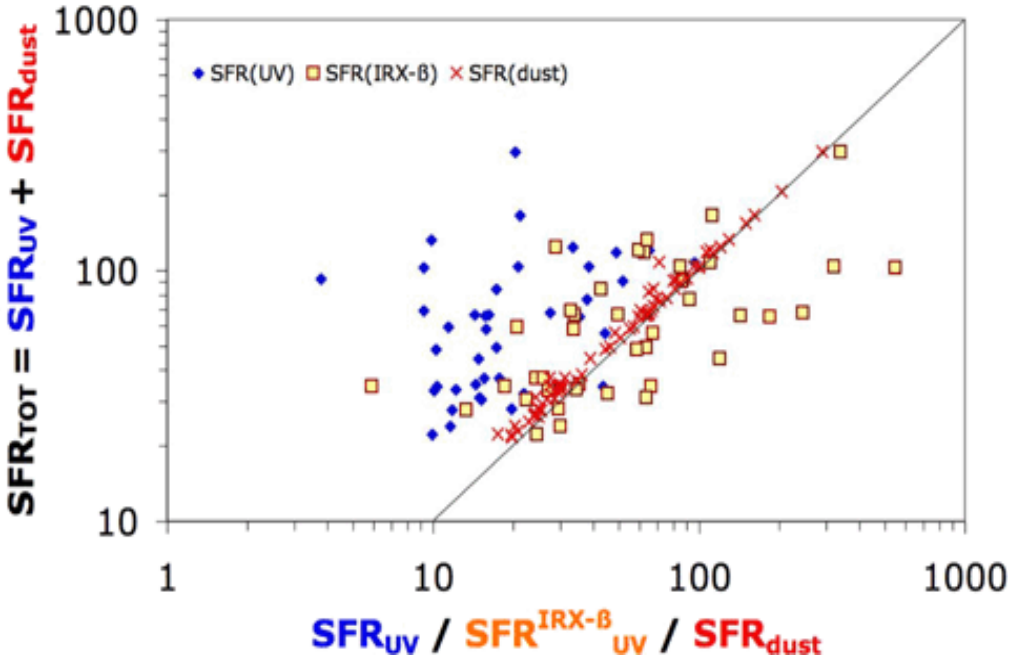
$f_\lambda \propto \lambda^\beta$(1200-2500Å), β might be a proxy for the dust attenuation but to be used with much caution







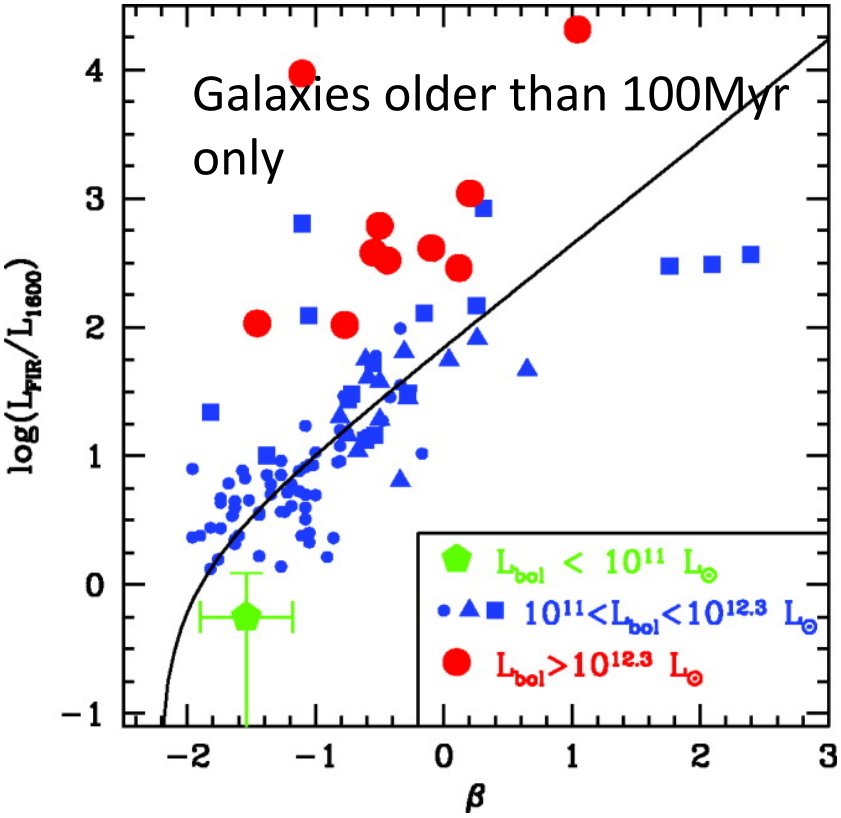
Some studies at high z conclude to the reliability of the starburst law



at z≈1

Burgarella et al. 07

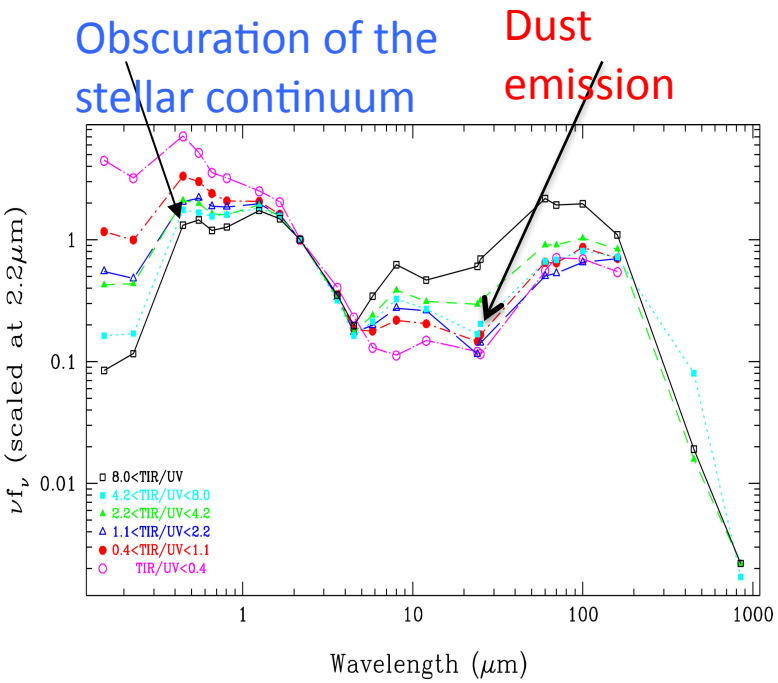
SFR^{β}(UV) give consistent but dispersed values when compared to SFR(IR+UV)



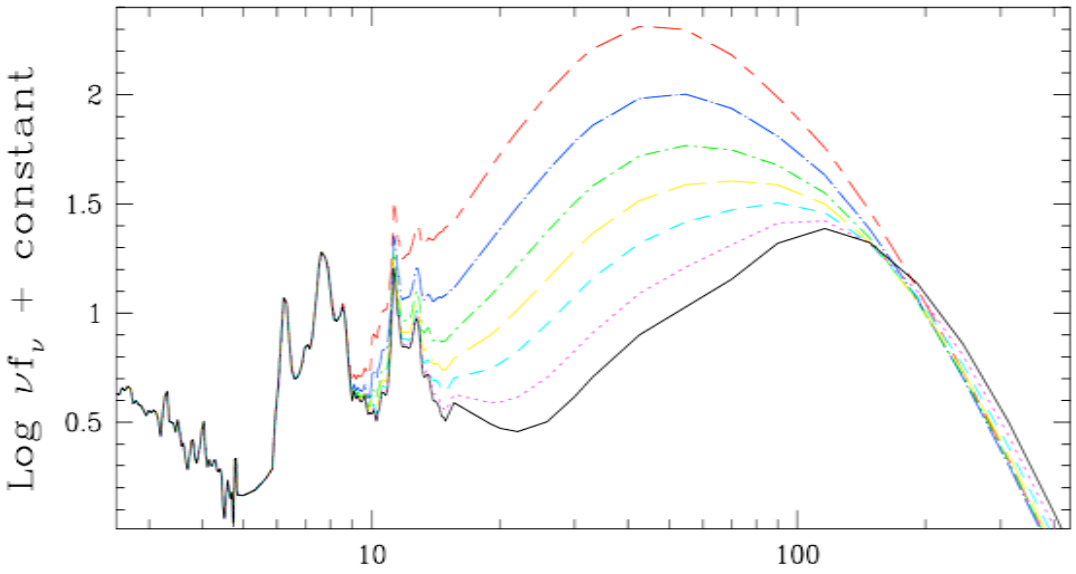
At z ~2 Reddy et al. 06

Optically and Near-IR selected star forming galaxies follow the « Meurer law » (except for the brightest objects in IR)

