# Galaxies: observations, physics and evolution

*Véronique Buat*

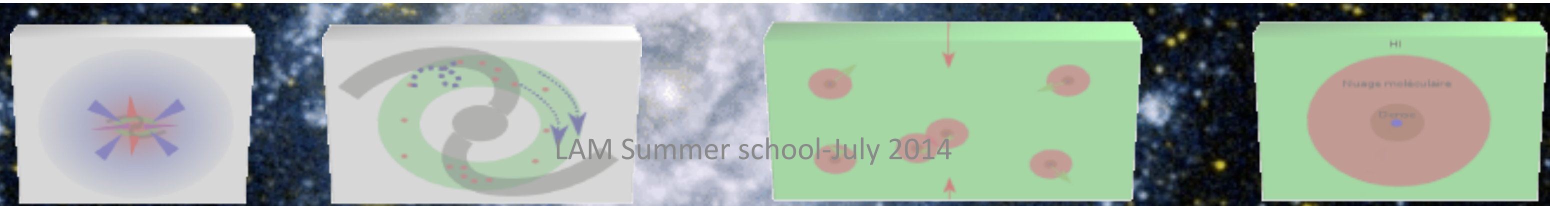
I: The whole Energy Distributions of galaxies: observations of the different components

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*



# Linking stellar and dust emission

## Physical processes and related parameters

Véronique Buat

LAM Summer school-July 2014

# Outline

- SFR determination: basic parameters
- SFRs based on the dust emission and composite tracers
- How to correct stellar light for dust attenuation?
- M* determination
- Fitting the whole Spectral Energy Distribution

# Outline

- **SFR determination: the basic equation**
  **Emission lines &UV continuum, timescales & star formation histories**
- SFRs based on the dust emission and composite tracers
- How to correct stellar light for dust attenuation
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# A basic equation to derive the SFR (assuming no dust attenuation):

$$L(\lambda,t) = \int_0^t \int_{M_{low}}^{M_{up}} F_\lambda(m,\theta)\, SFR(t-\theta)\, \Psi(m)\, dm\, d\theta$$

Intrinsic luminosity emitted by all the stars of the galaxy

t=0 the first stars in the galaxy

stellar tracks

Star Formation rate function ($M_{sun}$/yr)

Initial Mass Function (IMF) from $M_{up}$ to $M_{low}$,

**Simple recipes:**
SFR is assumed to be constant over T
SFR proportional to the **intrinsic** monochromatic Luminosity:

$$SFR = \left\{ \int_{M_{low}}^{M_{up}} \int_0^T F_\lambda(m,\theta)\, d\theta)\Psi(m)\, dm \right\}^{-1} L(\lambda,T)$$

**Only useful if the luminosity reaches a steady state L(λ,T) = L(λ)**

**Stellar Populations synthesis models** with various SFR(t)
+Fits with a large set of data at different wavelengths (SED fitting)

**SFR(t)**

**L(λ,T) calculated at any time for any λ**
**→ SED fitting technics**

**Simple recipes:**
SFR is assumed to be constant over T
SFR proportional to the **intrinsic** monochromatic Luminosity:

$$SFR = \left\{ \int_{M_{low}}^{M_{up}} \int_{0}^{T} F_{\lambda}(m,\theta)\, d\theta)\Psi(m)\, dm \right\}^{-1} L(\lambda,T)$$

**Only useful**
**if the luminosity reaches a steady state**
**L(λ,T) = L(λ)**

$$\mathrm{SFR}\ (M_{\odot}\ yr^{-1}) = 1.4 \times 10^{-28}\ L_{\nu}\ (\mathrm{ergs\ s^{-1}\ Hz^{-1}}).$$

*1500-2800 A, Salpeter IMF, >$10^8$ years of CSFR*

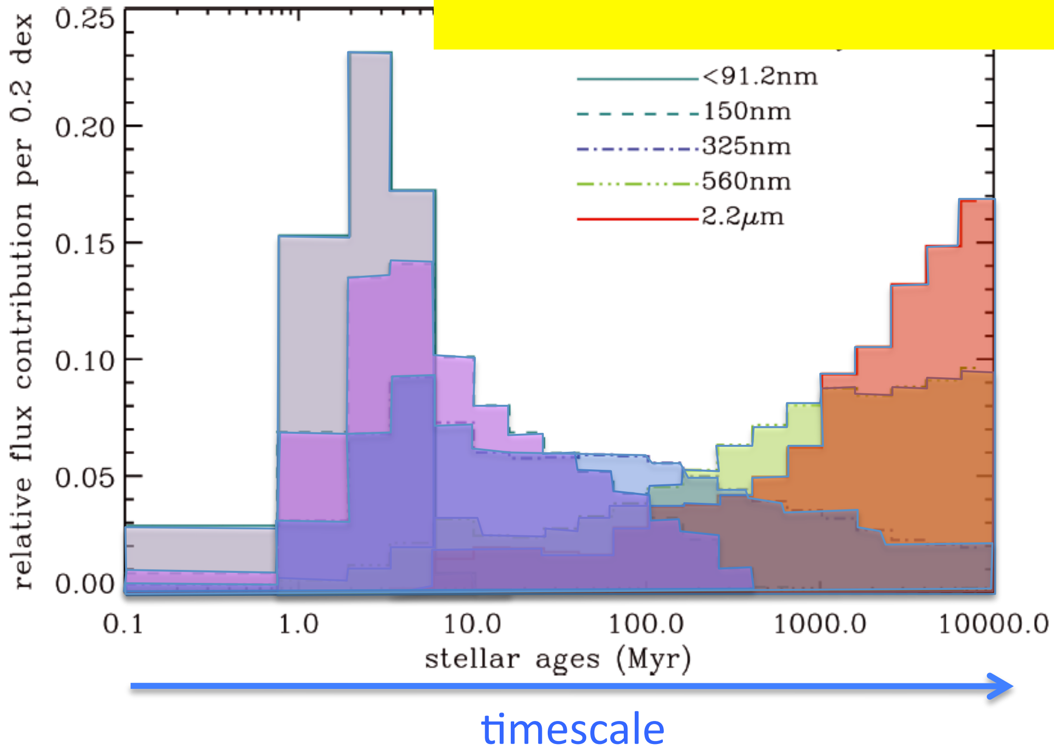
$$\mathrm{SFR}\ (M_{\odot}\ yr^{-1}) = 7.9 \times 10^{-42}\ L(H\alpha)\ (\mathrm{ergs\ s^{-1}}) = 1.08 \times 10^{-53}\ Q(H^0)\ (\mathrm{s^{-1}}).$$

*Case B recombination, $T_e$ =$10^4$ K, Salpeter IMF, « nearly » instantaneous SFR*

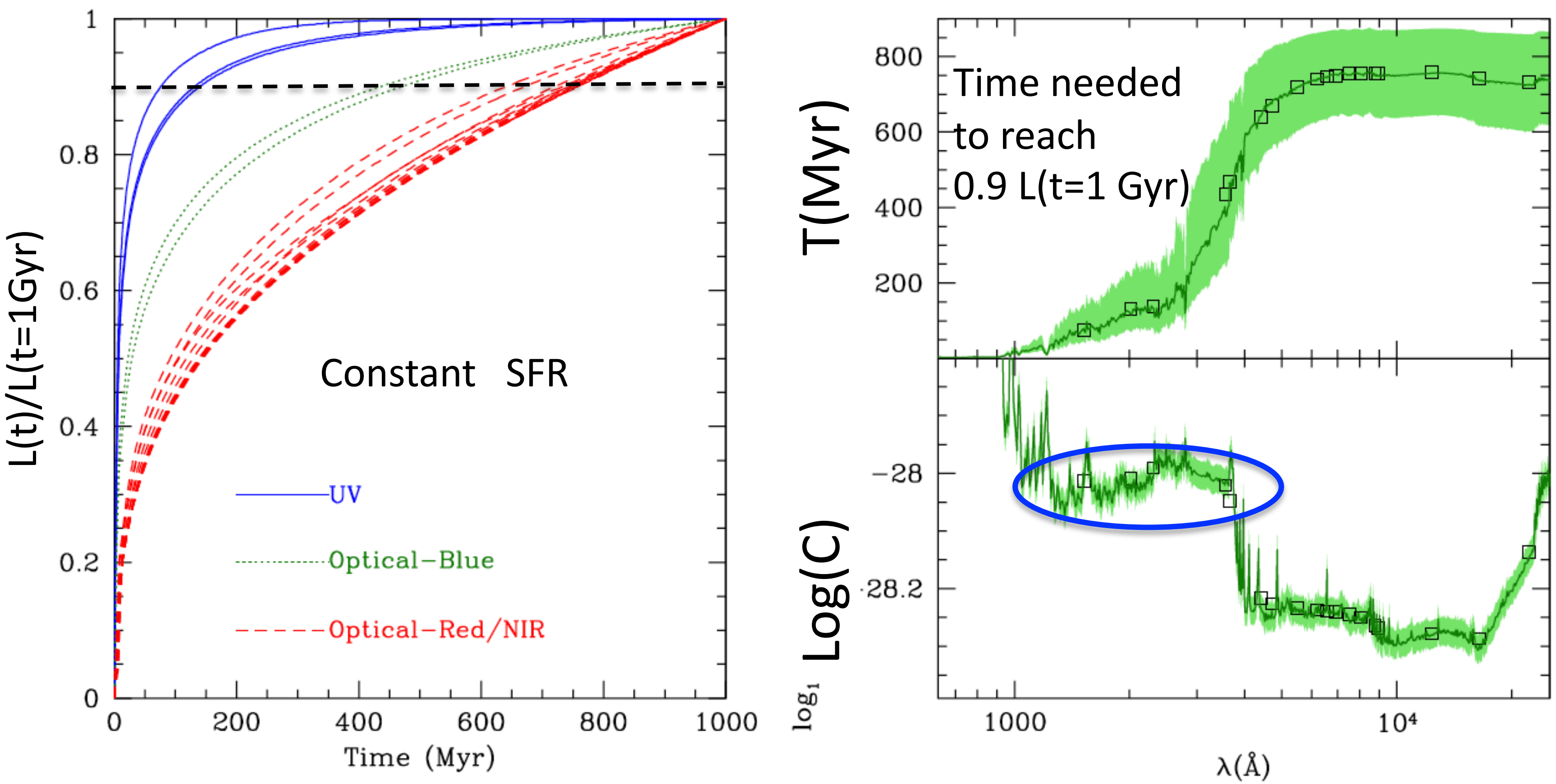
*from Kennicutt 1998, ARAA*

# Stellar populations and their emission at different wavelengths

UV → Young stars
Visible → intermediate age stars
Near-IR → Old stars



# Timescale to reach a steady state an to apply $SFR\ (M_\odot\ yr^{-1}) = C\ L_\nu\ (erg\ s^{-1}\ Hz^{-1})$




***Boissier 2013***

# Calibrations given for a constant SFR: SFR ($M_\odot$ $yr^{-1}$) = C $L_\nu$ (erg $s^{-1}$ $Hz^{-1}$)

| Observation | Time-scale | C | Comments |
|---|---|---|---|
| YSOs, stars and remnants | variable | | Traditional method in the Milky Way, difficult in distant objects |
| 1524Å(FUV-GALEX)<br>2018Å(UV-FOCA)<br>2308Å(NUV-GALEX)<br>3561Å(u)<br>3651Å(U) | 75 Myr<br>131 Myr<br>139 Myr<br>434 Myr<br>469 Myr | in Eq. 24<br>$0.97\ 10^{-28}$<br>$0.98\ 10^{-28}$<br>$1.02\ 10^{-28}$<br>$0.95\ 10^{-28}$<br>$0.89\ 10^{-28}$ | Easy at high redshift, but large/uncertain extinction<br><br>Longer time-scales |
| H$\alpha$ | 6.5 Myr | in Eq. 26<br>$5.1\ 10^{-42}$ | Strong line, short time-scale but difficulties with extinction, NII contamination, diffuse/absorbed fractions, sensitive to the upper IMF slope |
| Ly$\alpha$ | 6.5 Myr | | Ly$\alpha$/H$\alpha$=8.11 in theory but has to be multiplied by the unknown escape fraction |

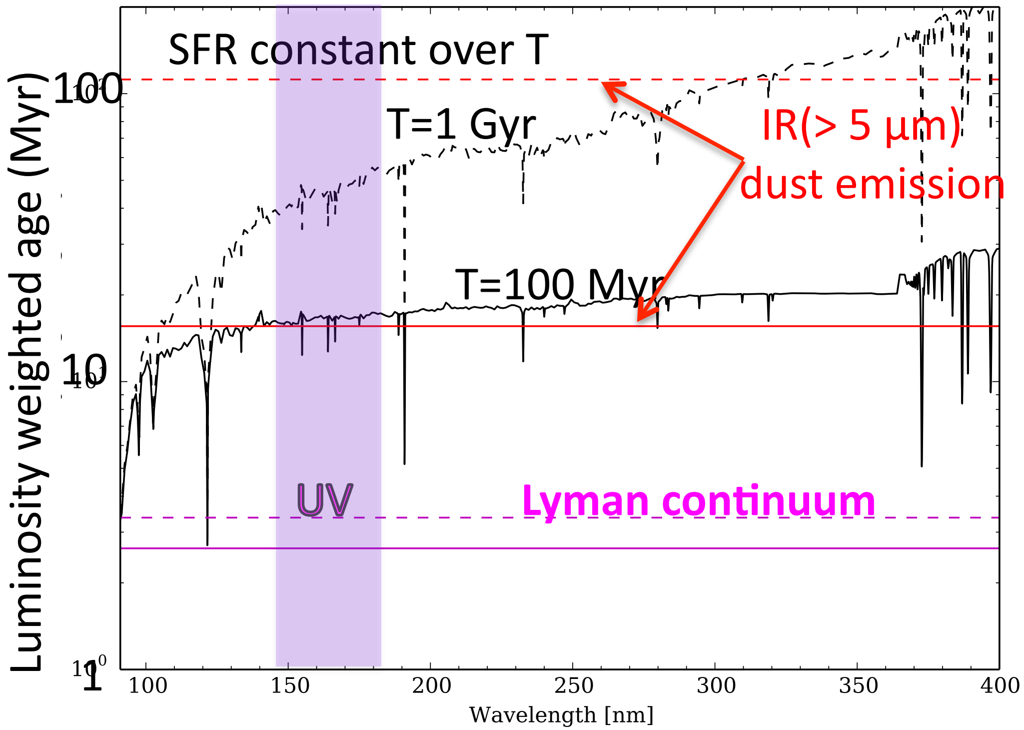
Lyman continuum (Hα, Lyα)

Table 1: *Primary SFR tracers. Timescales and coefficients are computed using Starburst99, solar metallicity, with the Kroupa (2001) "universal" IMF (0.1 to 100 $M_\odot$, slope $x = 0.3/1.3$ below/above 0.5 $M_\odot$). Values are given (adopting a constant SFR) when the luminosity reach 90% of the luminosity after 1 Gyr.*

**Boissier 12**, see also Kennicutt & Evans 12, Calzetti 12

## Which stars do produce most of the light?

**Luminosity weighted age** $$\int_0^T \frac{t \times L_\lambda(t)}{L_\lambda(t)} dt$$




→Luminosity weighted ages ages depend on the SFH

**→Impact of long lived stars on SFR estimates**

**•UV → luminosity weighted age < 100 Myr**

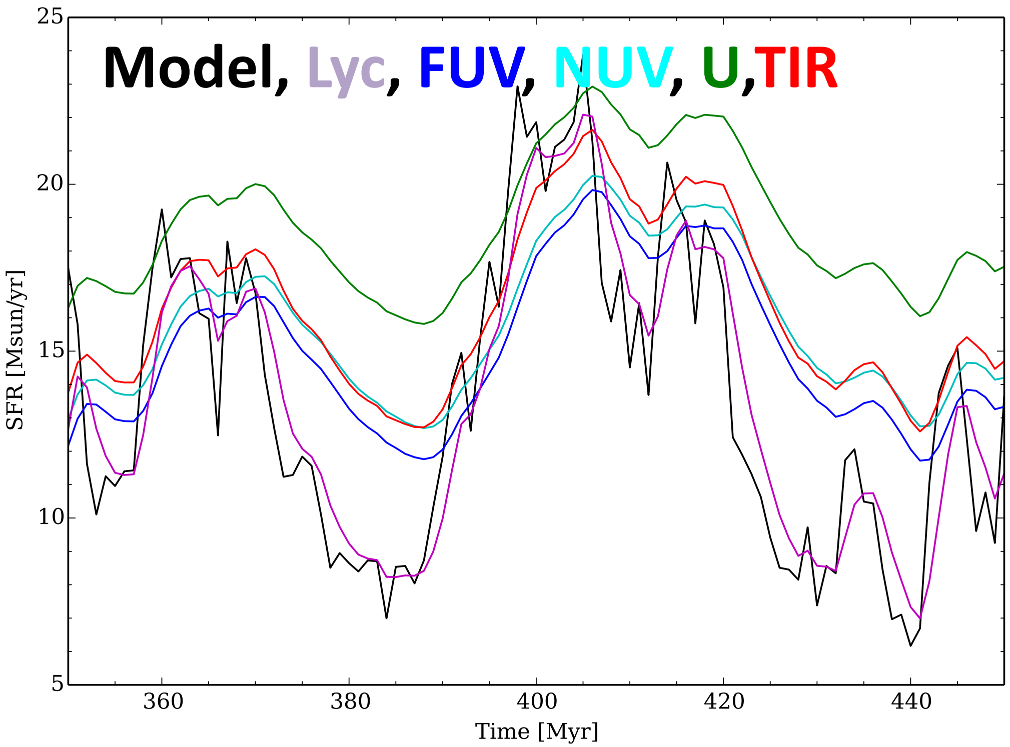
**•Lyc photons: « instantaneous measure»**

*See also Kennicutt & Evans 12*

***Boquien, Buat & Perret 2014***

# Models from MIRAGE hydrodynamical simulations

*Boquien, Buat & Perret 2014*




•SFR estimators in **Lyc**, **FUV**, **NUV**, **U**,**TIR,** assuming a **constant SFR over 100 Myr**