SFRs measured from the (mid and far) IR emission of galaxies



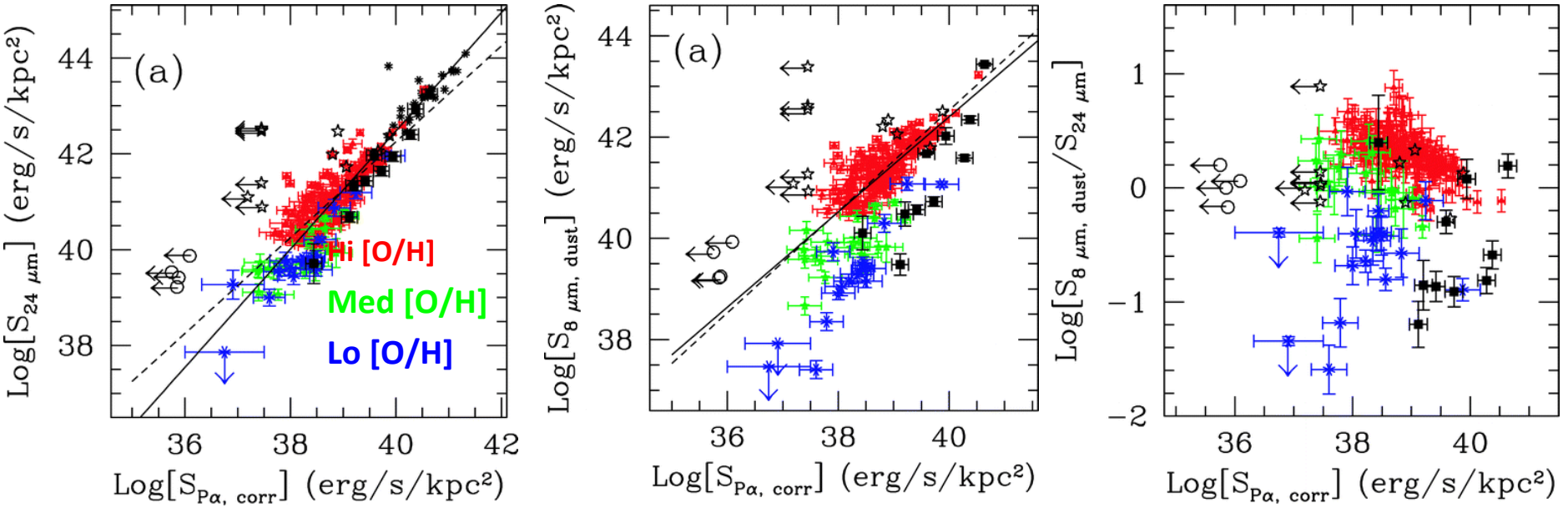
From Dale et al. 07



Dale & Helou (2002)

Luminosities at 24 and 8 µm as SFR estimators

Monochromatic fluxes to avoid the extrapolation to the whole IR range



$L_{24\mu m}$ is a reliable SF tracer, more difficult for $L_{8\mu m}$

Low metallicity regions exhibit a low 8 to 24 µm flux ratio

$$SFR(M_{sun}\ yr^{-1}) = 1.27\ 10^{-38}\ (L_{24\mu m}\ (erg\ s^{-1}))^{-0.8850}$$

Calzetti et al. 07

Global IR(≈5-1000µm) dust emission

Assumption:L_{IR} identified as the bolometric luminosity of the young stellar population (age less than ≤≈10^8 yrs)

SFR(M_{sun} yr^{-1}) = 4.5 10^{-44} L_{IR} (erg s^{-1}) (K98)

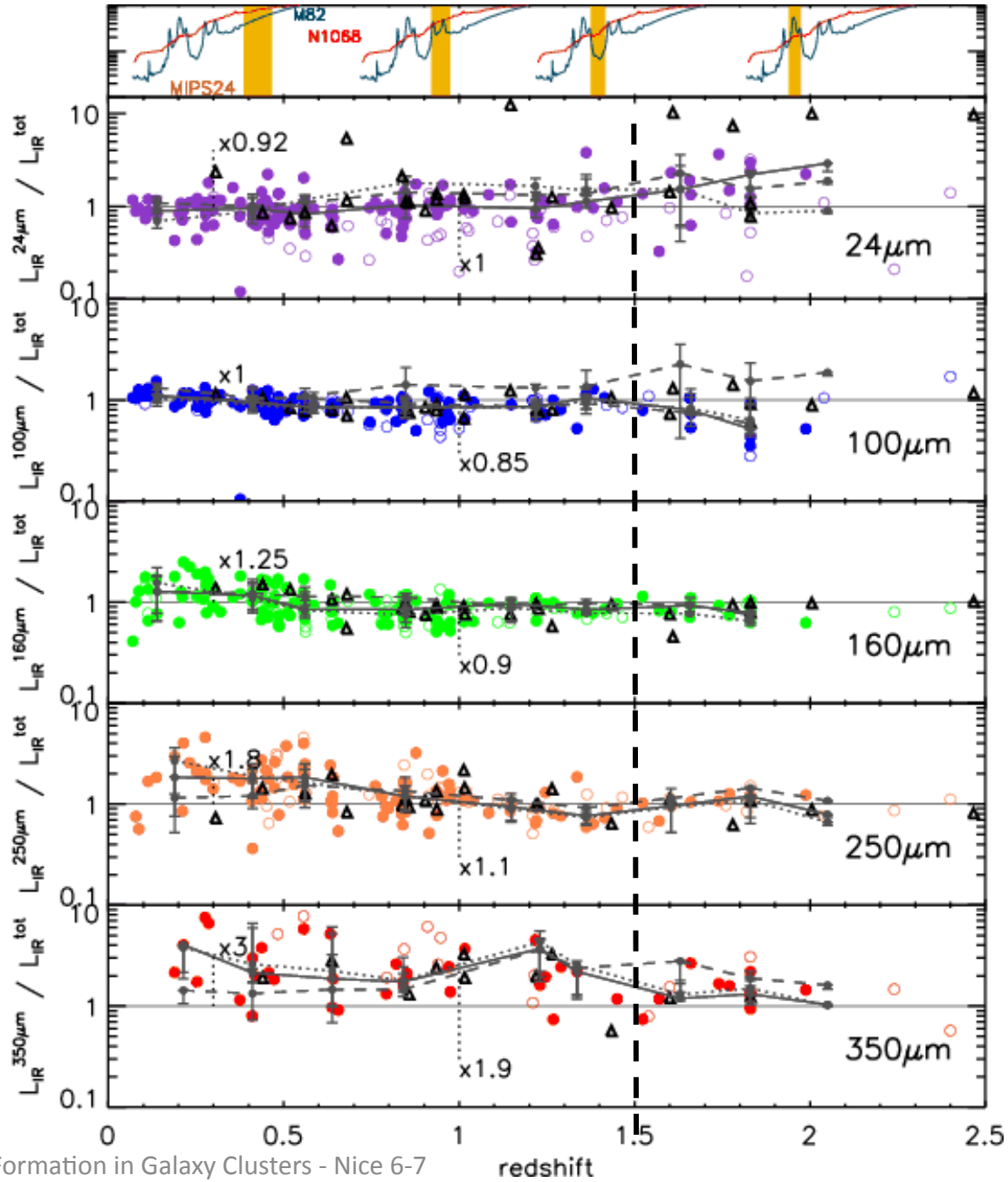
But several issues:

- Dust may also be heated by **old stars**
- Galaxies are observed in UV & Optical: a fraction of the **stellar emission escapes** the galaxies and is not re-processed by the dust, related to dust attenuation
- One needs to estimate the **TOTAL (5-1000 µm) dust emission** and the extrapolation may be very uncertain, especially at high z (use of templates)

Herschel-PACS/SPIRE Elbaz et al. 2010, A&A special issue

L_{IR}^{tot}: 8-1000 µm; best fit with Chary & Elbaz 01 templates above 30 µm (rf)
$L_{IR}(\lambda)$ from SED-L_{IR} library CE01

- For z<1.5, 24 µm data give correct L_{IR}^{tot} (σ: 40%), 160, 250 and 350 µm data over-estimate L_{IR}^{tot} (local SEDs uncertain in far-IR)
- For z > 1.5, best estimates with 160 and 250 µm data, 24 µm data over-estimate L_{IR}^{tot}



A powerful strategy:

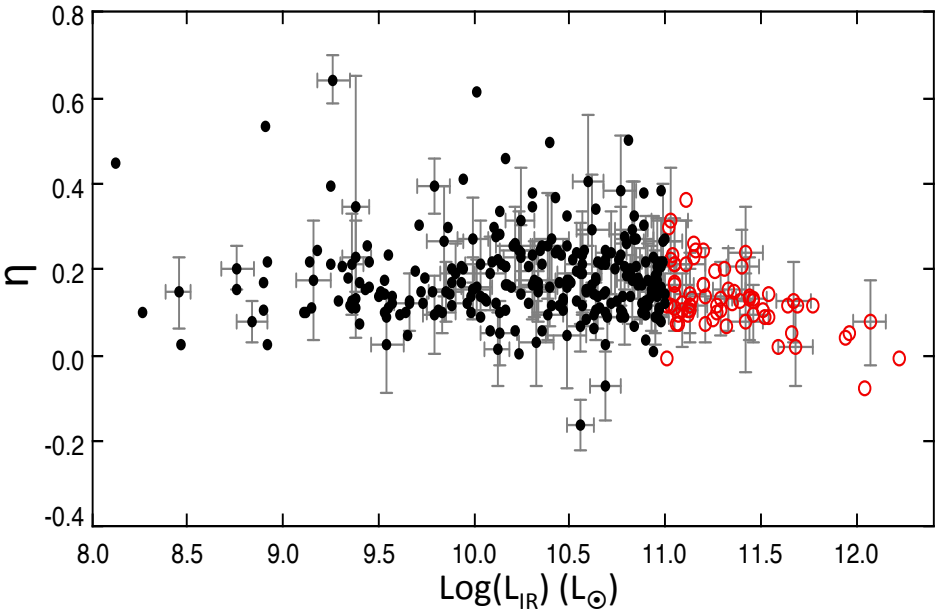
adding UV and IR measurements to estimate the SFRs

- $SFR(M_{sun}\ yr^{-1}) = (1-\eta)\ SFR(IR)+SFR(UV_{obs})$ *Hirashita et al. 03, Iglesias-Paramo et al. 04,06*
- $SFR\ (M_{sun}\ yr^{-1}) = 1.72\ 10^{-10}\ (L(IR)_{young\ stars}+L(UV_{obs}))$ *Bell 03, Bell et al. 05*

η corresponds to the fraction of L(IR) due to the heating by old stars

At z=0 η= 0.3,0.4 for normal galaxies , η= 0 for starburst galaxies

Hirashita et al. 03, Iglesias-Paramo et al. 04,06, Bell 03



Buat et al. 2011:
AKARI-SDSS-GALEX data:
η= 0.17 +/- 0.10

Stellar mass estimates : M/L VERSUS COLOURS recipes from optical-NIR SEDs and population synthesis models

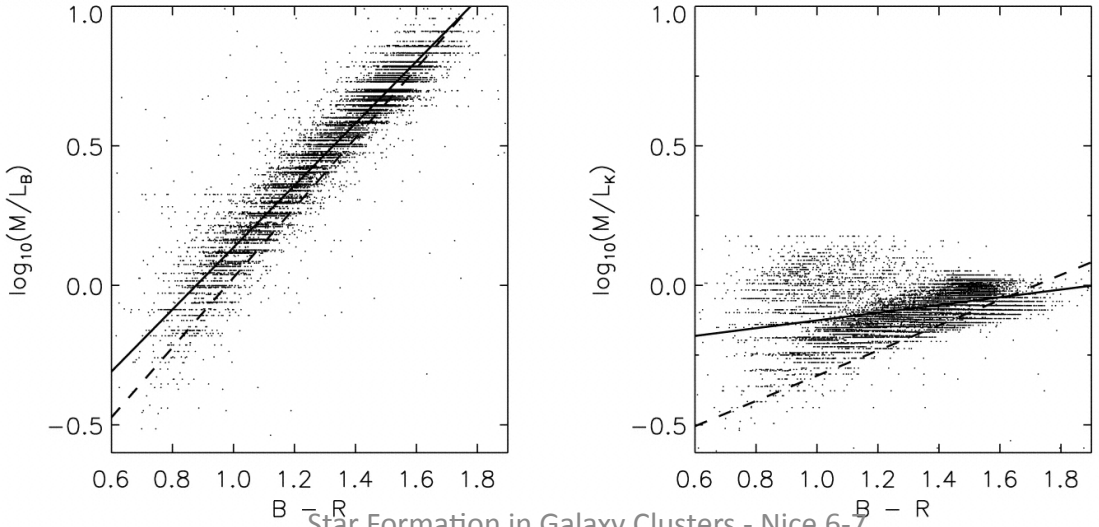
TABLE 7

STELLAR MASS-TO-LIGHT RATIO AS A FUNCTION OF COLOR

Color	a_g	b_g	a_r	b_r	a_i	b_i	a_z	b_z	a_J	b_J	a_H	b_H	a_K	b_K
$u-g$	−0.221	0.485	−0.099	0.345	−0.053	0.268	−0.105	0.226	−0.128	0.169	−0.209	0.133	−0.260	0.123
$u-r$	−0.390	0.417	−0.223	0.299	−0.151	0.233	−0.178	0.192	−0.172	0.138	−0.237	0.104	−0.273	0.091
$u-i$	−0.375	0.359	−0.212	0.257	−0.144	0.201	−0.171	0.165	−0.169	0.119	−0.233	0.090	−0.267	0.077
$u-z$	−0.400	0.332	−0.232	0.239	−0.161	0.187	−0.179	0.151	−0.163	0.105	−0.205	0.071	−0.232	0.056
$g-r$	−0.499	1.519	−0.306	1.097	−0.222	0.864	−0.223	0.689	−0.172	0.444	−0.189	0.266	−0.209	0.197
$g-i$	−0.379	0.914	−0.220	0.661	−0.152	0.518	−0.175	0.421	−0.153	0.283	−0.186	0.179	−0.211	0.137
$g-z$	−0.367	0.698	−0.215	0.508	−0.153	0.402	−0.171	0.322	−0.097	0.175	−0.117	0.083	−0.138	0.047
$r-i$	−0.106	1.982	−0.022	1.431	0.006	1.114	−0.052	0.923	−0.079	0.650	−0.148	0.437	−0.186	0.349
$r-z$	−0.124	1.067	−0.041	0.780	−0.018	0.623	−0.041	0.463	−0.011	0.224	−0.059	0.076	−0.092	0.019