•**No attenuation** except in TIR :all the stellar luminosity is re-emitted by dust)

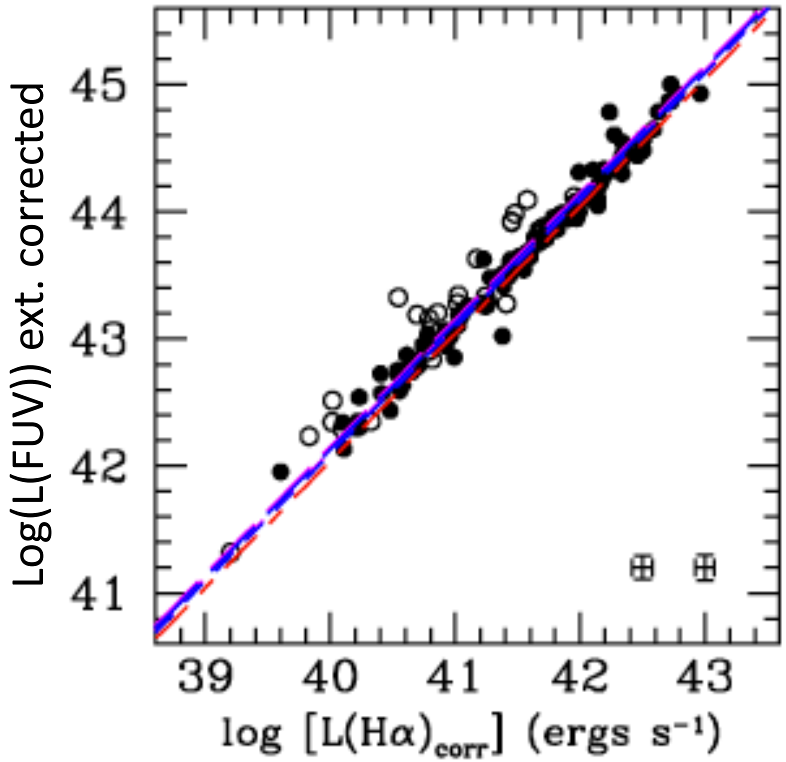
Except for Lyc**, overestimation of the SFR: 25% in FUV , 65% in U**

**Explained by the contribution of stars older than 100 Myr**

→ **SFR estimators on timescales larger than 100 Myr** are better for non starbursting galaxies

# Is a constant SFR a reliable assumption in galaxies? Probably **YES** for the nearby universe

• SINGS
○ MK06



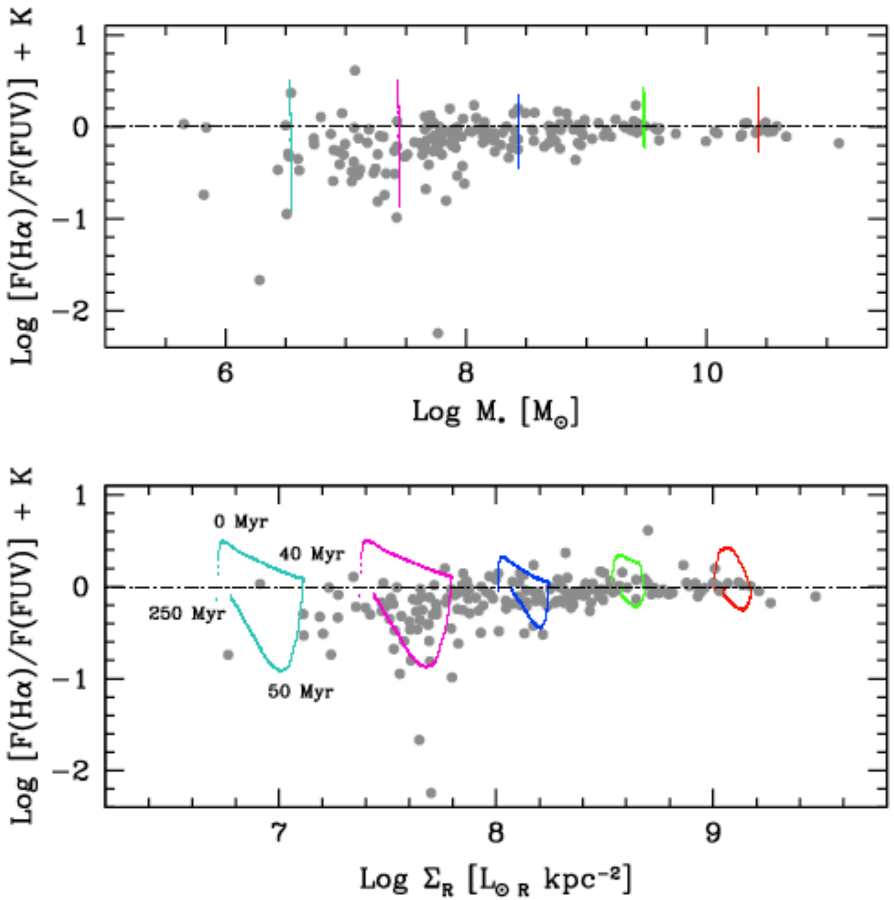

*Hao+11*

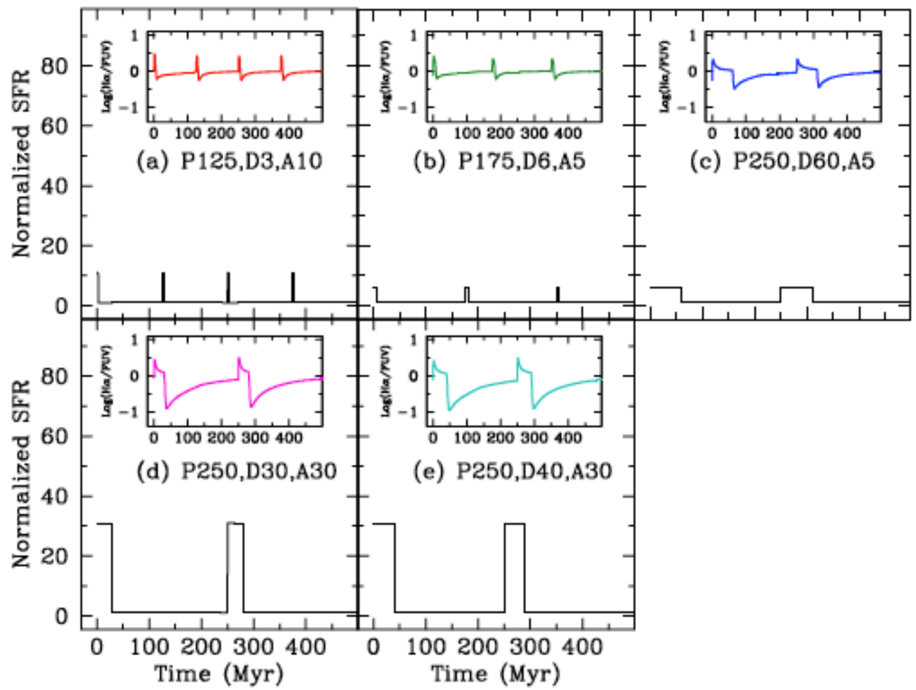
Extinction corrected Hα and FUV luminosities fully consistent with a constant SFR over 100 Myr

**But dwarf galaxies**: best cases to measure SFH variations,

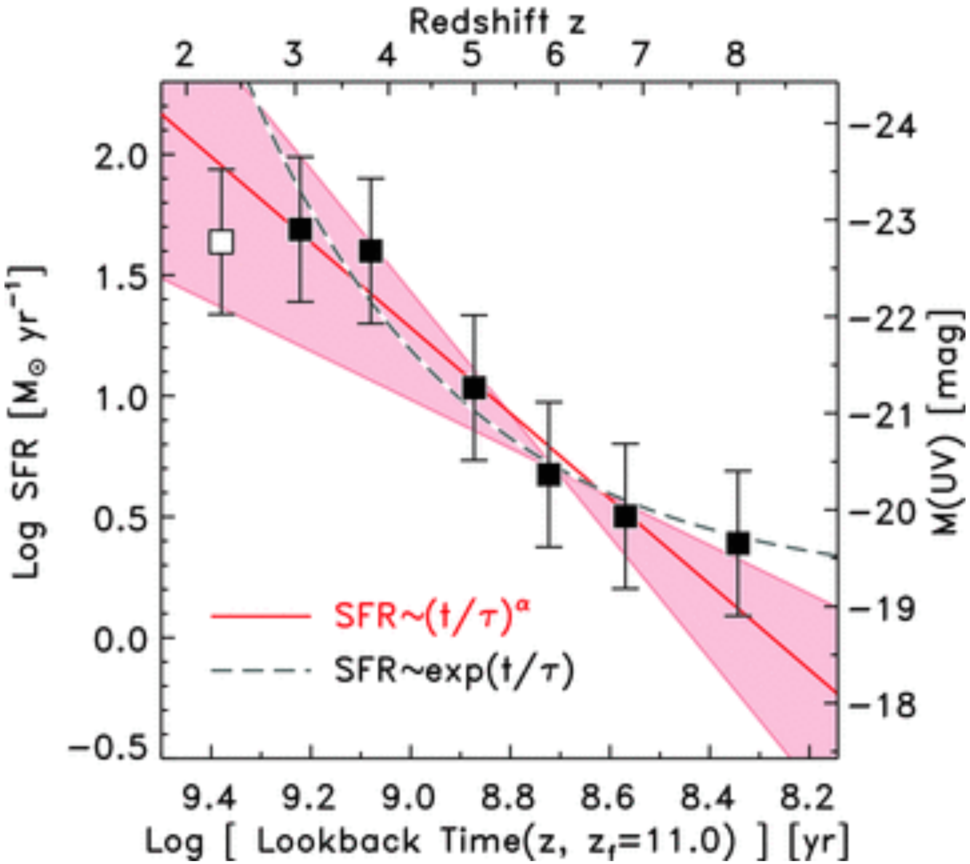
*Weisz+12, Lee+09*

Variations of the SFH seen in Hα/UV ratio:



# Recent insight on the SF at high z
# Z> 2: evidence for an increasing star formation




*Papovich+11*

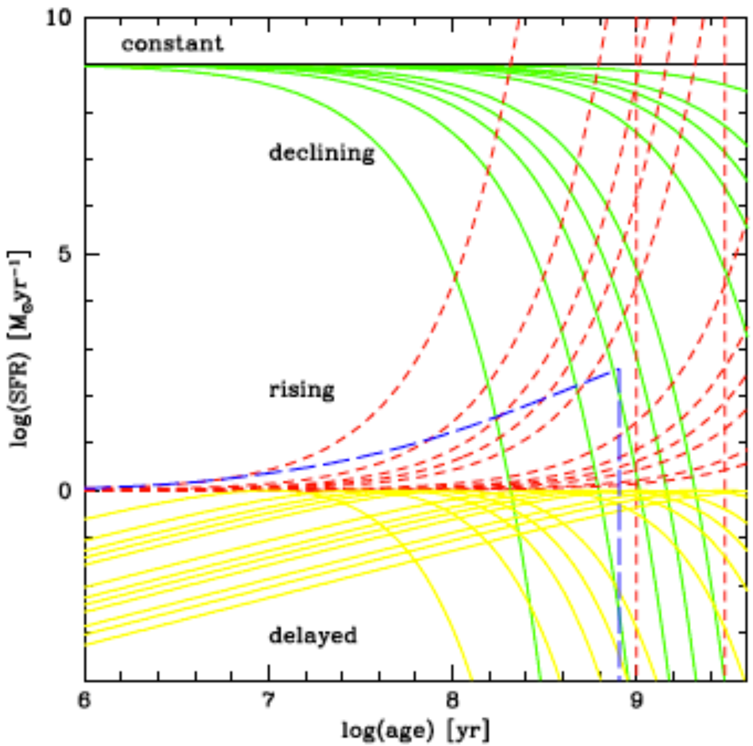
Power law alpha=1.7
Increasing exp tau~0.5 Gyr
(Papovich+11)

More physical models:
Increasing SFR allows a SF starting at very high z
(Maraston+10, Lee+11, Renzini09)

# Star formation history: simple modeling versus 'realistic' simulations

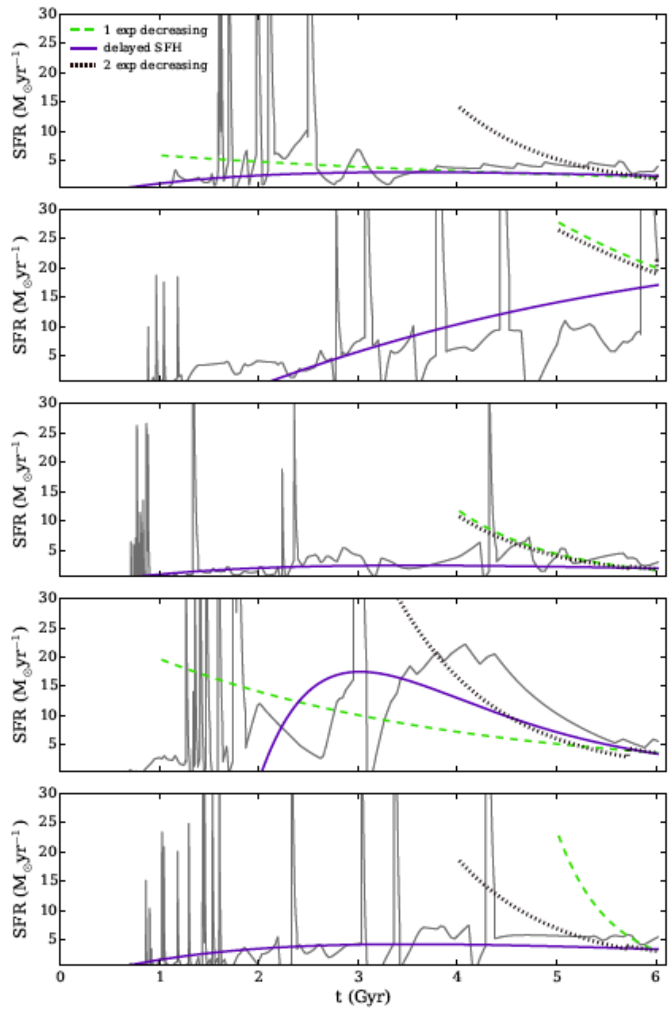
**Simple models are usually assumed**

*Schaerer+14*




**SFH from numerical models, compared to simple models**

*Ciesla+15*



# Dependence of the calibrations on the metallicity and IMF

**Table 1.** Calibration constants for the $H_\alpha$ and [OII] luminosity SFR relations. (Values in brackets are for $f = 1$).

| $M_{up}$ | 100 $M_\odot$ | | 120 $M_\odot$ | |
|---|---|---|---|---|
| $Z$ | $C_{H_\alpha}$ | $C_{[OII]}$ | $C_{H_\alpha}$ | $C_{[OII]}$ |
| | $\left[\times 10^{41} \frac{\text{erg s}^{-1}}{M_\odot \text{ yr}^{-1}}\right]$ | | $\left[\times 10^{41} \frac{\text{erg s}^{-1}}{M_\odot \text{ yr}^{-1}}\right]$ | |
| 0.0004 | 2.7 | 0.5 | 3.0 | 0.5 |
| 0.004 | 2.3 | 1.4 | 2.6 | 1.6 |
| 0.008 | 1.4 (2.1) | 1.5 (2.2) | 1.7 (2.3) | 1.8 (2.6) |
| 0.02 | 1.3 (1.8) | 1.3 (1.9) | 1.6 (2.2) | 1.6 (2.3) |
| 0.05 | 1.2 (1.7) | 1.2 (1.8) | 1.4 (1.9) | 1.4 (2.0) |

**Hα** **[OII]**

IMF

metallicity

**Table 2.** Calibration constants for the UV luminosities SFR relations.

| $M_{up}$ | 100 $M_\odot$ | | 120 $M_\odot$ | |
|---|---|---|---|---|
| $Z$ | $C_{1500}$ | $C_{2800}$ | $C_{1500}$ | $C_{2800}$ |
| | $\left[\times 10^{27} \frac{\text{erg s}^{-1}\text{ Hz}^{-1}}{M_\odot \text{ yr}^{-1}}\right]$ | | $\left[\times 10^{27} \frac{\text{erg s}^{-1}\text{ Hz}^{-1}}{M_\odot \text{ yr}^{-1}}\right]$ | |
| 0.0004 | 14.6 | 13.7 | 14.8 | 13.9 |
| 0.004 | 12.8 | 11.8 | 13.1 | 12.0 |
| 0.008 | 11.9 | 10.8 | 12.2 | 11.0 |
| 0.02 | 10.6 | 10.0 | 11.0 | 10.3 |
| 0.05 | 9.3 | 8.9 | 9.8 | 9.2 |

**Far-UV** **Near-UV**

Bicker& Fritze, 2005

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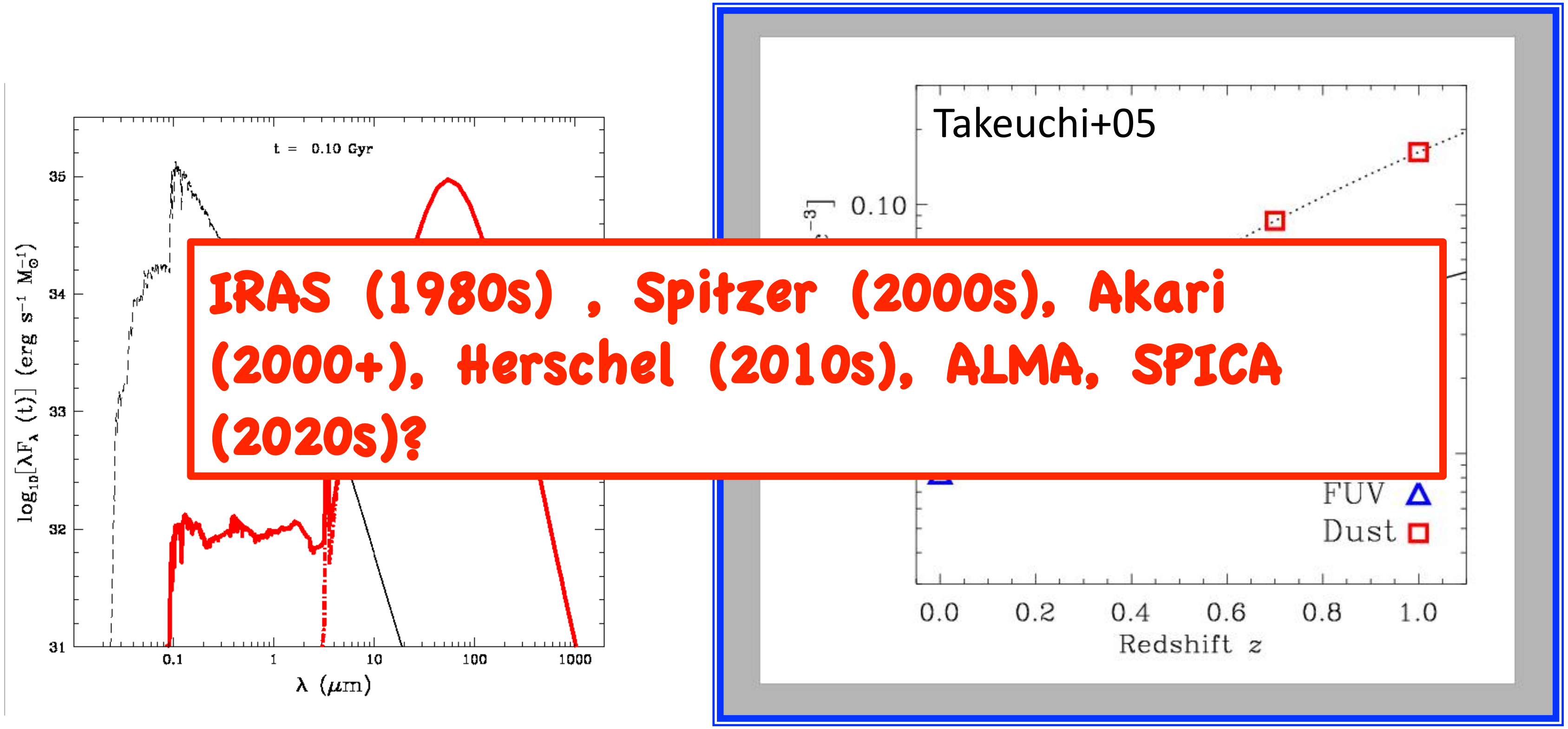
- SFR determination: the basic equation
- **SFRs based on the dust emission and composite tracers**

  **Monochromatic fluxes, Global dust emission, Combination of optical and IR measurements**
- How to correct stellar light for dust attenuation?
- M* determination
- Fitting the whole Spectral Energy Distribution



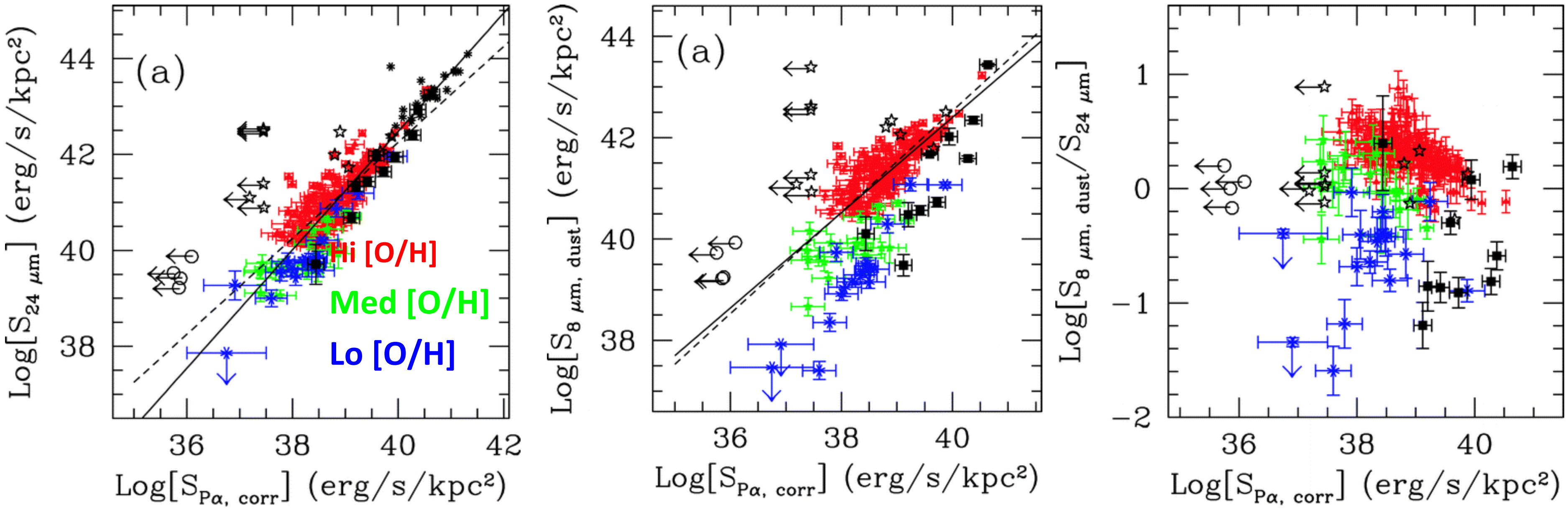

IRAS (1980s) , Spitzer (2000s), Akari (2000+), Herschel (2010s), ALMA, SPICA (2020s)?

At least half of the SFR is locked in IR at z=0 and the fraction increases with z (up to z=~2)

# Luminosities at 24 and 8 µm as SFR estimators

→Using monochromatic fluxes avoids the extrapolation to the whole IR range

→Direct comparison with the Paα recombination line




$L_{24\mu m}$ 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*

# $L_{IR}$ (5-1000 µm) : a reliable measure of the SFR?

**Complete dust obscuration, dust heating fully due to young stars**

Timescale for the calculations: constant SFR over 10 -100 Myr

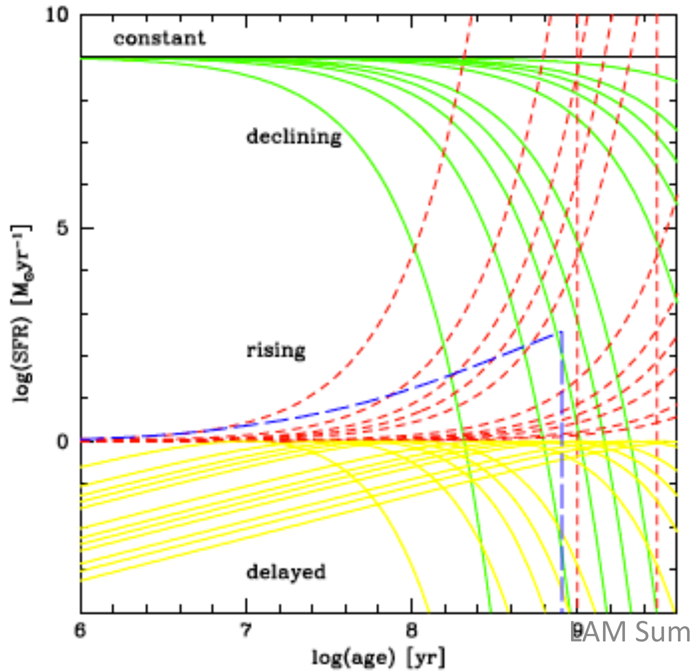
**$L_{IR} = L_{bol}$ (e.g. Kennicutt 98)**

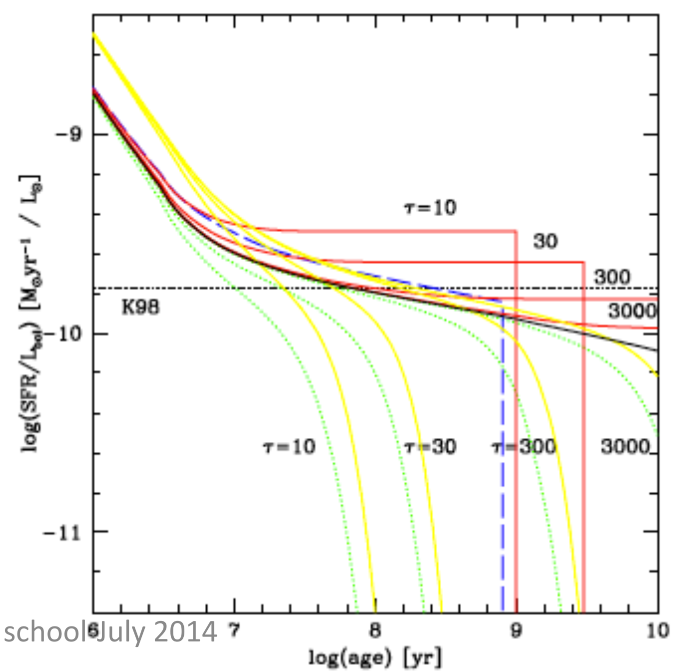
→ *Starlight not absorbed by dust: under-estimate of SFR*

→ *dust heating by evolved stars: over-estimate of SFR*

→ **Calibration can vary for different SFHs, as discussed before for the UV emission**

→ **IR templates not well known (as seen before)**



# $L_{IR}$ (5-1000 µm) : a reliable measure of the SFR?

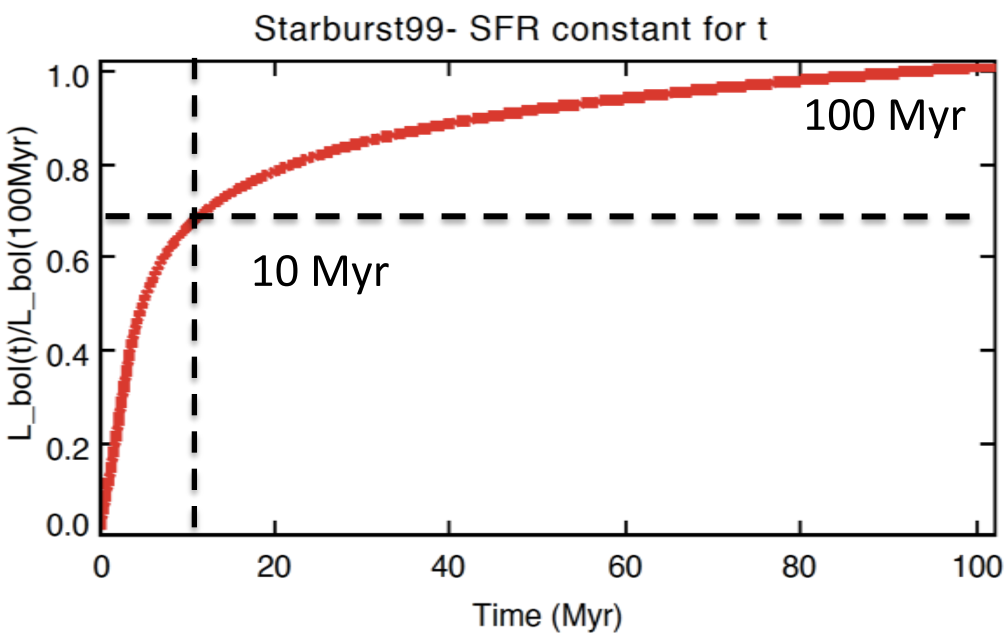
**A very strong hypothesis:**

**complete dust obscuration, dust heating fully due to young stars**

Timescale for the calculations: constant SFR over 10 -100 Myr

**$L_{IR} = L_{bol}$ (Kennicutt98)**

→calibration varying by ~30% from 10 to 100 Myr (SB99)



# Composite tracers: stellar and dust emissions

(*Hirashita+06, Iglesias-Paramo+07,Kennicutt+09, Calzetti+07,09,Hao+11, Kennicutt & Evans, 12, Leroy+09,12, Zhu+08, Elbaz+07, Daddi+07, Wuyts+11 etc…*)

Combining $L_{IR}$ and $L_{FUV}$ would give the total light from young stars.
In a very simplified way we can write:

$$\mathbf{L_{FUV}(corr) = L_{FUV}(obs) + \eta\, L_{IR}}$$

UV light absorbed by dust, a fraction of the total IR luminosity

→ $$A_{FUV} = 2.5 * \log(1+\eta\, 10^{IRX})$$

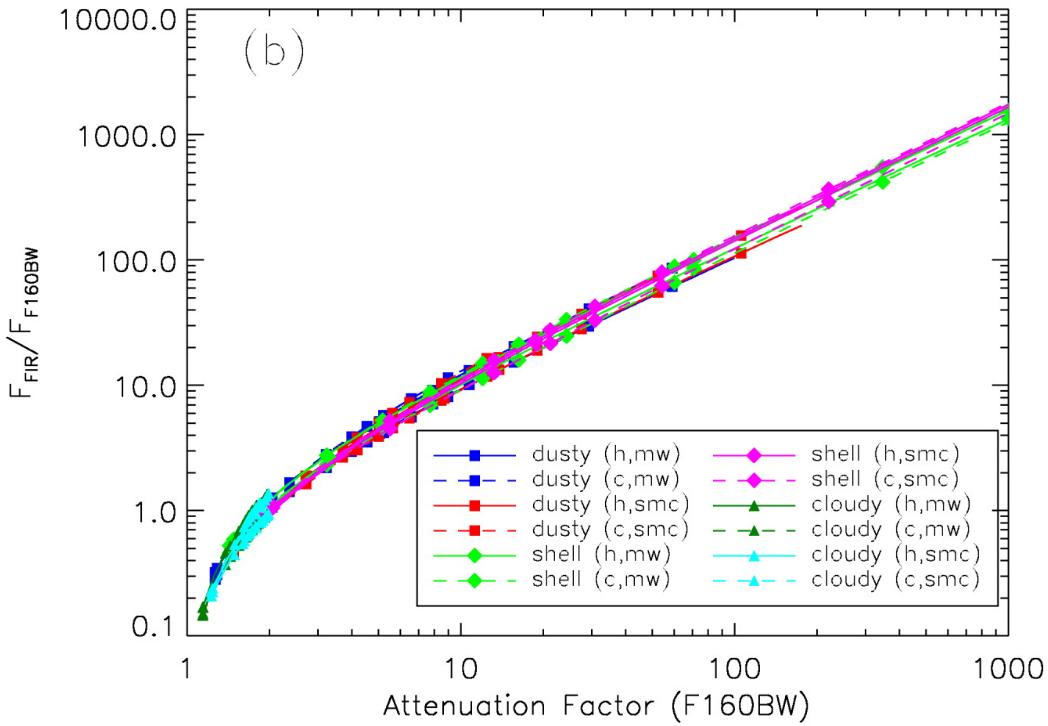
$$\mathbf{A_{FUV} = f(IRX)\ ,\ IRX = L_{IR}/L_{FUV}}$$

with $L_{IR}$ *: 5-1000 μm,* $L_{FUV}$ *= ν.Fν at 150 nm*
*(e.g. Meurer et al. 99, Hao et al. 11, Kennicutt & Evans 12)*

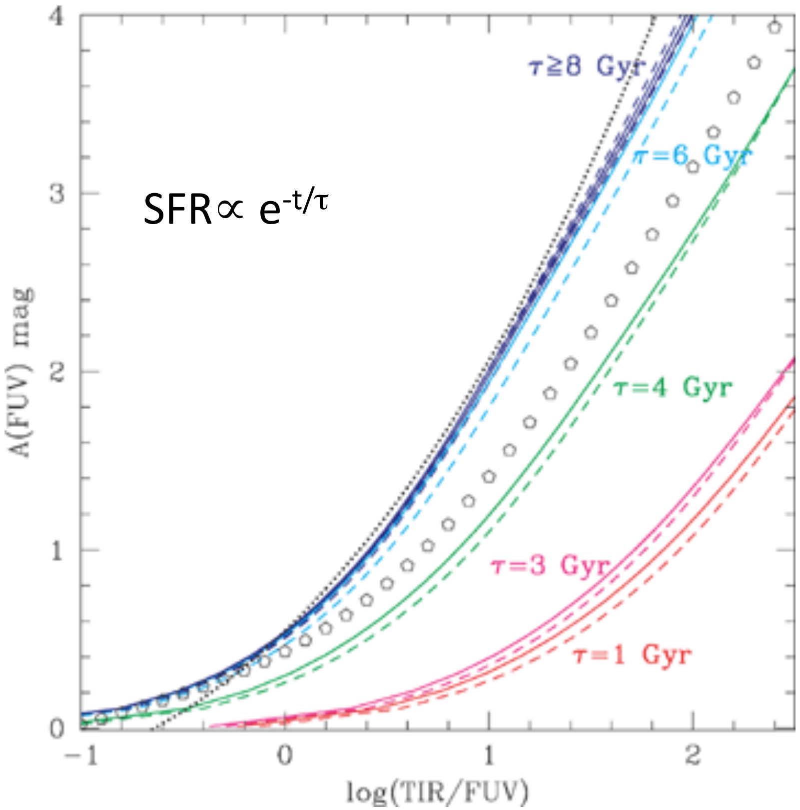
Some authors used a polynomial dependence on IRX (Buat+05,11, Cortese+08, Boquien+12)