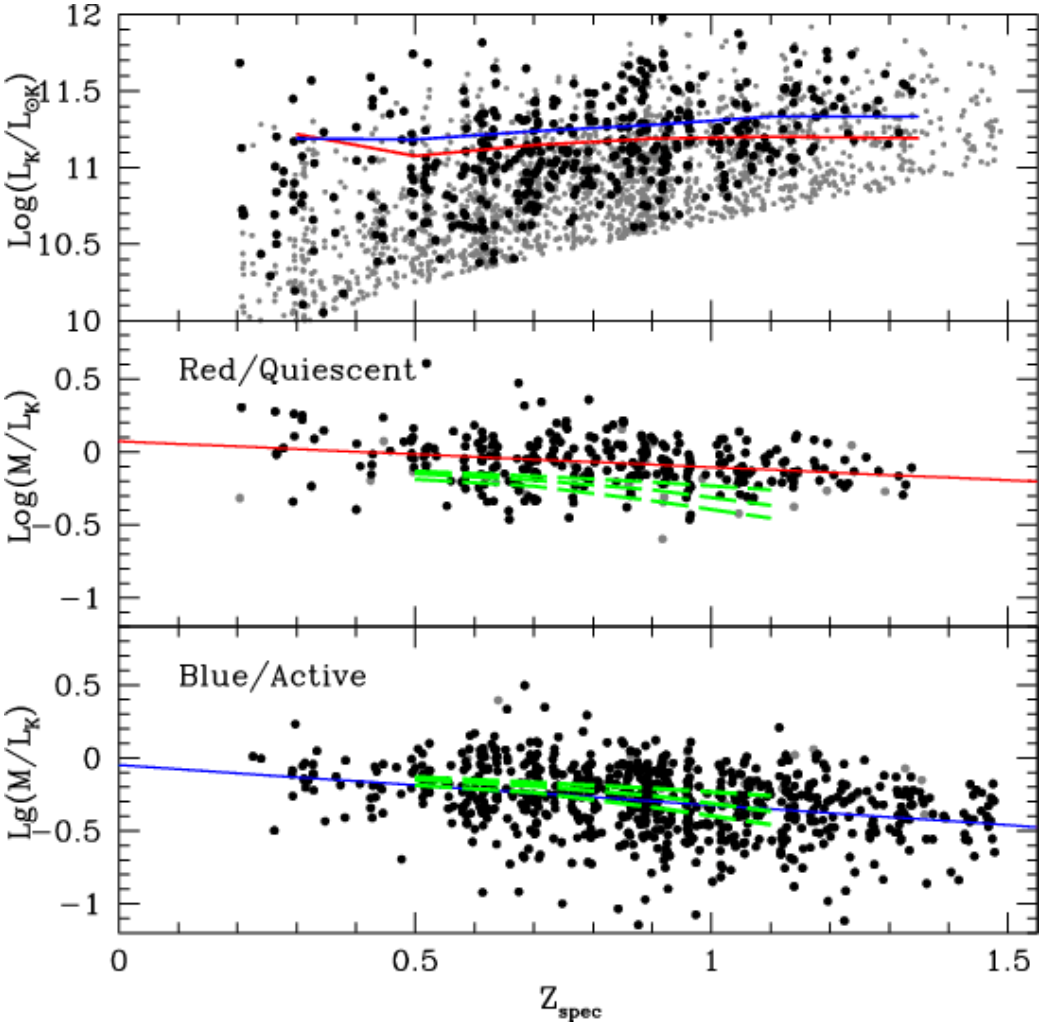
Color	a_B	b_B	a_V	b_V	a_R	b_R	a_I	b_I	a_J	b_J	a_H	b_H	a_K	b_K
$B-V$	−0.942	1.737	−0.628	1.305	−0.520	1.094	−0.399	0.824	−0.261	0.433	−0.209	0.210	−0.206	0.135
$B-R$	−0.976	1.111	−0.633	0.816	−0.523	0.683	−0.405	0.518	−0.289	0.297	−0.262	0.180	−0.264	0.138

NOTES.—Stellar M/L ratios are given by $\log_{10}(M/L) = a_\lambda + (b_\lambda \times \text{color})$, where the M/L ratio is in solar units. If *all* galaxies are submaximal, then the above zero points (a_λ) should be modified by subtracting an IMF dependent constant as follows: 0.15 dex for a Kennicutt or Kroupa IMF, and 0.4 dex for a Bottema IMF. Scatter in the above correlations is ~0.1 dex for all optical M/L ratios, and 0.1–0.2 dex for NIR M/L ratios (larger for galaxies with blue optical colors). SDSS filters are in *AB* magnitudes; Johnson *BVR* and *JHK* are in Vega magnitudes.



Bell et al. 2003

M/L varies with z
Arnouts et al. 2007



Outline on SED fitting methods

Main ingredients:

*__Wavelength range:__ UV-optical-NIR (sometimes + far-IR)

*__Star Formation History__: Single stellar populations, sometimes more complex ones (bursts)

*__IMF__: Salpeter, Kroupa, Chabrier

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•__AGN contribution__: Herschel is providing new insights

Estimation of parameters

*X^2 minimization, confidence intervals

*Bayesian analysis (Kauffmann et al. 03, Walcher et al. 07, Cigale)

Various existing codes:

-photo-Z (Le Phare, Hyperz, Eazy): few templates but not always

-physical properties: (Cigale, Pegase, Grasil, Walcher et al., da Cunha et al.)

Tests on mock/simulated catalogues of galaxies

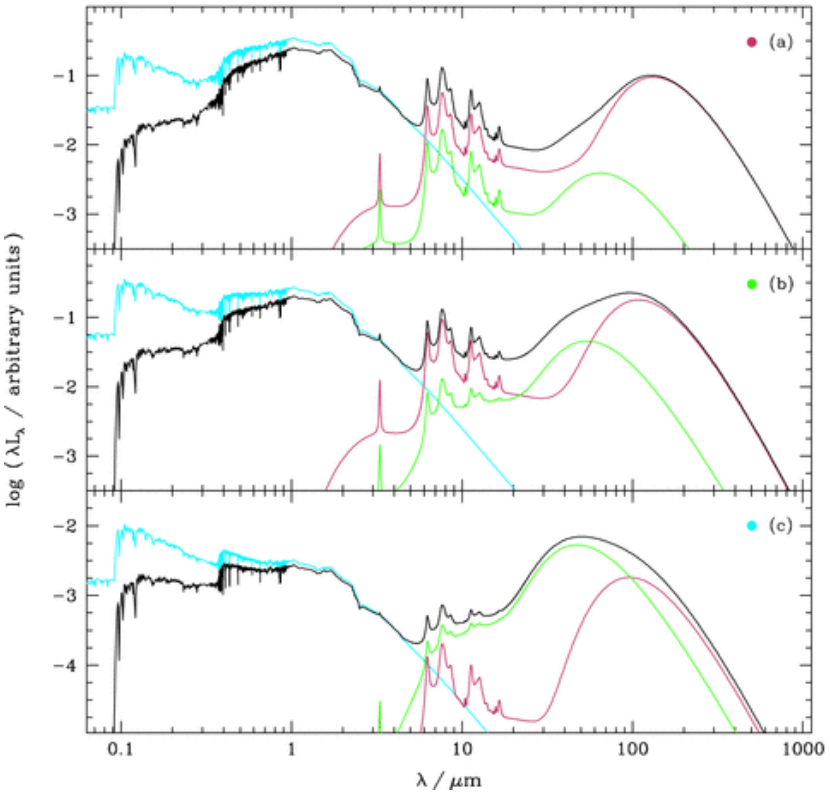
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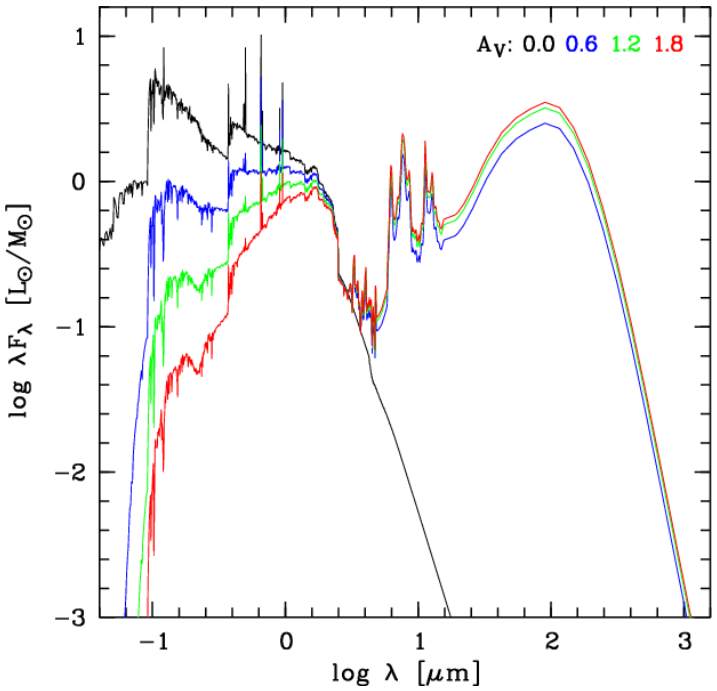
SED FITTING codes associating UV-optical (stellar) and mid- far-IR (dust) emissions

combining a UV-optical SED & a dust IR emitting component:

Energetic balance fully conserved between stellar and dust emission.