→ $$\mathbf{SFR\ (M_\odot\ yr^{-1}) = C\ L_{FUV}(corr)}$$

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



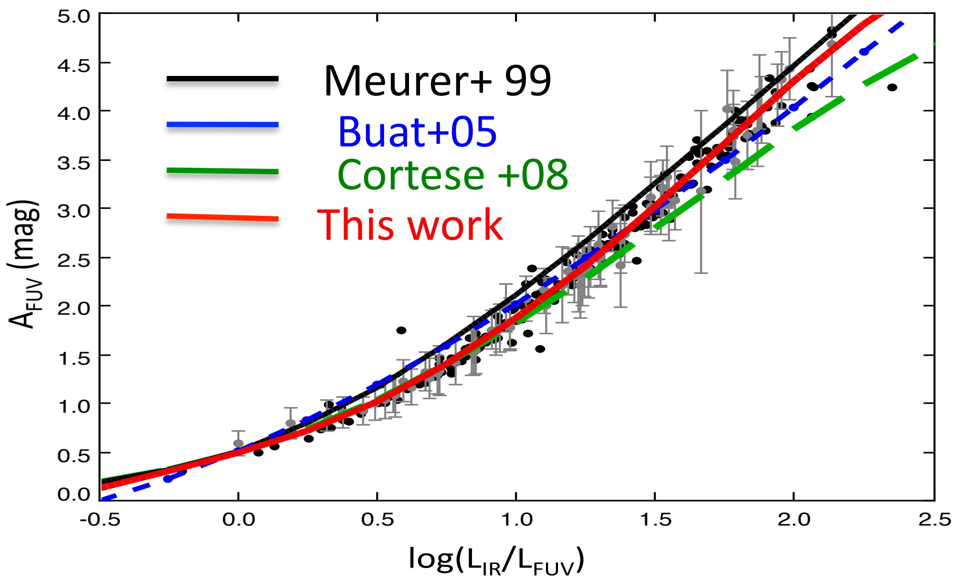

Star forming galaxies and various geometries/dust properties
*Gordon et al. 2000*




*Cortese et al. 08*

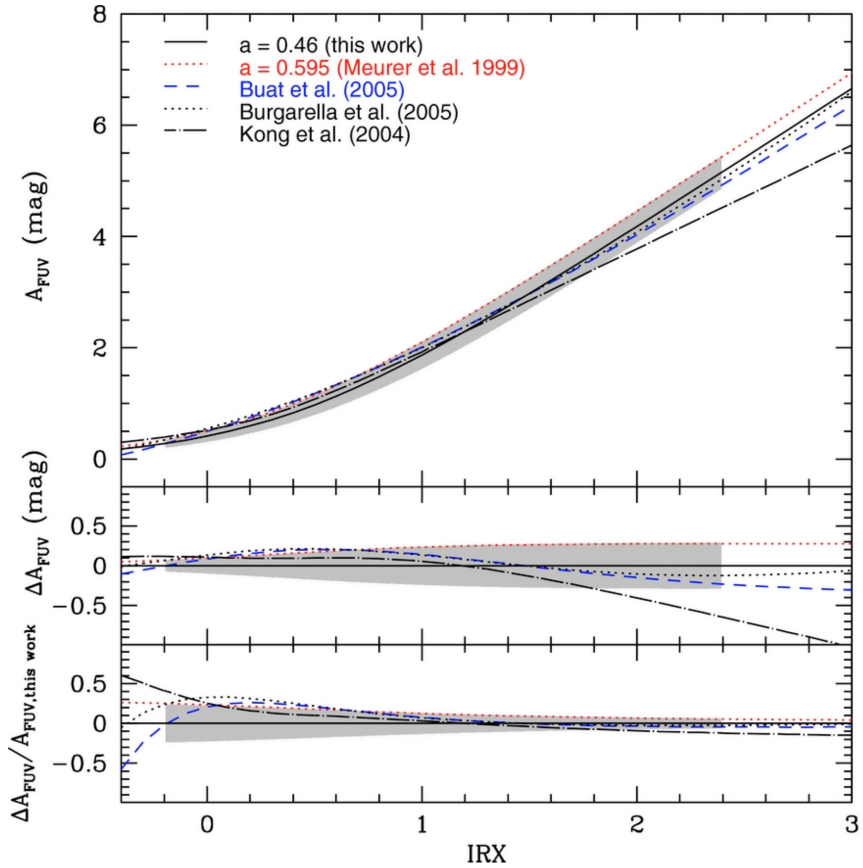
The calibration depends on the star formation history

# Data: $A_{FUV} = f(IRX=L_{IR}/L_{FUV})$



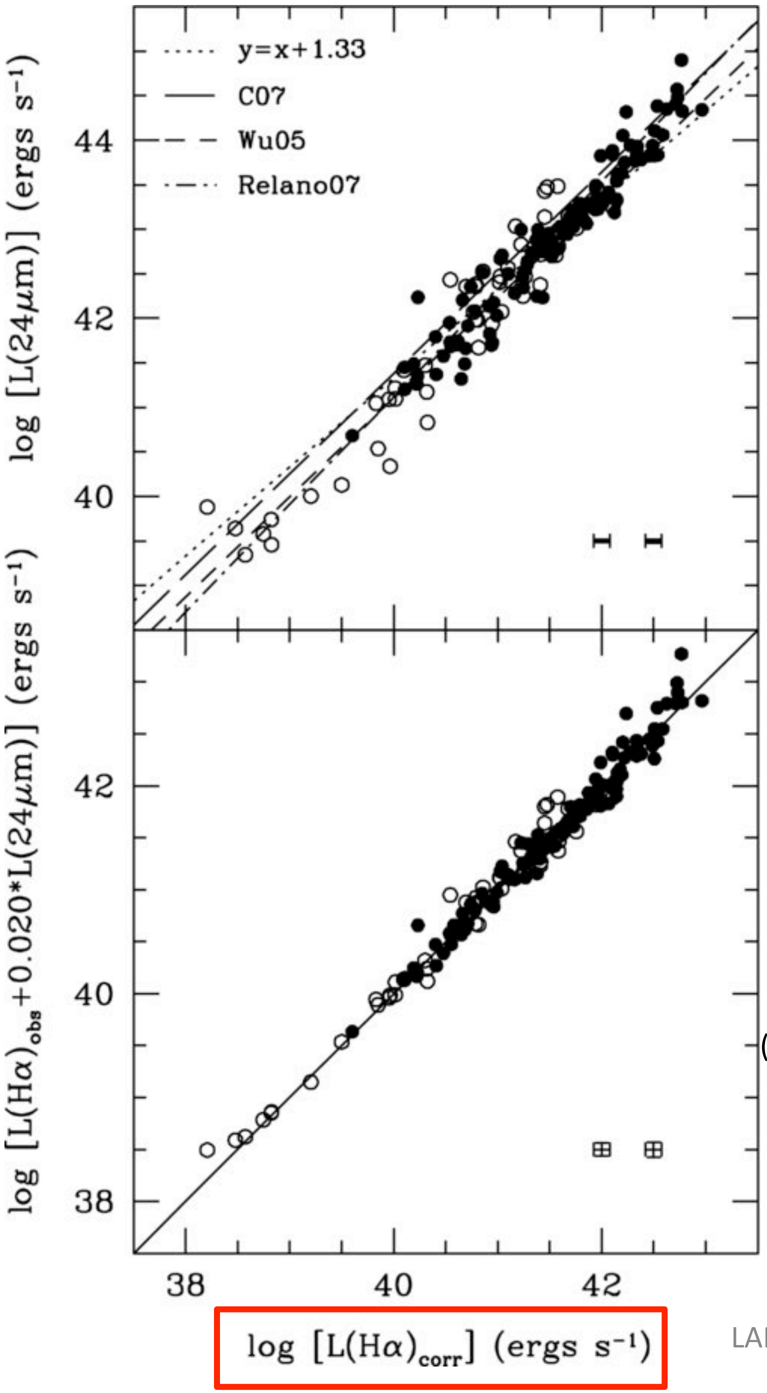

Buat+11: AKARI selection, z=0, variations between different estimates ~0.3 mag

$A_{FUV}$=0.483+0.812*IRX +0.373*$IRX^2$+0.299*$IRX^3$-0.106*$IRX^4$




Hao+11: SINGS and MK06 data

$A_{FUV}$ = 2.5 * log(1+0.46 $10^{IRX}$)




Various combinations of luminosity from young stars (Hα, FUV, NUV)

and

from dust (L(TIR), L(24μm), L(8μm)

TABLE 1
MULTI-WAVELENGTH DUST-CORRECTIONS

| Composite Tracer | Reference |
|---|---|
| $L(FUV)_{corr} = L(FUV)_{obs} + 0.46\ L(TIR)$ | 1 |
| $L(FUV)_{corr} = L(FUV)_{obs} + 3.89\ L(25\ \mu m)$ | 1 |
| $L(FUV)_{corr} = L(FUV)_{obs} + 7.2\ E14\ L(1.4\ GHz)^{a}$ | 1 |
| $L(NUV)_{corr} = L(NUV)_{obs} + 0.27\ L(TIR)$ | 1 |
| $L(NUV)_{corr} = L(NUV)_{obs} + 2.26\ L(25\ \mu m)$ | 1 |
| $L(NUV)_{corr} = L(NUV)_{obs} + 4.2\ E14\ L(1.4\ GHz)^{a}$ | 1 |
| $L(H\alpha)_{corr} = L(H\alpha)_{obs} + 0.0024\ L(TIR)$ | 2 |
| $L(H\alpha)_{corr} = L(H\alpha)_{obs} + 0.020\ L(25\ \mu m)$ | 2 |
| $L(H\alpha)_{corr} = L(H\alpha)_{obs} + 0.011\ L(8\ \mu m)$ | 2 |
| $L(H\alpha)_{corr} = L(H\alpha)_{obs} + 0.39\ E13\ L(1.4\ GHz^{a}$ | 2 |

(1)Hao et al. 2011; (2) Kennicutt et al. (2009)

***Composite tracer****s: Kennicutt & Evans, 2012, see also Calzetti+07, Zhu+08, Hirashita+03, Bell03, Leroy+08,12*

***Monochromatic IR tracers****: Calzetti+05,07,09; Wu+05, Zhu+08, Rieke+09*

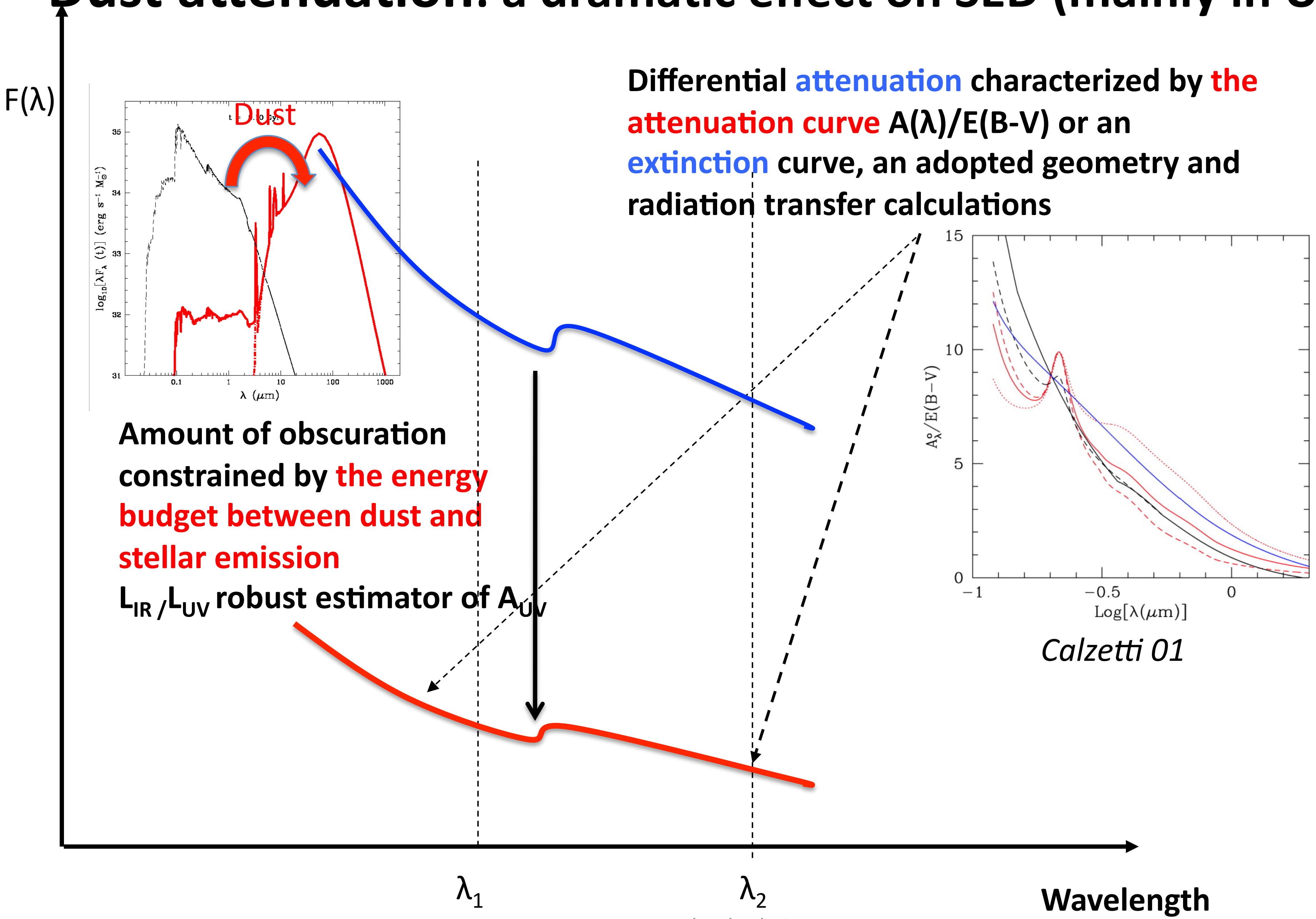
# Outline

- SFR determination: the basic equation
- SFRs based on the dust emission and composite tracers

  Monochromatic fluxes, Global dust emission, Combination of optical and IR measurements
- **How to correct stellar light for dust attenuation?**

  **useful recipes**
- M*  determination
- Fitting the whole Spectral Energy Distribution

# Dust attenuation: a dramatic effect on SED (mainly in UV)

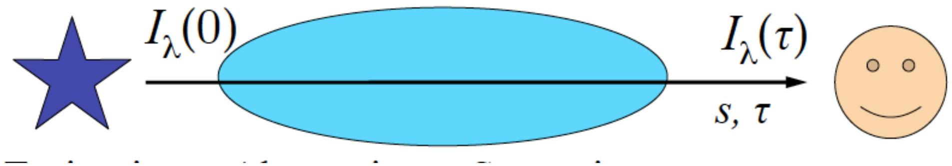



*Calzetti 01*

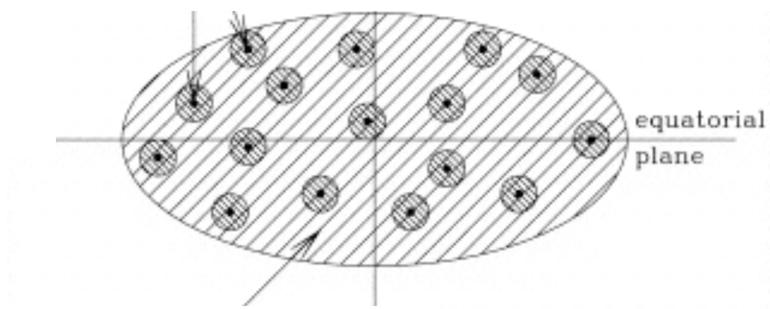
# Attenuation & extinction laws in galaxies