Da Cunha et al 2008, 2010



CIGALE, Noll et al. 2009

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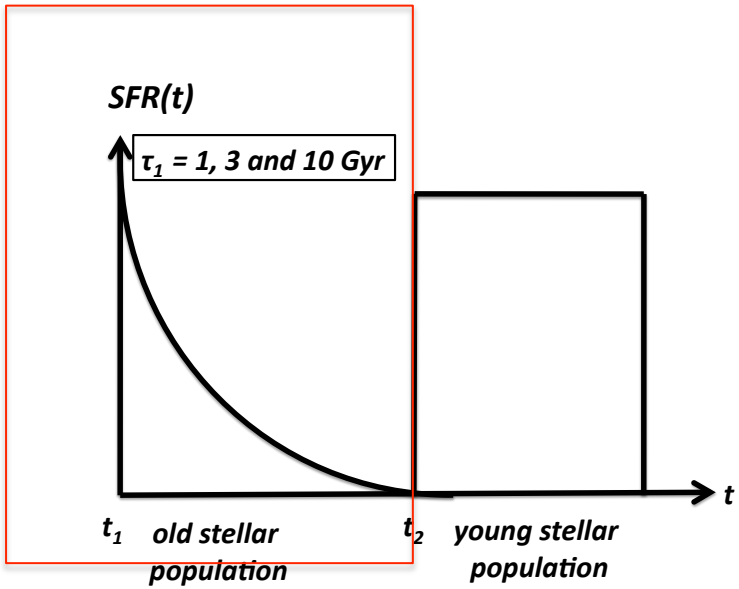
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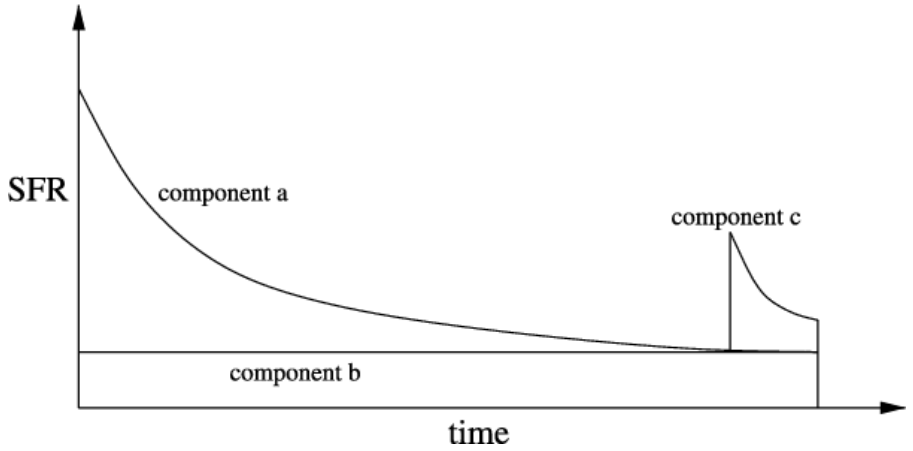
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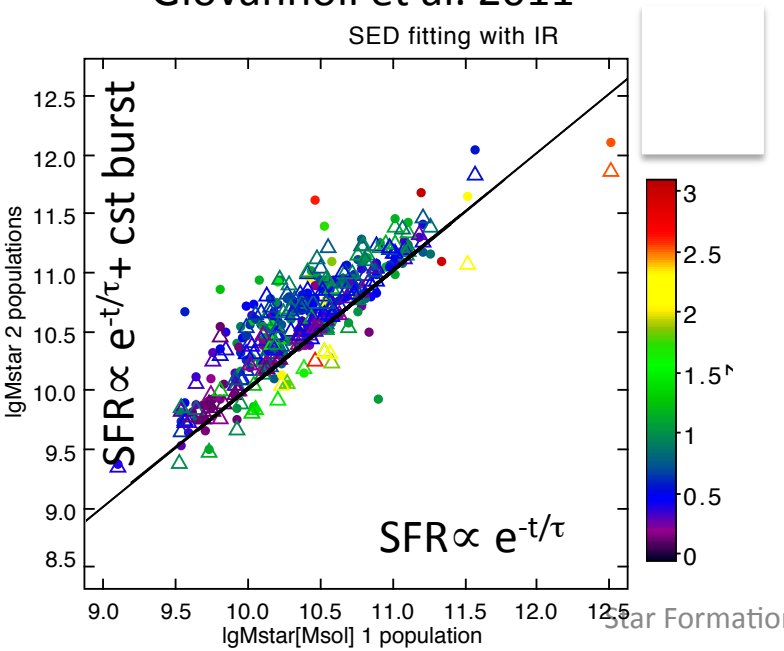
Star Formation Histories:different assumptions

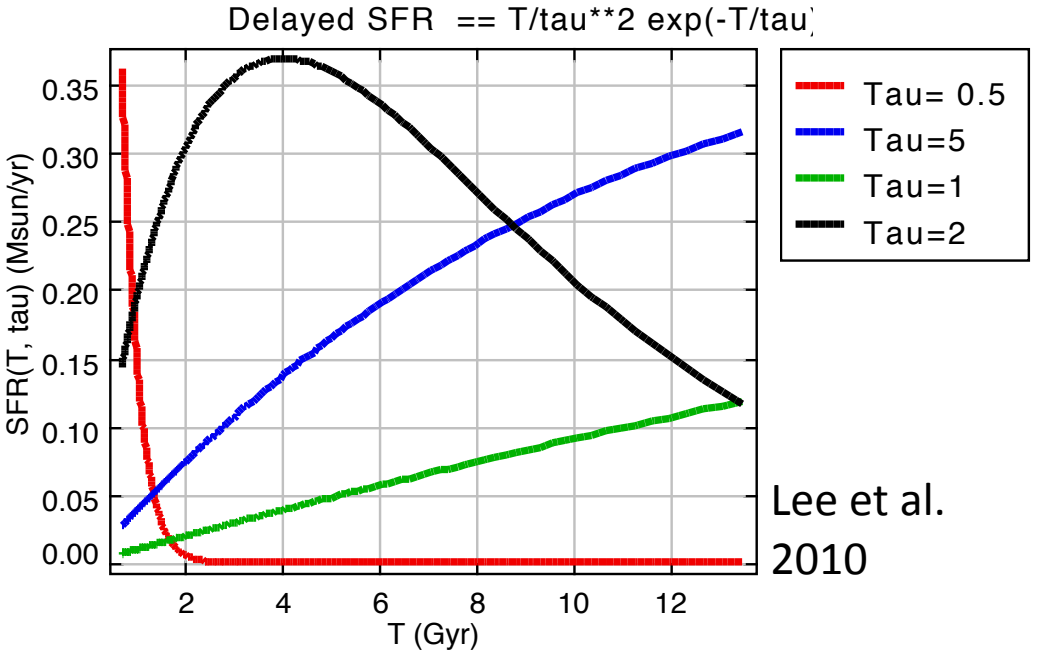


Giovannoli et al. 2011



Borch et al. 2006





Lee et al. 2010

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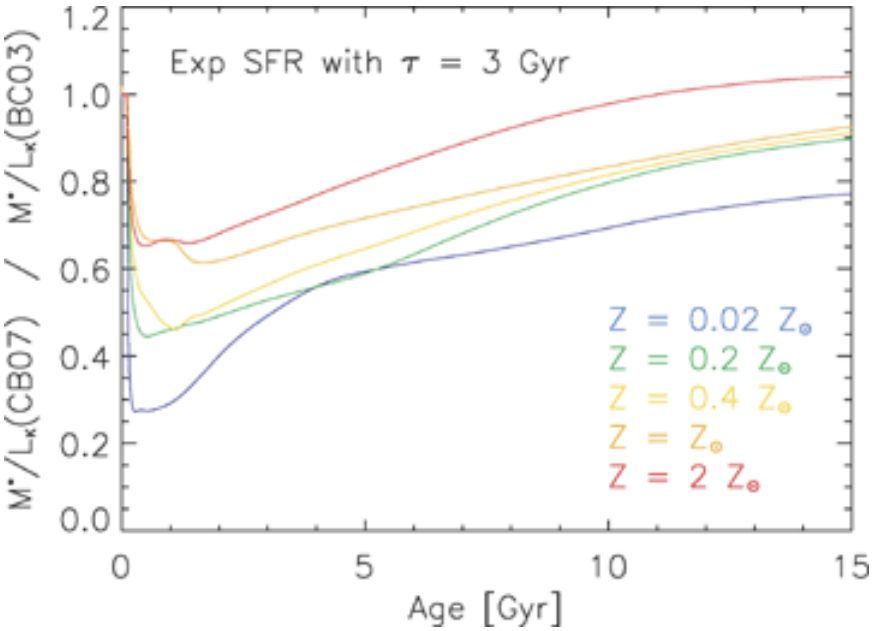
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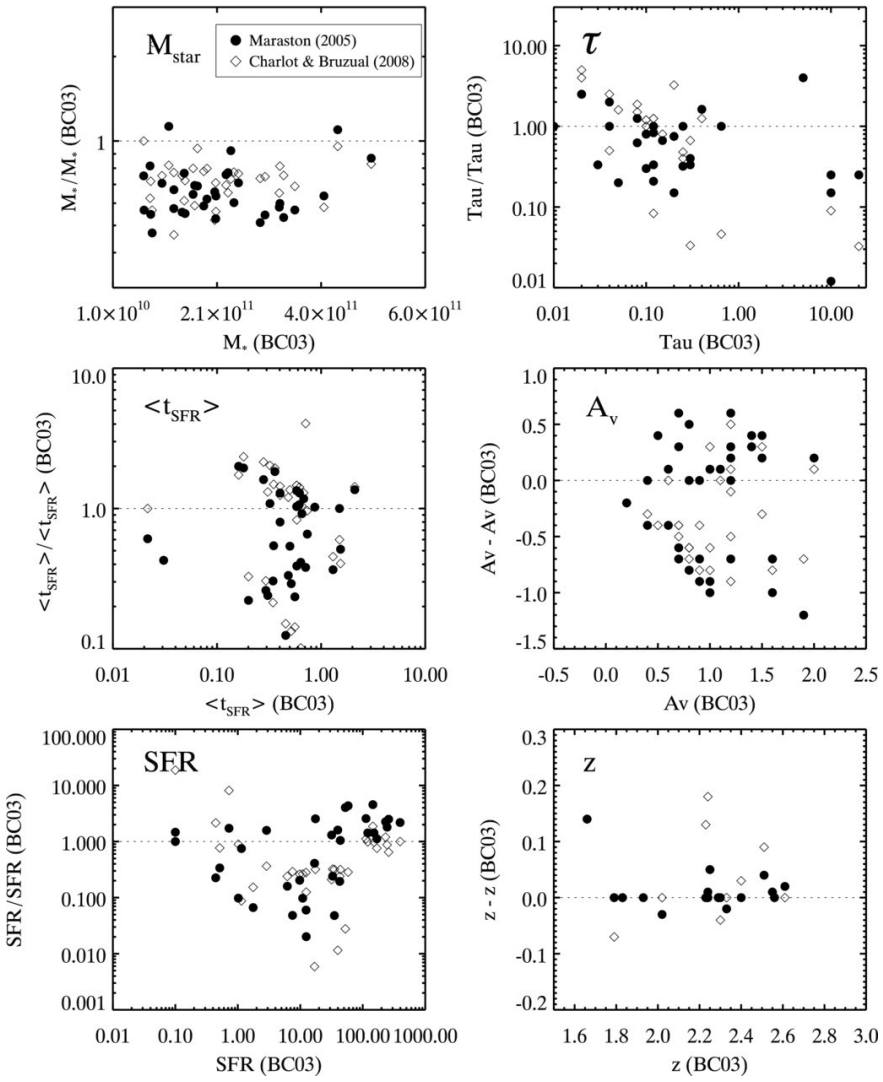
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The treatment **of TP-AGBs** modifies properties derived from SED fitting:



Eminian et al. 2008

The role of TP-AGB is still under discussion:
Kriek et al. 2010
Conroy & Gunn 2010



Muzzin et al. 2009

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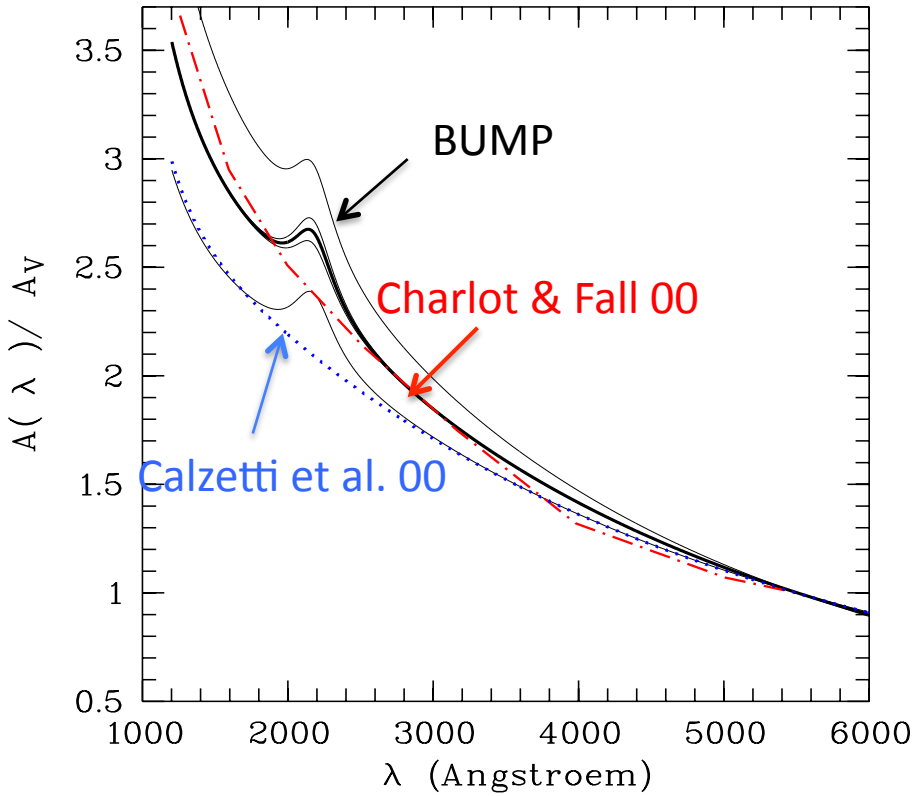
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Dust attenuation recipes

Buat et al. 2011, A&A submitted.



- Usually Calzetti et al. 2000 but suited for local starbursts
- Differential dust attenuation as a function of stellar age (e.g. Charlot & Fall 2000)
- Evidence for a bump (Burgarella et al 05, Ilbert et al. 09, Kriek et al. 11, Noll et al. 08, 09)

Outline on SED fitting methods

Main ingredients:

*__Wavelength range:__ UV-optical-NIR (sometimes + far-IR)
*__Star Formation History__: Single stellar populations, sometimes more complex ones (bursts)
*__IMF__: Salpeter, Kroupa, Chabrier
*__Stellar Population synthesis models__: Bruzual & Charlot (2003), Maraston 2005, Charlot & Bruzual (2007,2010), Pegase-differences in TP-AGBs tracks
*__Metallicity:__ mostly solar
*__Dust attenuation recipes__: Calzetti et al 2000, Charlot and Fall 2000, simple geometry, bumps to be added (Burgarella et al. 05, Ilbert et al. 2010, Buat et al 2011)
•__AGN contribution__: Herschel is providing new insights

Estimation of parameters

*X^2 minimization, confidence intervals
*Bayesian analysis (Kauffmann et al. 03, Walcher et al. 07, Cigale)

Various existing codes:

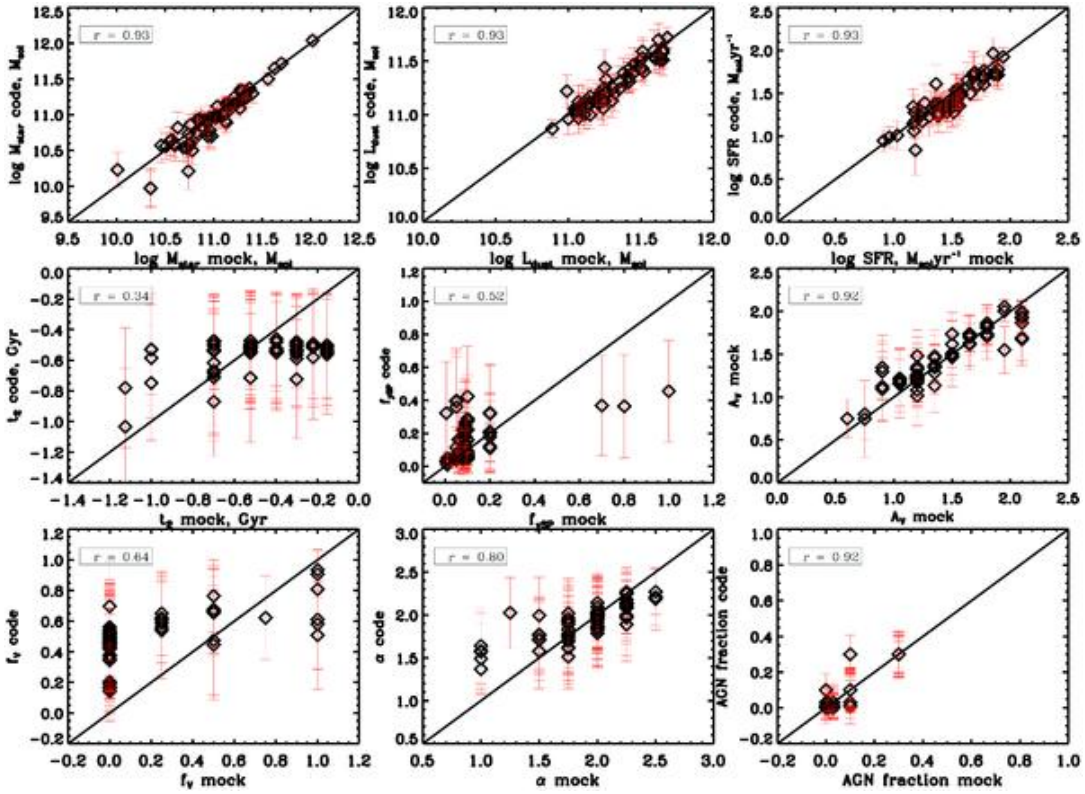
-photo-Z (Le Phare, Hyperz, Eazy): few templates but not always
-physical properties: (Cigale, Pegase, Grasil, Walcher et al., da Cunha et al.)

Tests on mock/simulated catalogues of galaxies

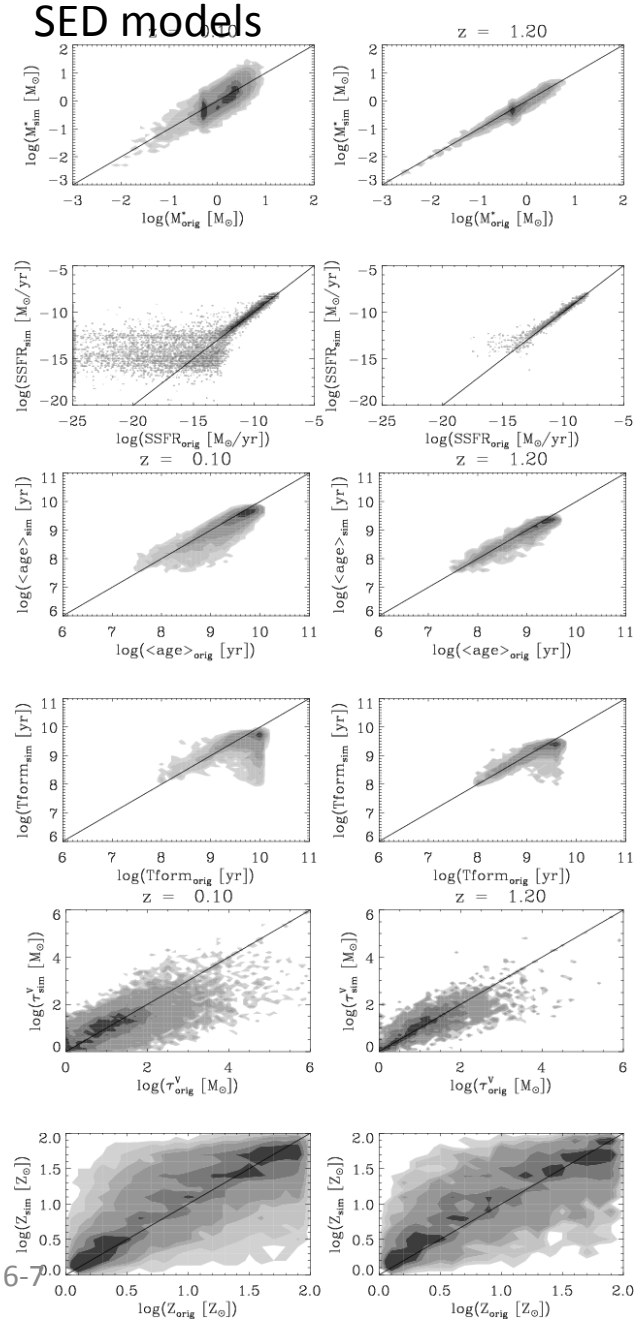
-Based on observation or SED models: Walcher et al. 07 Giovannoli et al. 11
-Based on models of galaxies: Lee et al. 10, Wuyts et al 09

Mock catalogues: pseudo-galaxies created from the SED models or the data to check the internal accuracy of the codes

Giovannoli et al. 2011, pseudo-galaxies from the data (best fit)



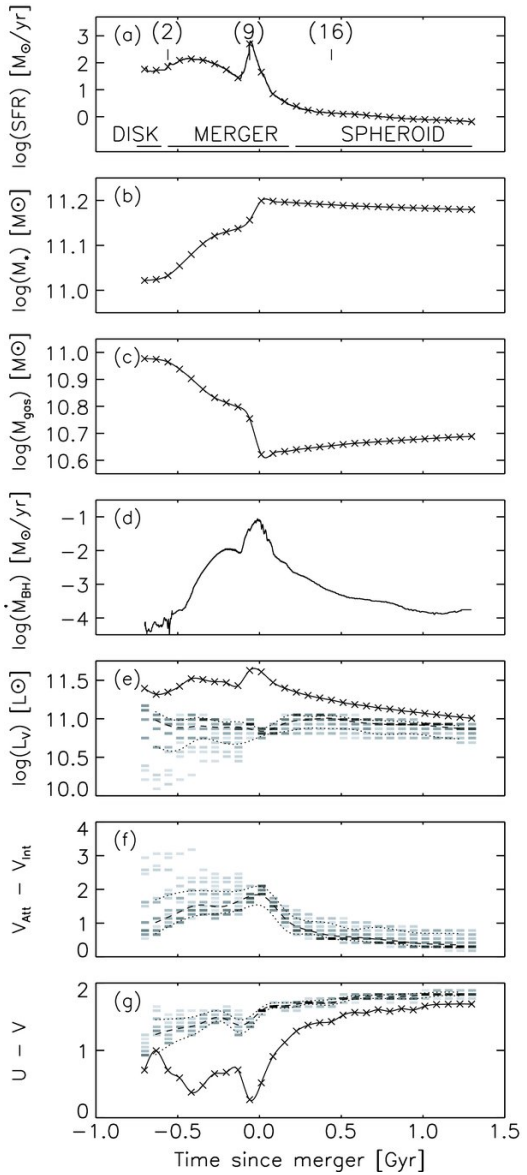
Walcher et al. 2008, from the SED models