They are different because of absorption & scattering of photons

**Extinction Only (UV, Opt, NIR)**

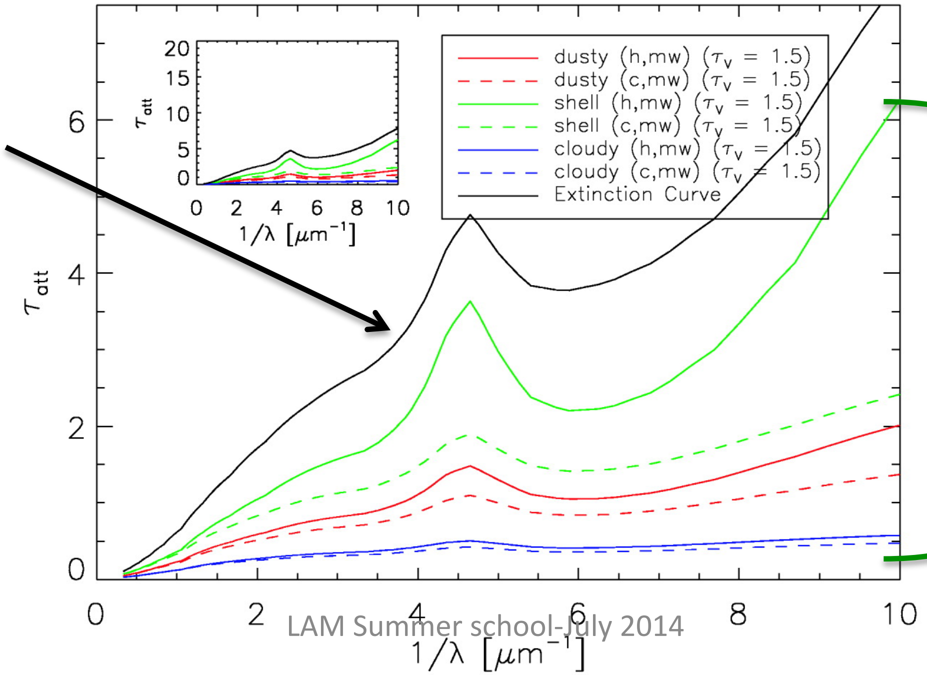



**Attenuation in a galaxy, stars and dust are mixed**



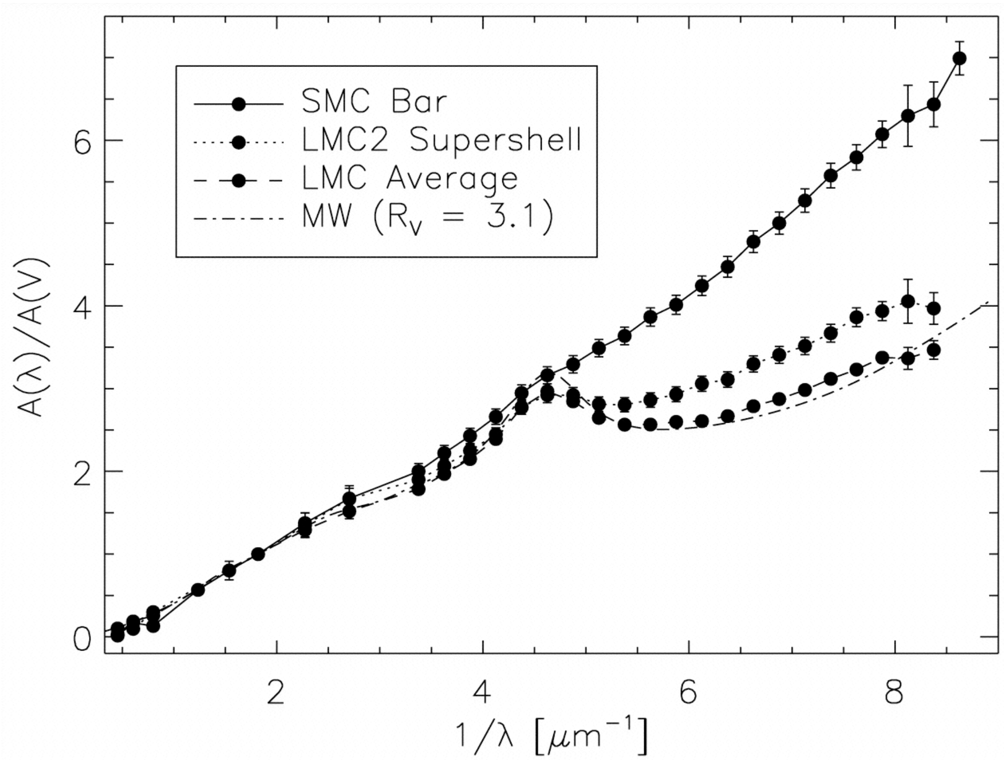

MW Extinction curve along one ligne of sight, depends on dust properties only

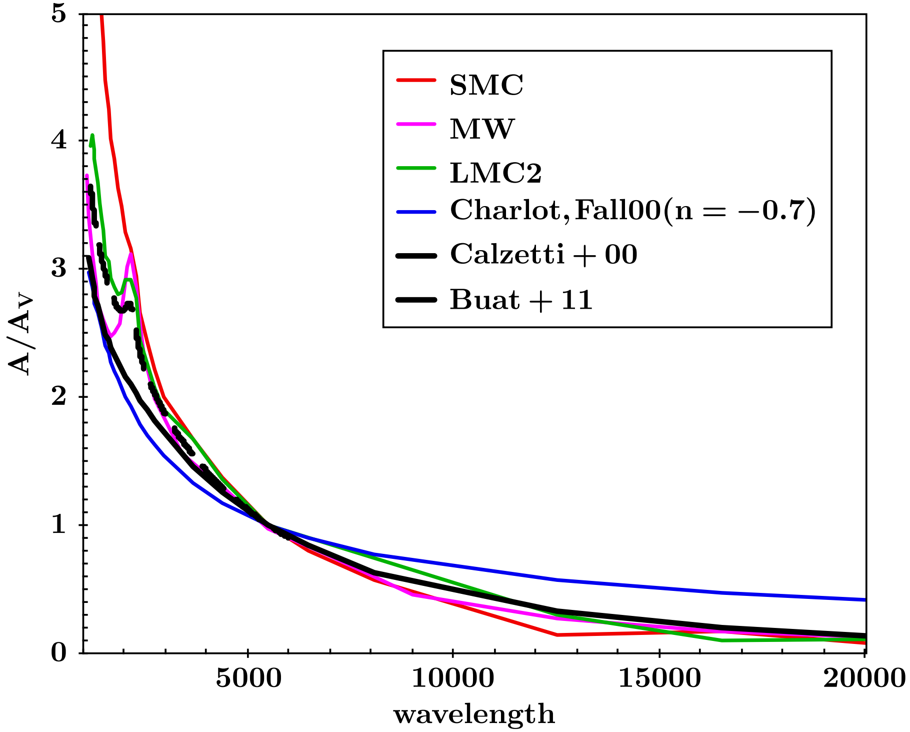
*Witt & Gordon 2000*




Attenuation law for extended objects depends on dust properties and dust-stars geometry

Extinction curves, Gordon+03



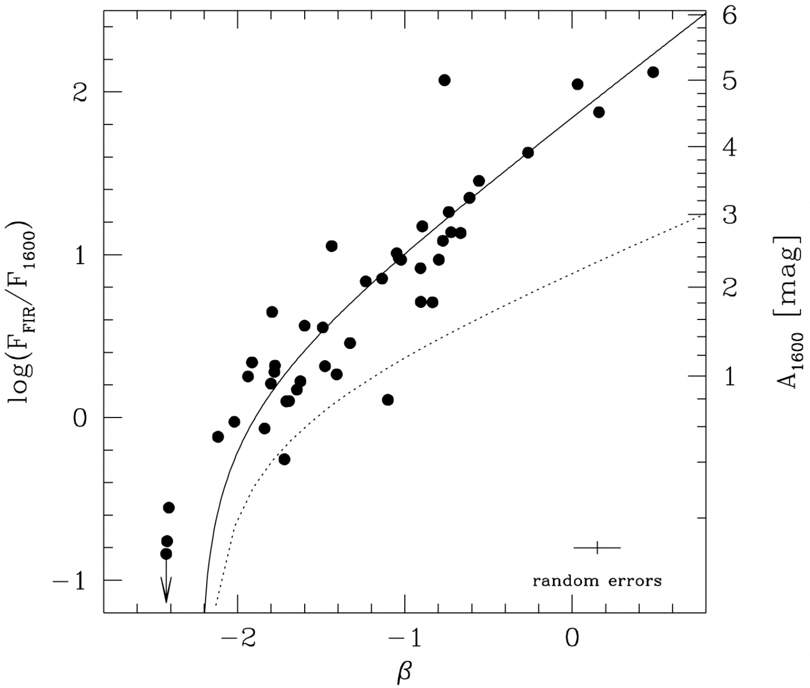



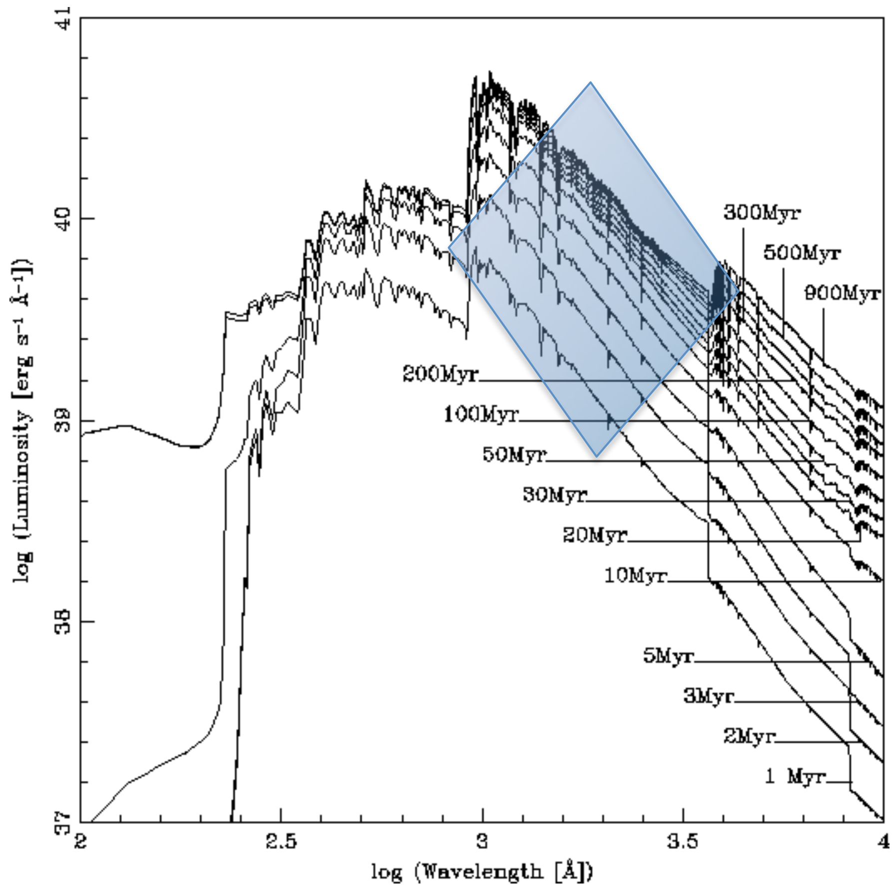

**Evidence for some bumps , steep and flat attenuation curves (Buat+11,12, Kriek & Conroy 13, Chevallard+13, Salmon+15)**

# What can we do when we have only UV-optical data?

**The slope of the UV continuum commonly used as a measure dust attenuation**

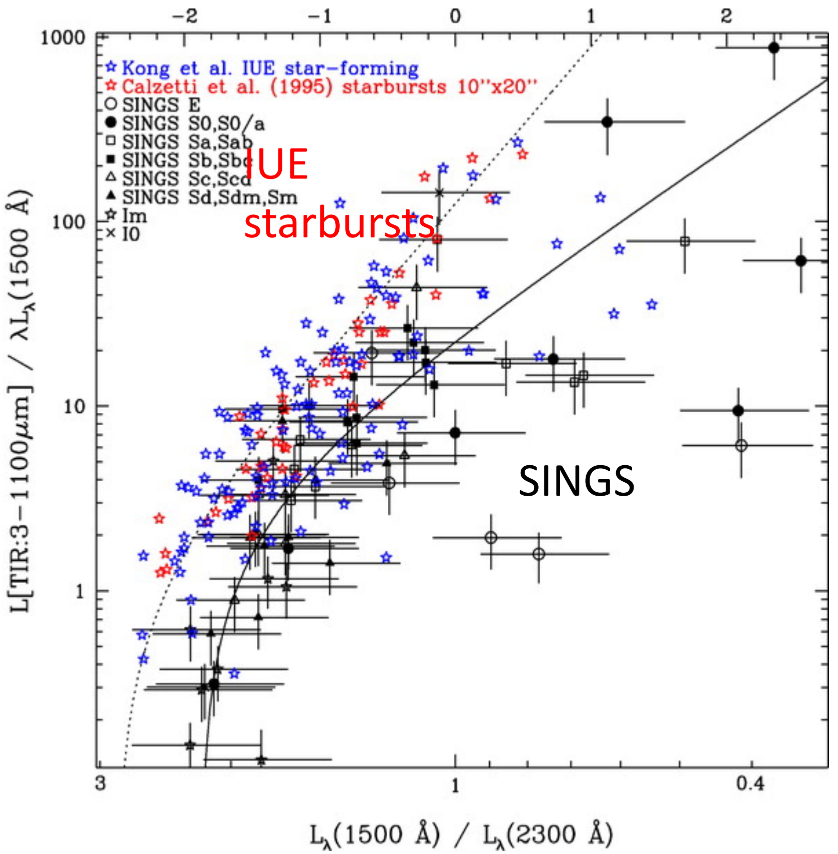
$f_\lambda \propto \lambda^\beta$(1200-2500Å), $\beta$: a proxy for dust attenuation in **local starburst galaxies** observed by IUE and IRAS




*Meurer et al. 95, 99,*
*Calzetti et al. 00*

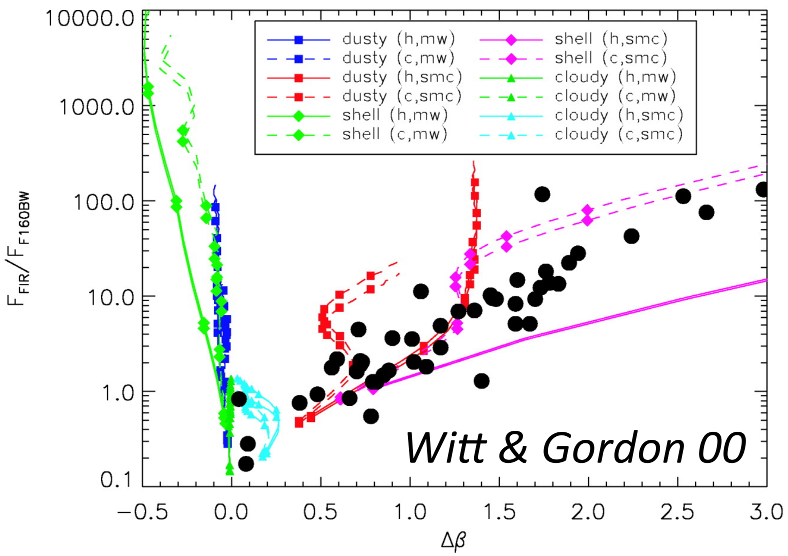
# Issues when using the slope of the UV contiuum to measure dust attenuation

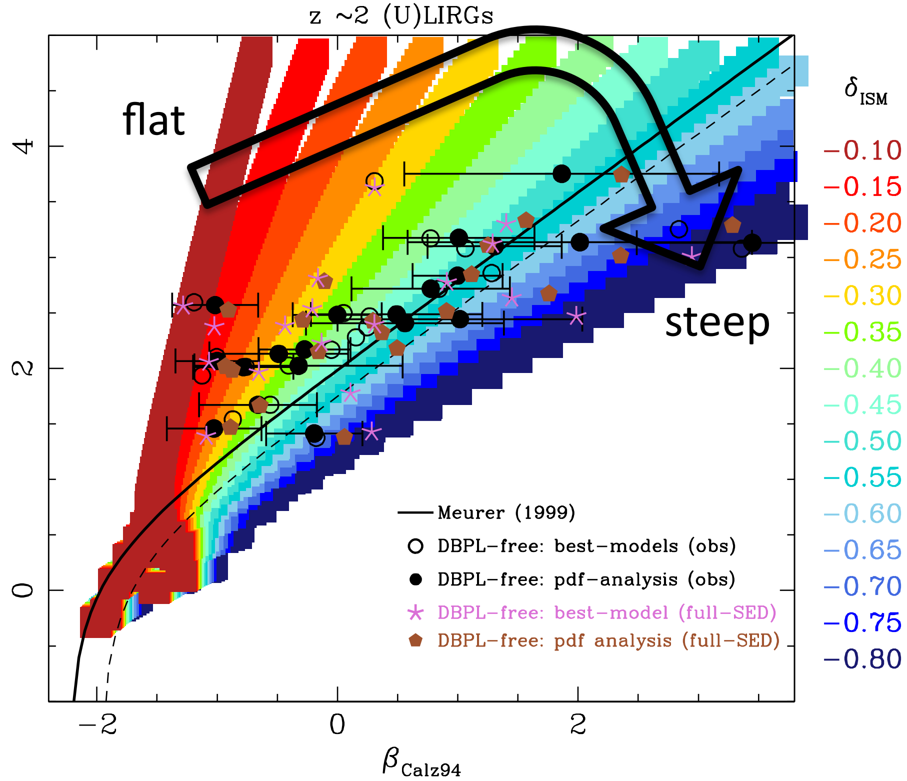


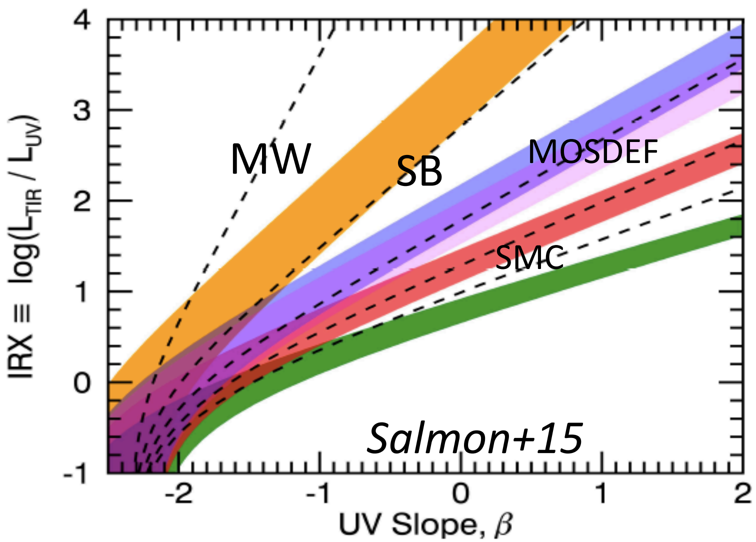

*Dale et al. 07*

Local Starburst and Star forming galaxies do not lie in the same area of the plot

# The IRX-β diagnostic is very sensitive to the shape of the attenuation curve in the UV



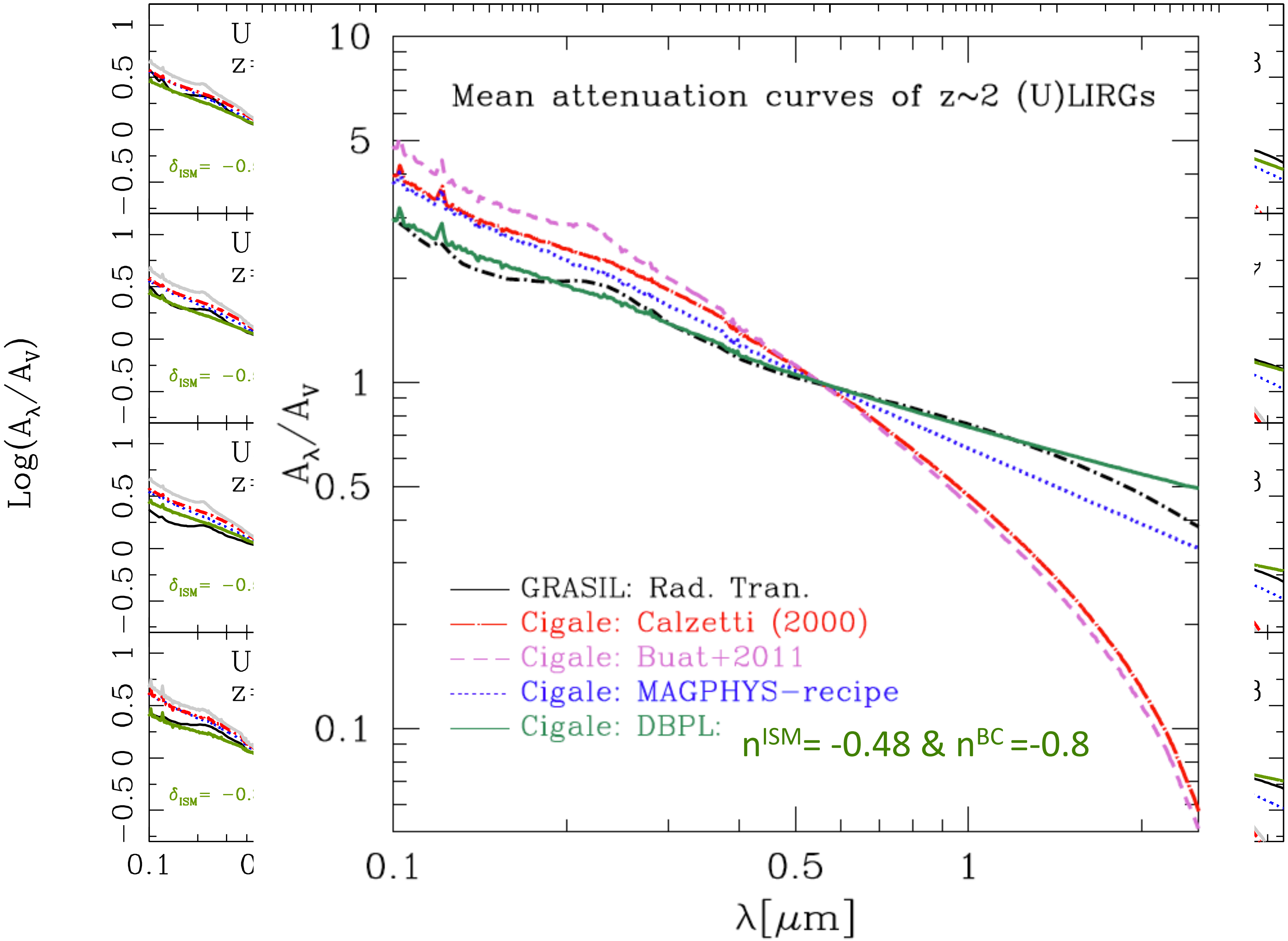




ULIRGs @ z=2 detected by Herschel

Edinburgh, july 2016

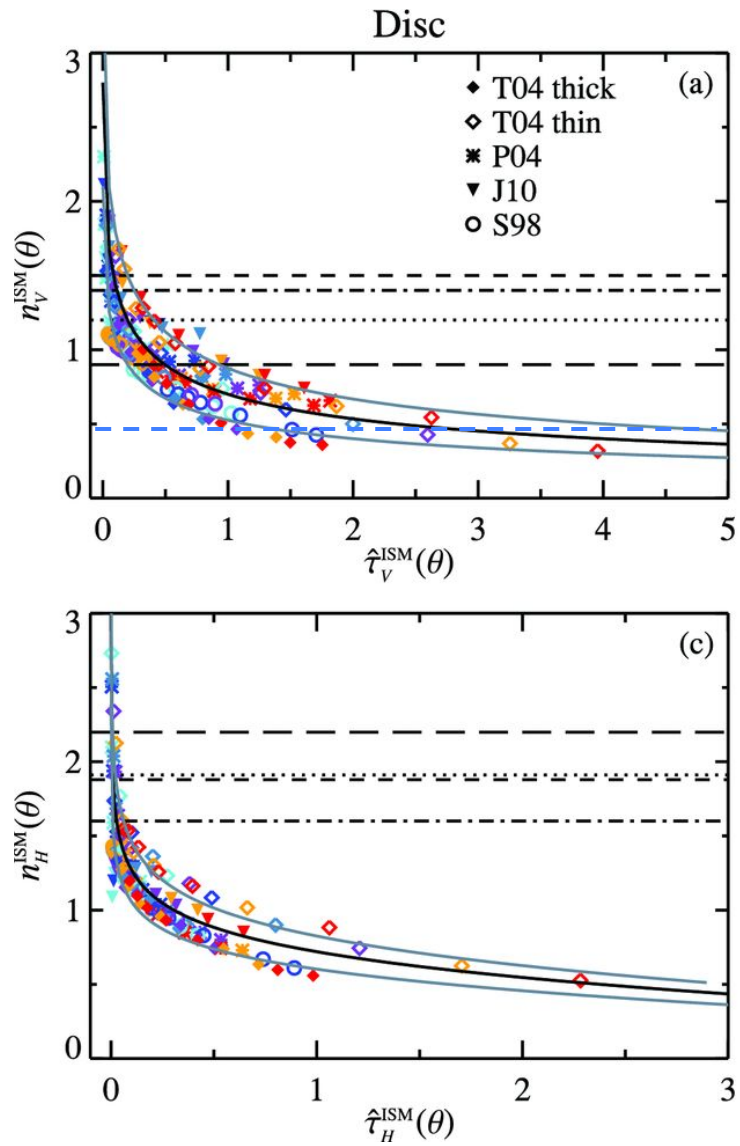
Lo Faro et al. In prep

Grasil power law fixed **power law free** Calzetti+00 Buat+11



*Flattening of the attenuation curve in high attenuated objects*
→*In agreement with Chevallard et al. 2013*:

Compilation of Radiative Transfer modeling results, confirming GRASIL calculations
→ All predict a grayer attenuation for an increasing attenuation



# Outline

- SFR determination: the basic equation
- SFRs based on the dust emission and composite tracers

  Monochromatic fluxes, Global dust emission, Combination of optical and IR measurements
- **M* determination → ONLY STELLAR MASSES**
- Fitting the whole Spectral Energy Distribution

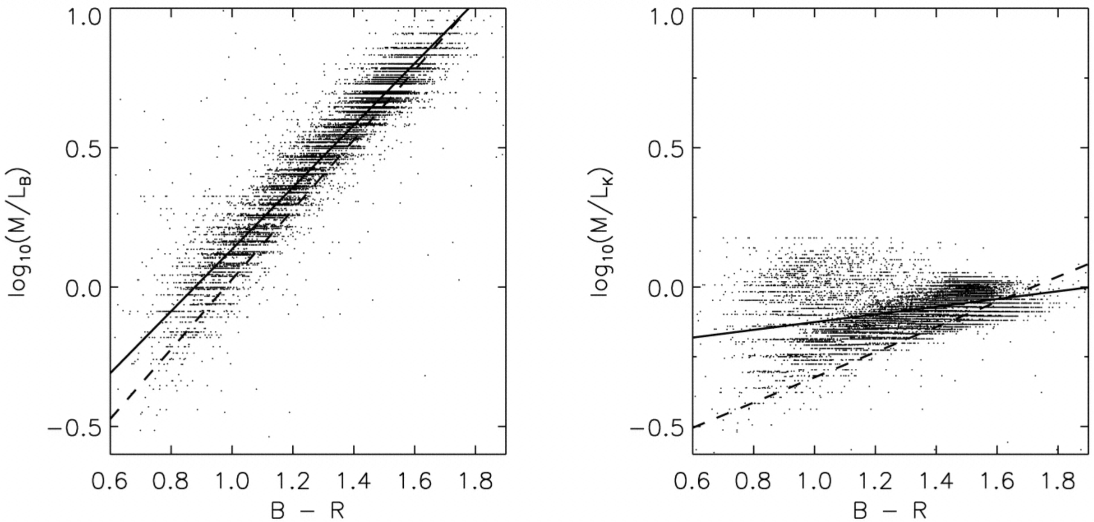
# Stellar mass estimates : M/L VERSUS COLORS recipes
## from optical-NIR SEDs and population synthesis models

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 |

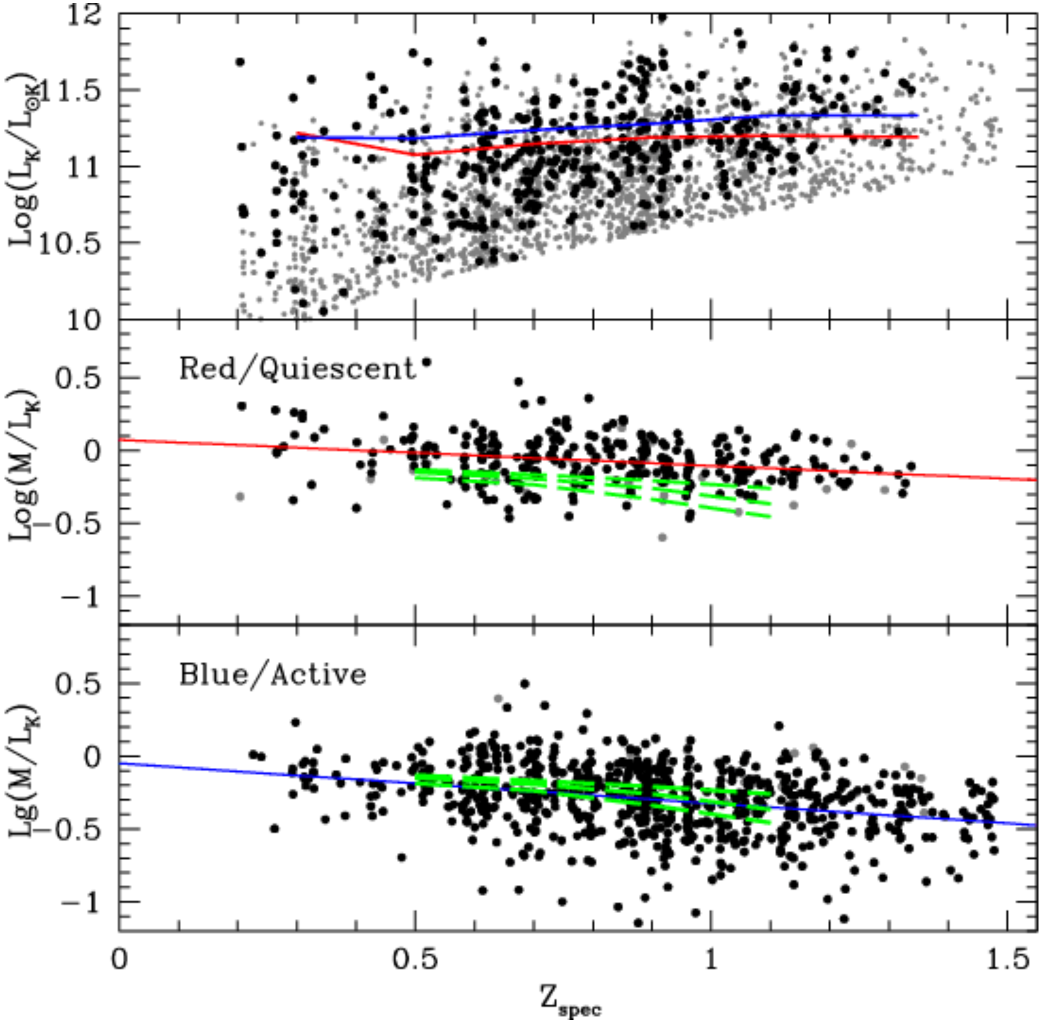
| Color | $a_B$ | $b_B$ | $a_V$ | $b_V$ | $a_R$ | $b_R$ | $a_I$ | $b_I$ | $a_J$ | $b_J$ | $a_H$ | $b_H$ | $a_K$ | $b_K$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $B-V$........ | −0.942 | 1.737 | −0.628 | 1.305 | −0.520 | 1.094 | −0.399 | 0.824 | −0.261 | 0.433 | −0.209 | 0.210 | −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 |

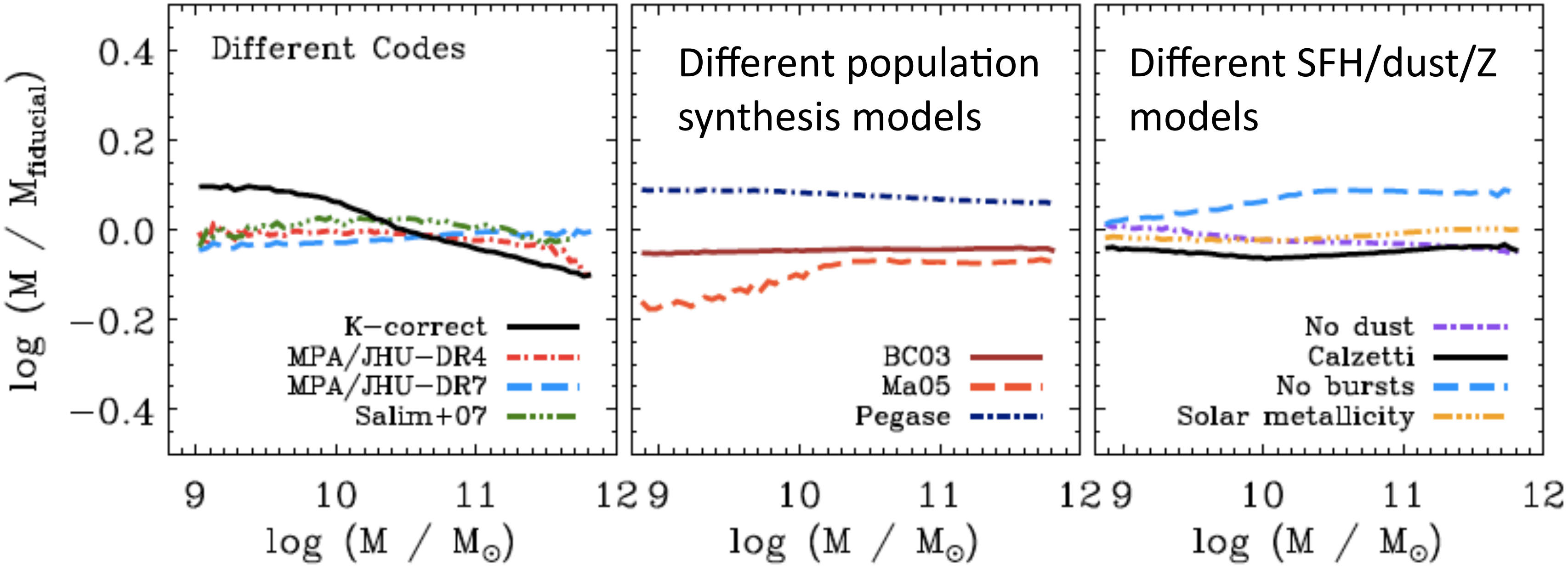
NOTES.—Stellar $M/L$ ratios are given by $\log_{10}(M/L) = a_\lambda + (b_\lambda \times \text{color})$, where the $M/L$ ratio is in solar units. If *all* galaxies are submaximal, then the above zero points ($a_\lambda$) should be modified by subtracting an IMF dependent constant as follows: 0.15 dex 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



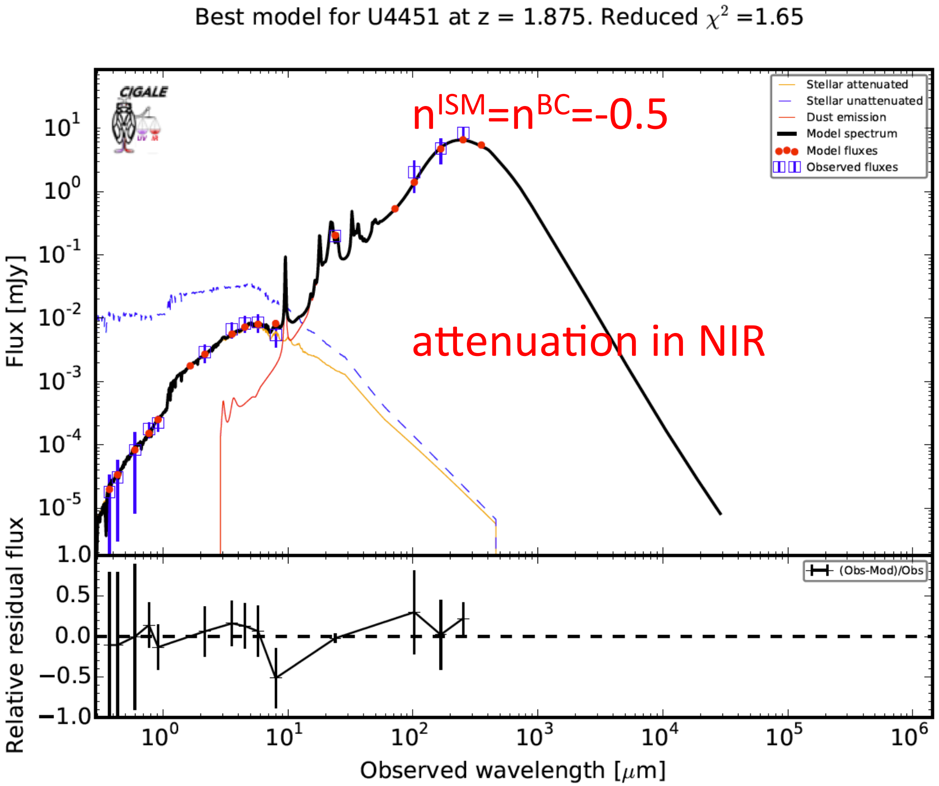


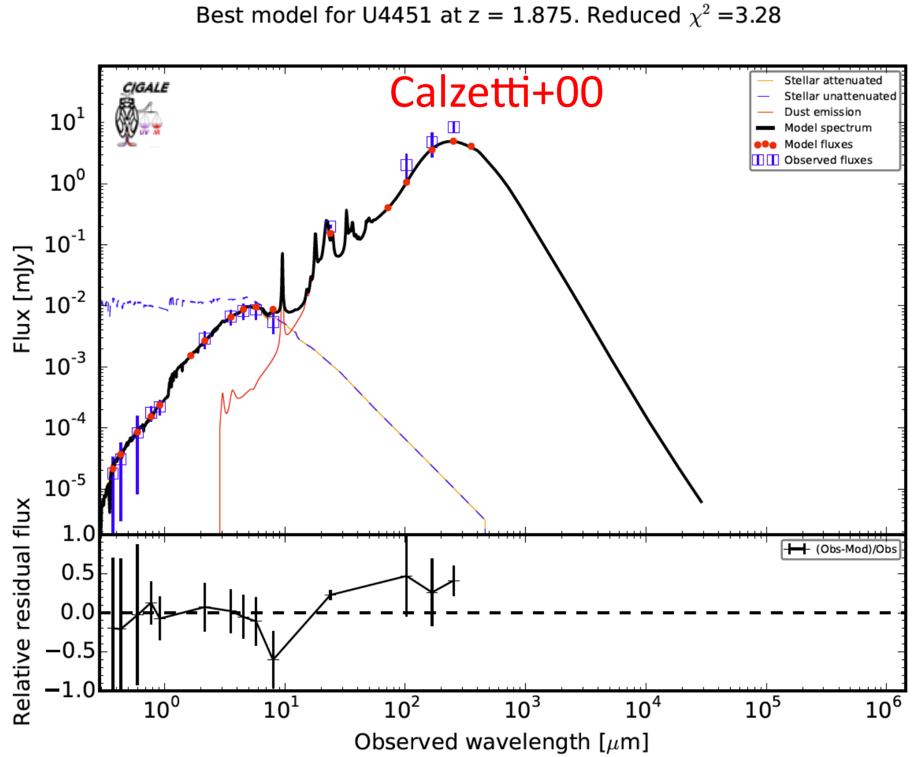

**The mean systematic differences between models do not exceed +/-0.2 dex**
**Stellar masses are securely estimated within a factor ~1.5**