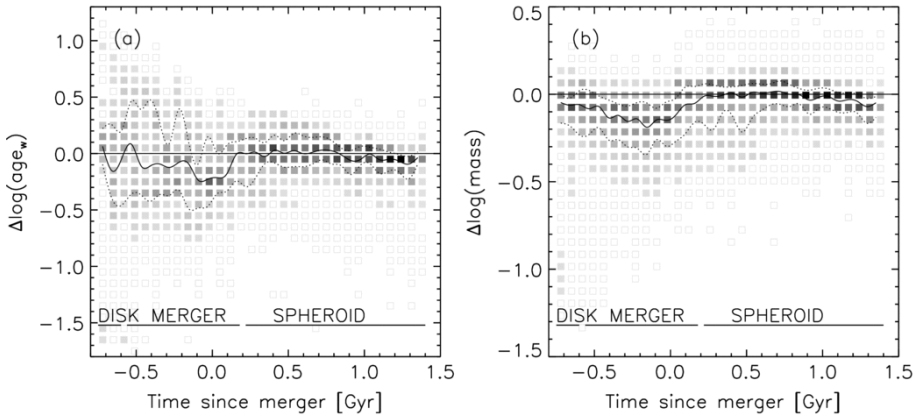


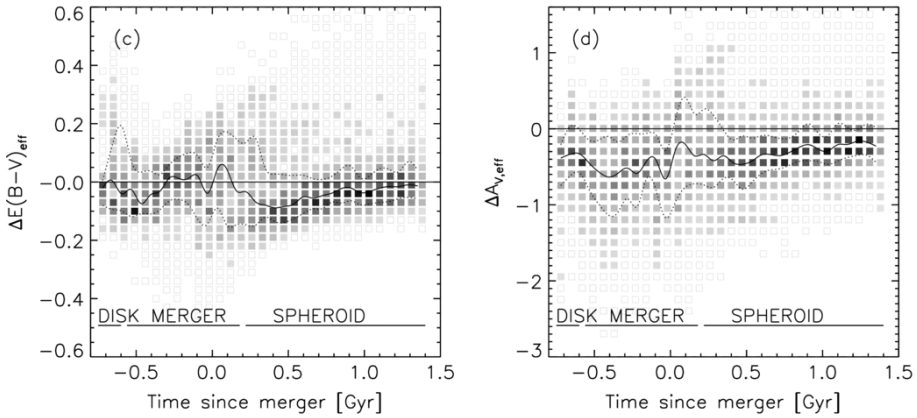
Catalogues of simulated galaxies: To test the ability of SED fitting to recover complex objects

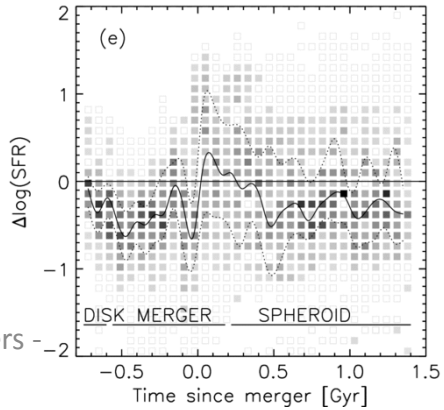
Hydrodynamical simulations

Wuyts et al. 2009

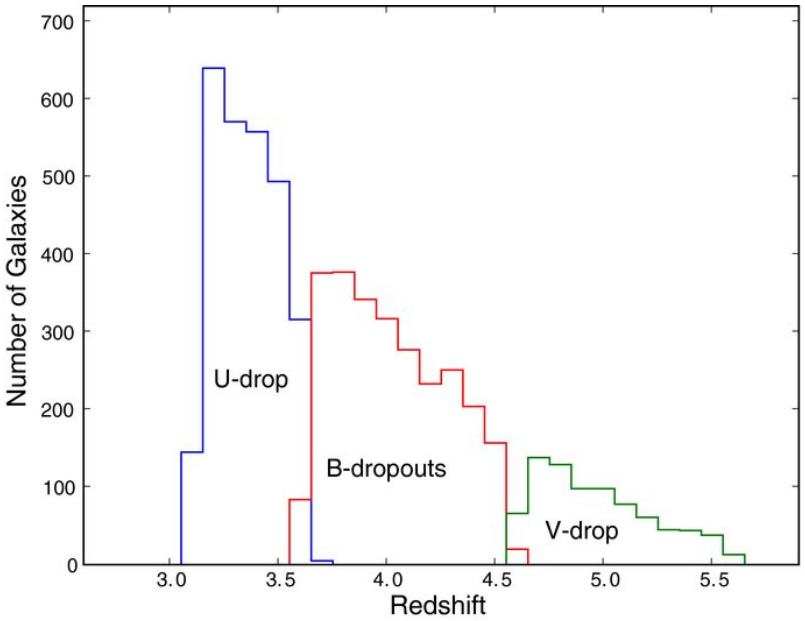




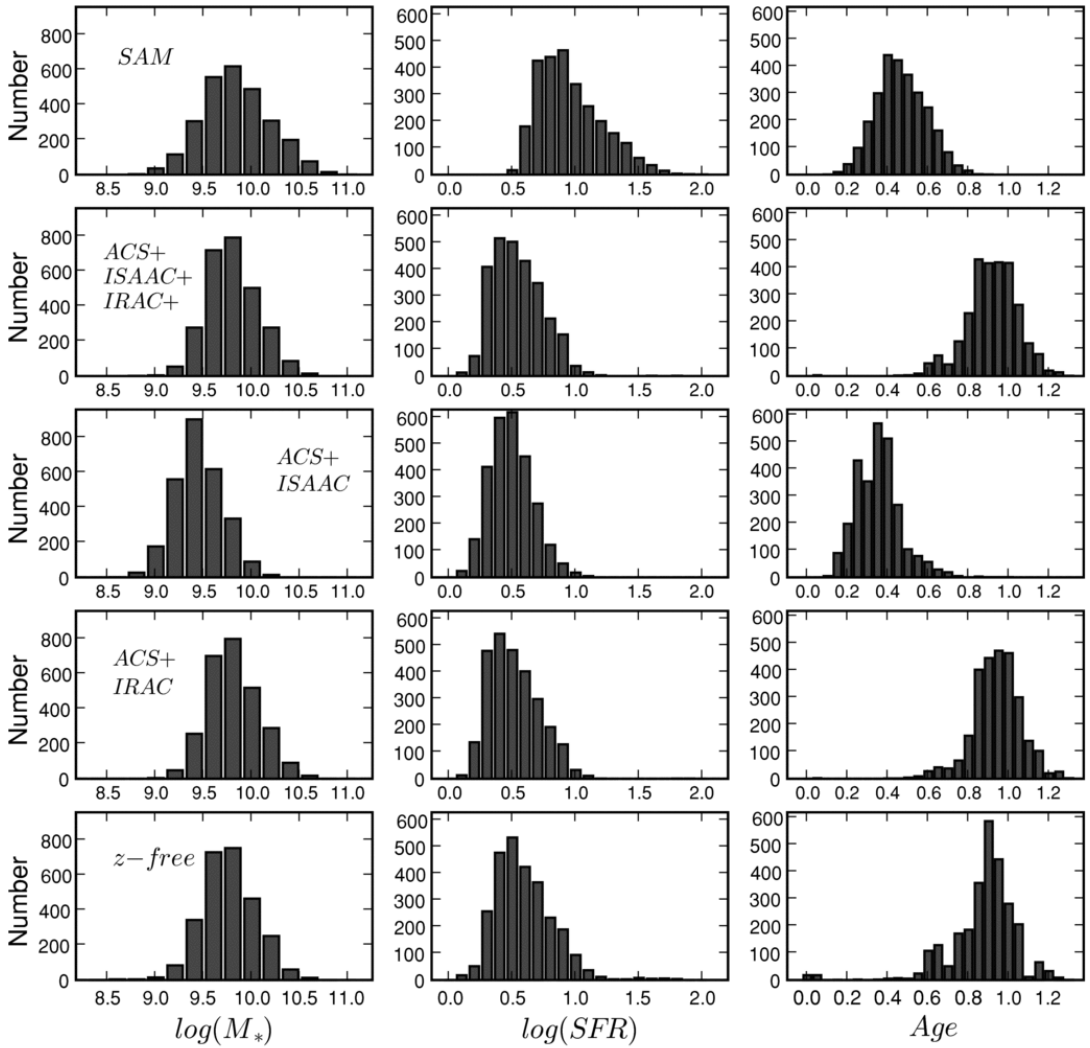




Lee et al. 2009- Semi Analytical Models and simulated Lyman-Break Galaxies



U-dropouts



To conclude….

- **Either mean empirical relations or fitting of the full SEDs can be used to estimate star formation rates and stellar masses in galaxies.**
- **Stellar masses, although generally robustly estimated, suffer from systematic variations due to the adopted stellar population models and star formation histories.**
- **SED fitting methods are based on many assumptions, some codes also accounts for the dust emission.**
- **The use of pseudo-galaxies is an efficient way to test the robustness of SED fitting methods**