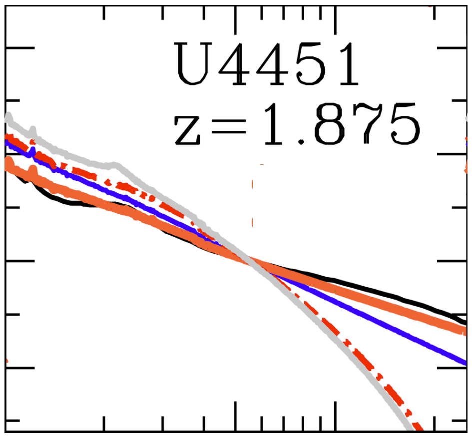
Comparison of different fitting codes, SPS models, and priors on derived stellar masses (from Moustakas et al. 2012). The fiducial masses are based on fitting SDSS and *GALEX* photometry of $z \sim 0$ galaxies using the `iSEDfit` code (Moustakas et al. 2012), with SSPs from FSPS (Conroy, Gunn & White 2009), including dust attenuation, a range in metallicities, and SFHs with both smooth and bursty components. The left panel compares stellar mass catalogs produced by different groups/codes. K-correct and MPA/JHU-DR7 are based on SDSS photometry; MPA/JHU-DR4 is based on SDSS spectral indices, and Salim+07 is based on SDSS and *GALEX* photometry. The middle panel shows the effect of different SPS models (i.e., different SSPs), and the right panel shows the effect of varying the priors on the model library. The mean systematic differences between mass estimators is less than ±0.2 dex. Figure courtesy of J. Moustakas.

Conroy 13

# How do ``flat'' attenuation curves affect the stellar mass determination?




**A larger amount of attenuation at longer wavelengths (NIR)** than allowed by Calzetti+00 att. law. (*Mitchell+13, Da Cunha+10*)

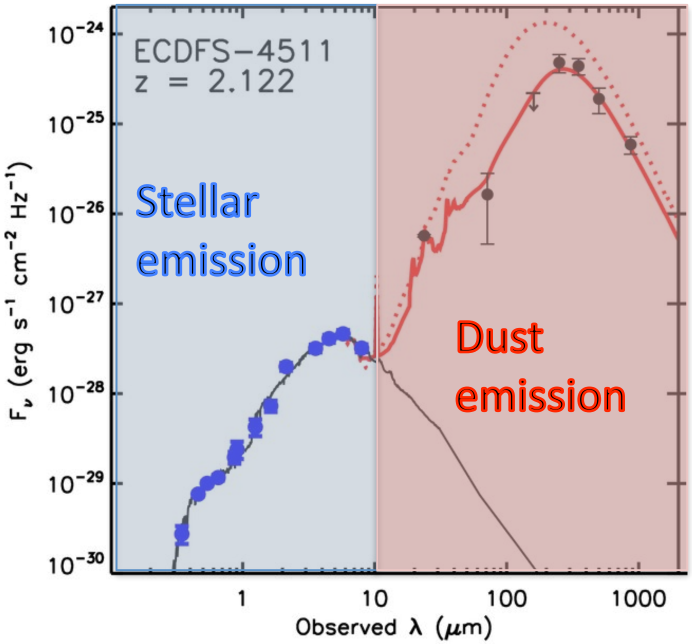
**→Affects the determination of the stellar mass (*Mitchell+13, Lo faro+13*)**

# Outline

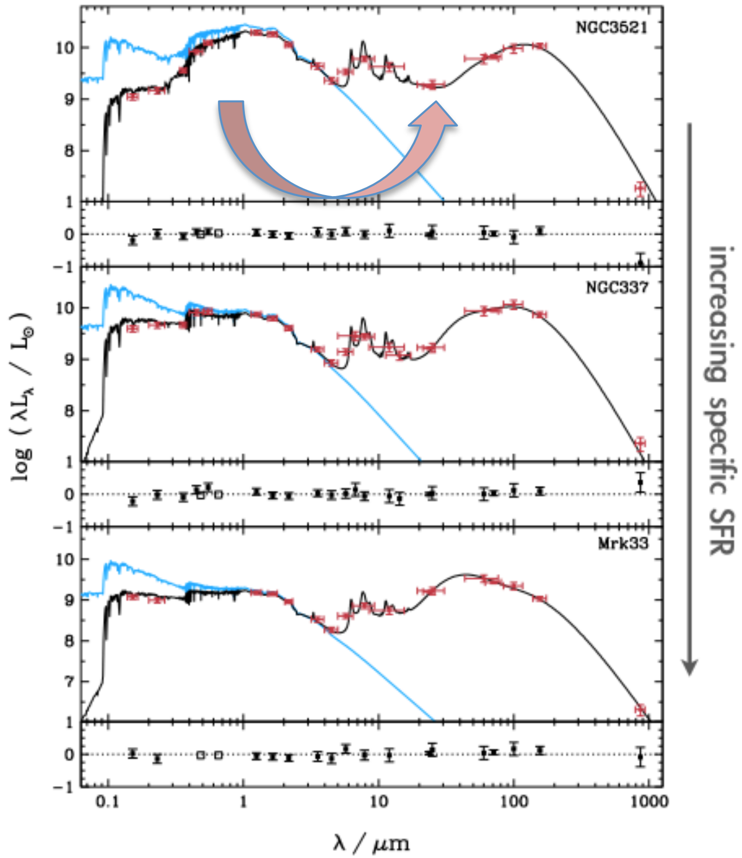
- SFR determination: the basic equation
- SFRs based on the dust emission and composite tracers

  Monochromatic fluxes, Global dust emission, Combination of optical and IR measurements
- M* determination
- **Fitting the whole Spectral Energy Distribution**

# Modeling the SEDs: SFR and M* (and other parameters) estimated in a consistent way




*Muzzin+10*
Stellar and dust emission fitted separately

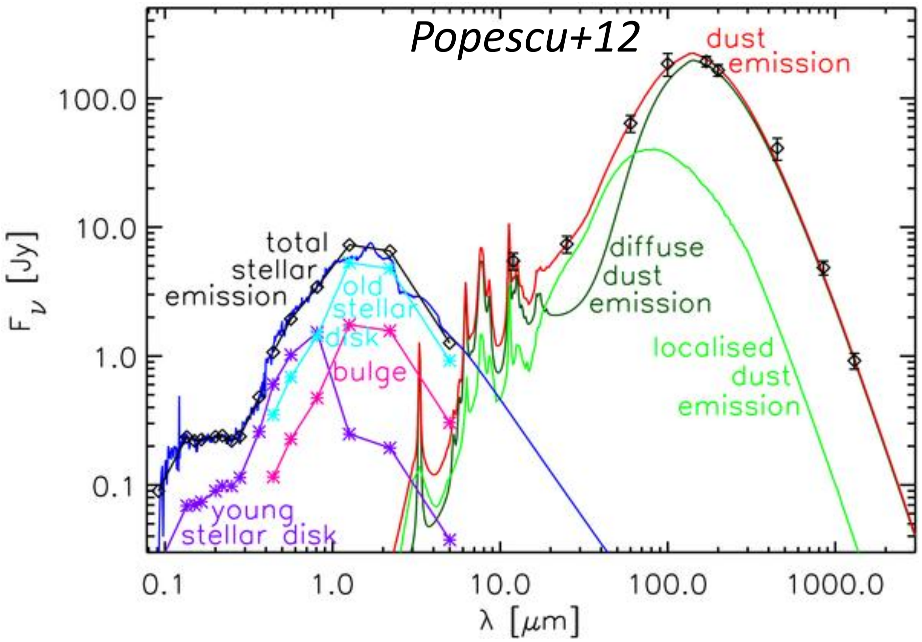


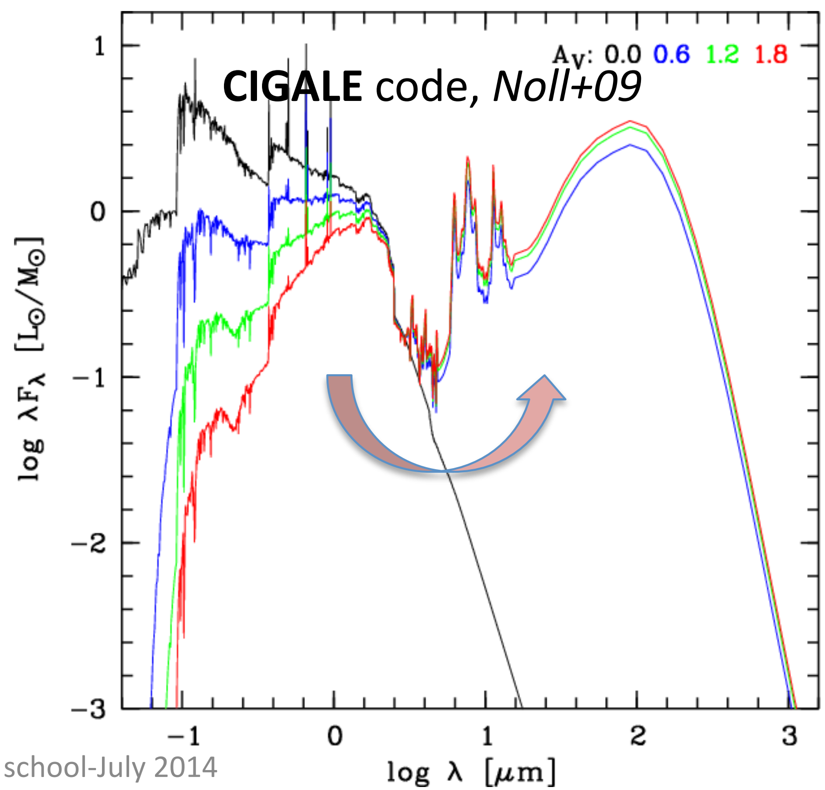

*Da Cunha+08*, **Magphys** code

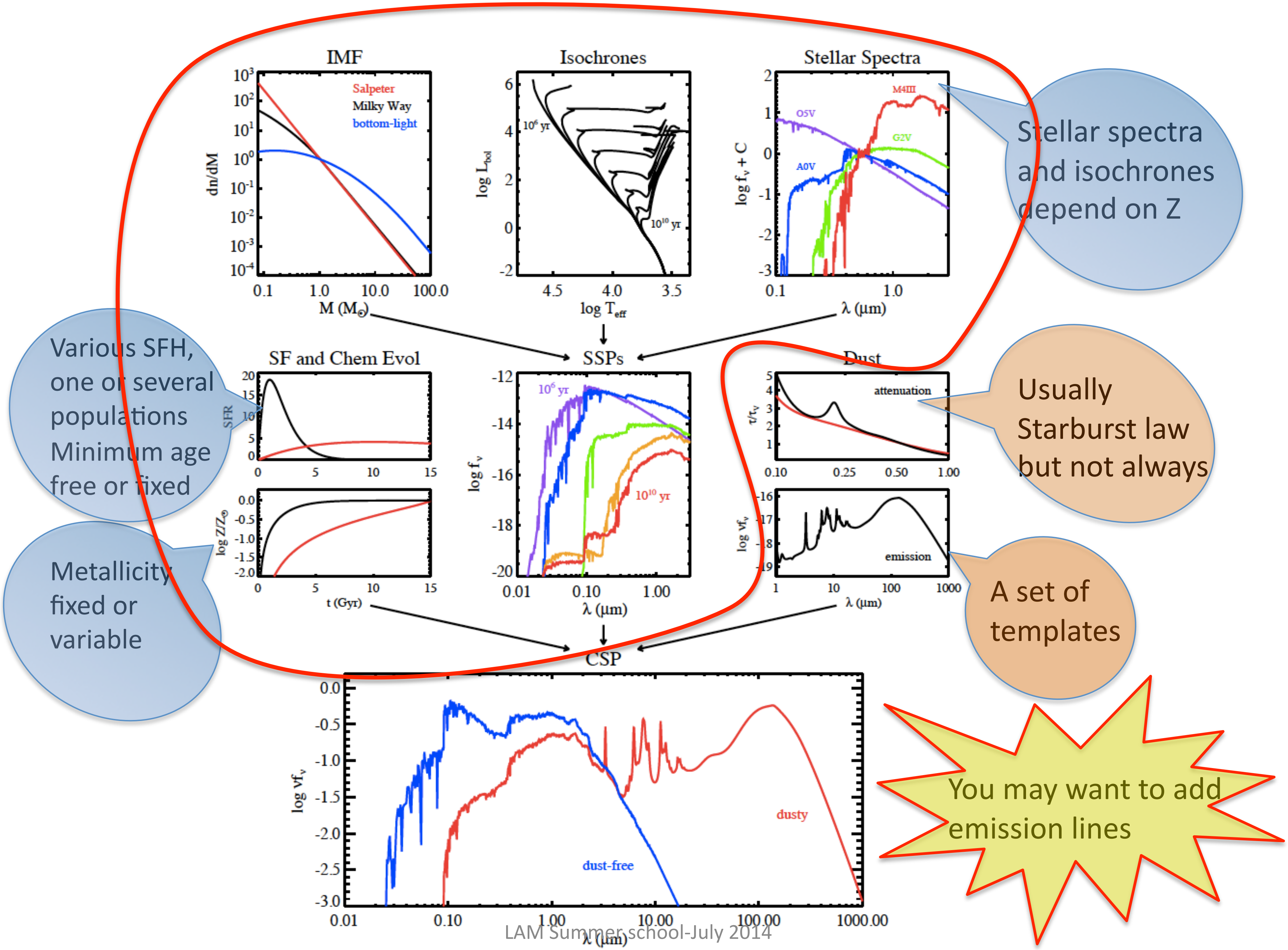
# Focusing on SED fitting with conservation of the energy bewteen UV-optical and IR

**Radiation transfer** & multi-components: valid for local resolved galaxies

**Simple recipes**: dust attenuation curves, IR libraries
Valid for large samples of unresolved galaxies




IMF
Salpeter
Milky Way
bottom-light
dn/dM
M (M⊙)
Isochrones
10^6 yr
10^10 yr
log L_bol
log T_eff
Stellar Spectra
M4III
O5V
G2V
A0V
log f_ν + C
λ (μm)
Stellar spectra and isochrones depend on Z
SF and Chem Evol
SFR
log Z/Z⊙
t (Gyr)
SSPs
10^6 yr
10^10 yr
log f_ν
λ (μm)
Dust
attenuation
τ/τ_V
emission
log νf_ν
λ (μm)
Various SFH, one or several populations
Minimum age free or fixed
Metallicity fixed or variable
Usually Starburst law but not always
A set of templates
CSP
log νf_ν
dusty
dust-free
λ (μm)
You may want to add emission lines

# Example of parameter sets to build models

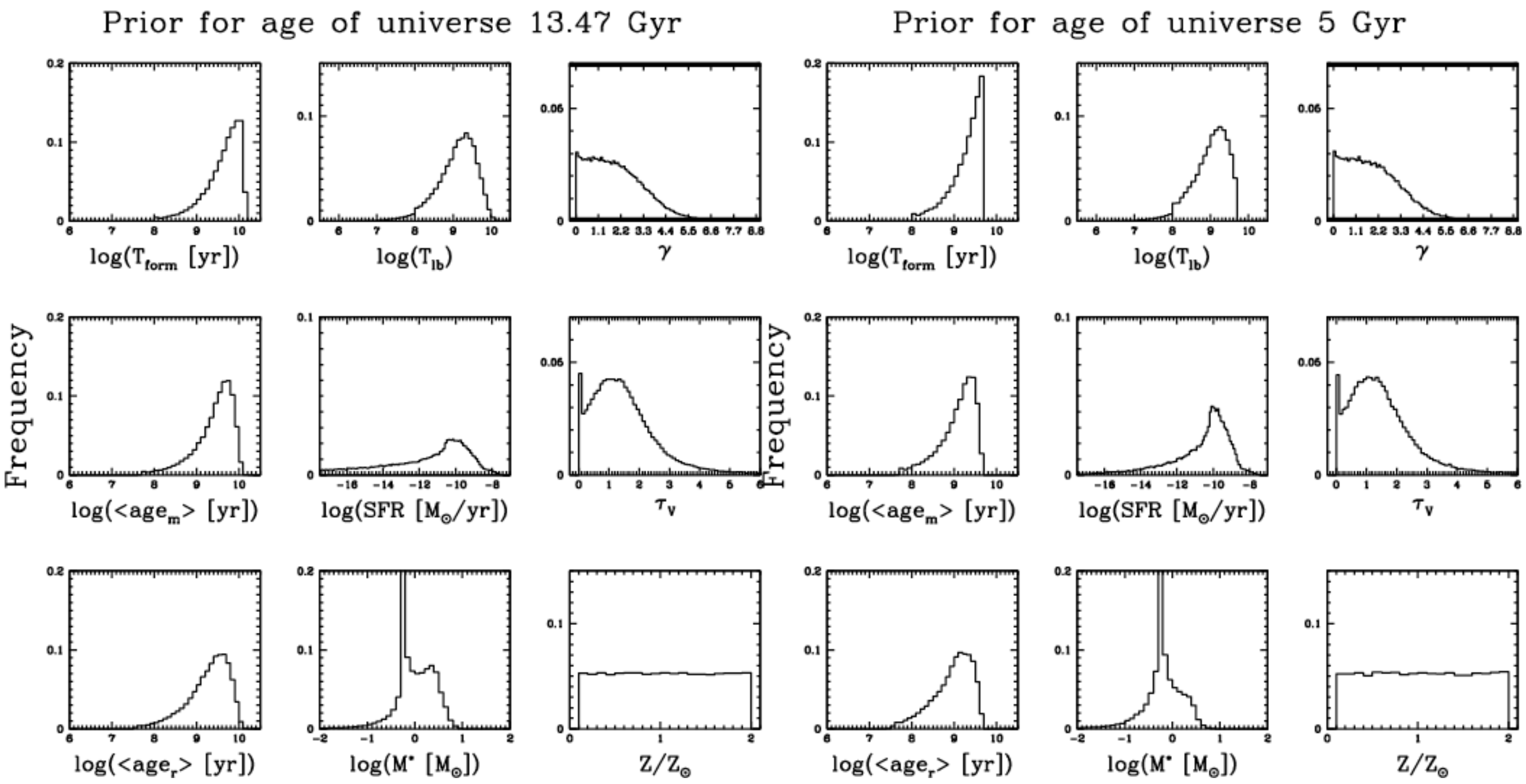
V. Buat et al.: AKARI-SDSS-GALEX galaxies

| Parameters | Symbol | Range |
|---|---|---|
| Star formation history | | |
| metallicities (solar metallicity) | $Z$ | 0.02 |
| $\tau$ of old stellar population models in Gyr | $\tau_1$ | 1; 3.0; 5.0; 10.0 |
| ages of old stellar population models in Gyr | $t_1$ | 13 |
| ages of young stellar population models in Gyr | $t_2$ | 0.025; 0.05; 0.1 ;0.3 ;0.5 ;1.0 |
| fraction of young stellar population | $f_{ySP}$ | 0.001; 0.01; 0.1; 0.999 |
| IMF | K | Kroupa |
| Dust attenuation | | |
| Slope correction of the Calzetti law | $\delta$ | -0.3; -0.2; -0.1; 0.0; 0.1; 0.2 |
| V-band attenuation for the young stellar population | $A_{V,ySP}$ | 0.15; 0.30; 0.45; 0.60; 0.75; 0.90; 1.05; 1.20; 1.35; 1.5; 1.65; 1.8; 1.95; 2.1 |
| Reduction of $A_V$ basic for old SP model | $f_{att}$ | 0.0; 0.50; 1.0 |
| IR SED | | |
| IR power-law slope | $\alpha$ | 1.0; 1.5; 1.75; 2.0; 2.25; 2.5; 4.0 |

**Table 2.** List of the input parameters of the code CIGALE and their selected range.

Discrete values, all are considered, the number of models is obtained by multiplying the number of parameters

# Example of parameter sets to build models (Walcher+08)




The parameters are randomly selected from the distributions
(e.g. Kauffmann+03, Salim+05, DaCunha+08 etc…)

# Parameter estimation

- **Classical $\chi^2$ minimization** to determine the (single) best fit model→ not optimal for a large range of parameters

$$\chi^2 = \sum_{i=1}^{N} \frac{(obs_i - \mathrm{mod}_i)^2}{\sigma_i^2}$$

To compare models: **reduced $\chi^2$** , but the degree of freedom is sometimes difficult to estimate

- **Perform an analysis of the probability distribution** (Kauffmann+03):

M ~ Model, D~Data

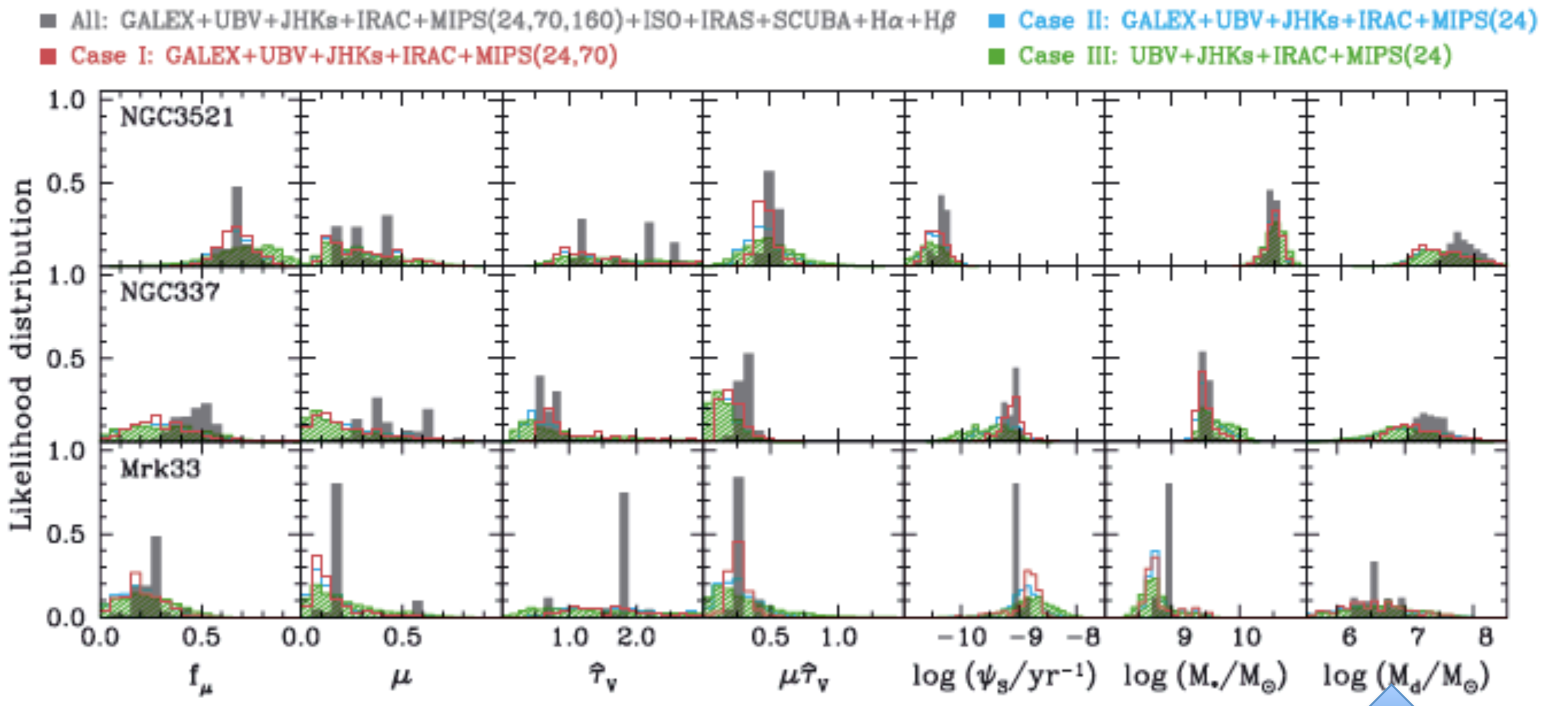
**Prob(M/D) ∝ P(M) × P(D/M)**

- For Gaussian uncertainties **P(D/M) = exp(-$\chi^2$/2)**
- **P(M)** corresponds to our prior knowledge in the absence of data, all models usually assumed to be equiprobable (the range of parameters must be realistic, you must be sure to reproduce all the data)
- **Probability distribution functions (PDF)** for each parameter are built by marginalizing over all the other parameters:

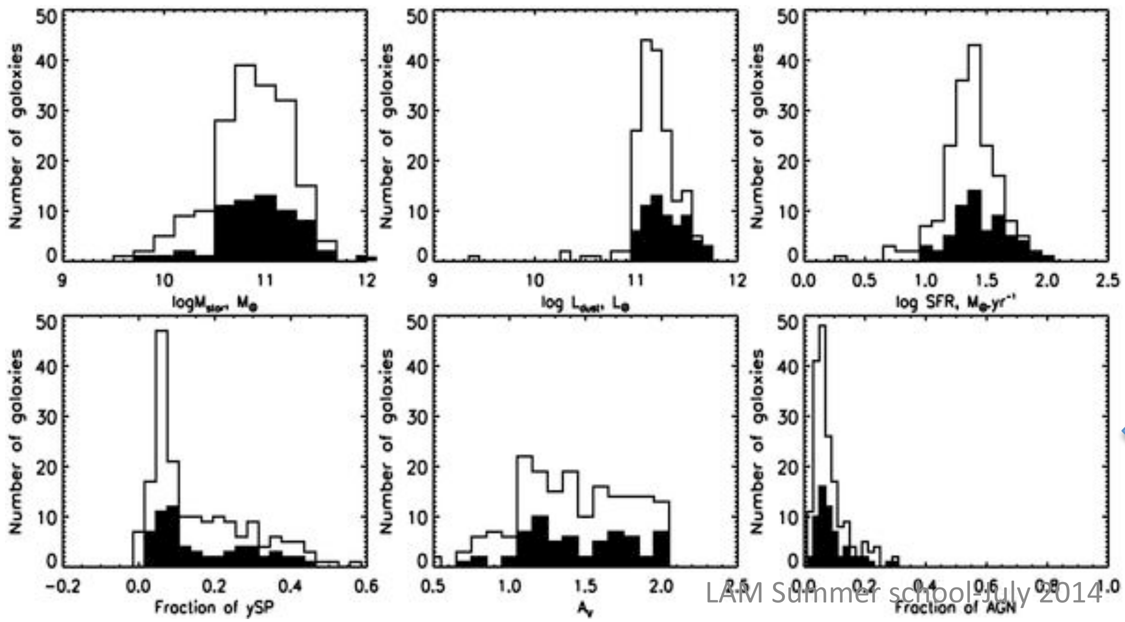
**→ mean, median, dispersion, quartiles of the PDF**

- **Monte Carlo Markov Chain** (MCMC) statistical analyses

http://www.sedfitting.org/SED08/Welcome.html



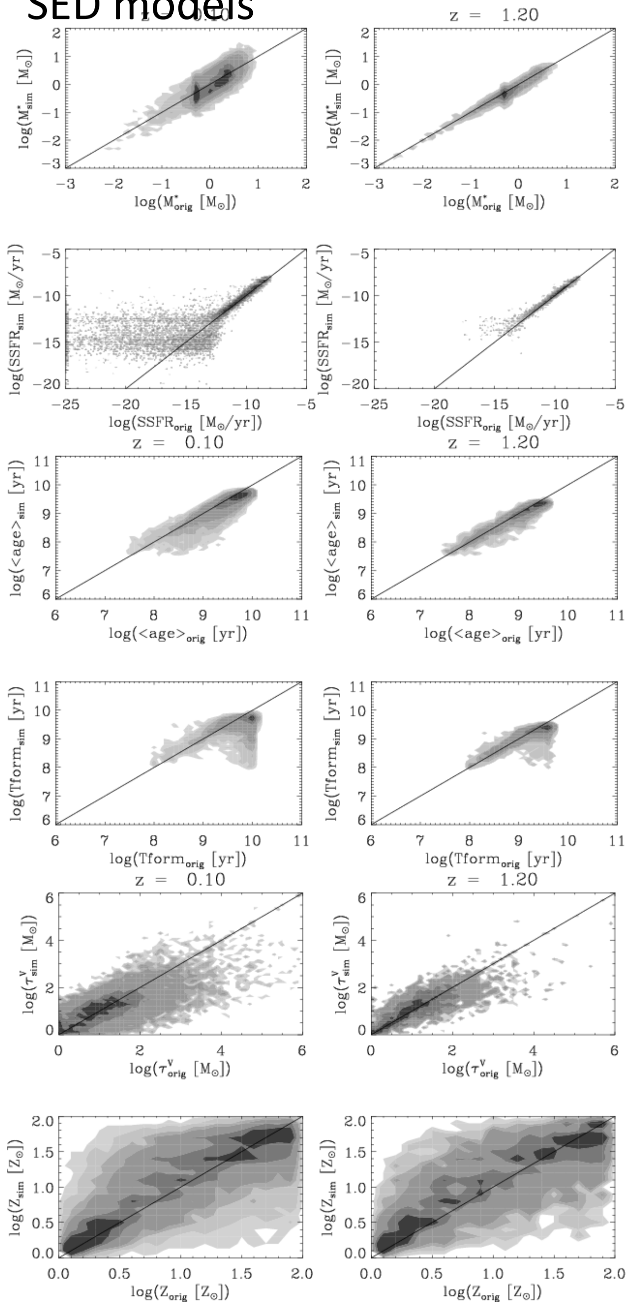

PDF of physical quantities derived from fits with different set of data for 3 galaxies (da Cunha+08)




Distribution of parameters for a sample of 200 galaxies (Giovannoli+11)

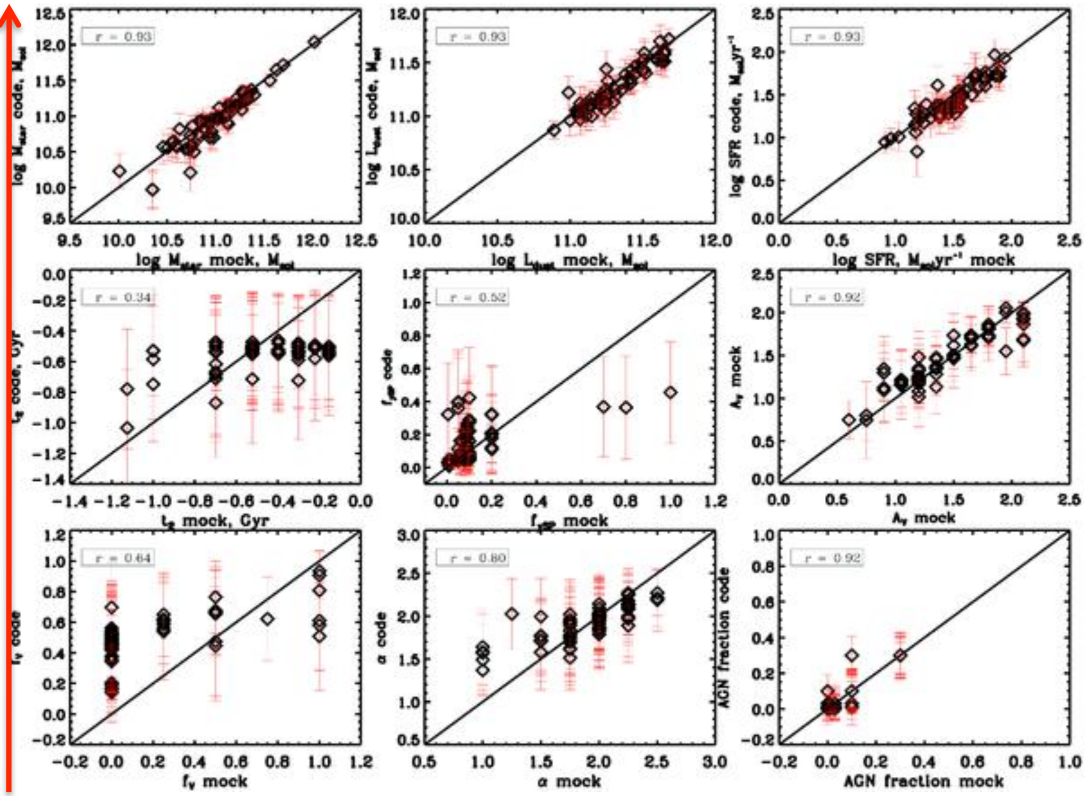
**Using Mock catalogues to control the results**:
pseudo-galaxies created from the SED models or the data to check the internal accuracy of the codes

Walcher et al. 2008, from the SED models



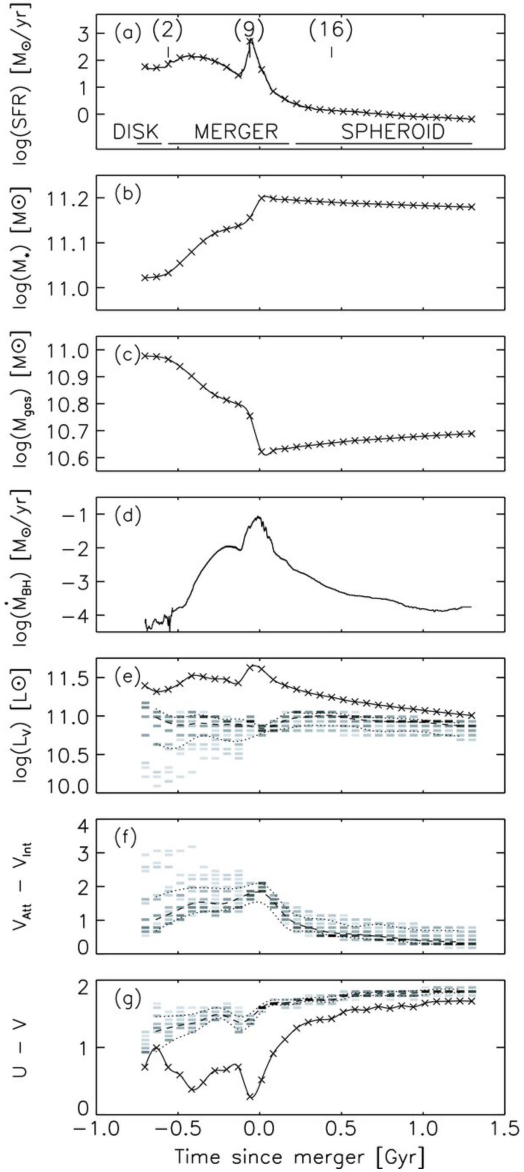

Giovannoli et al. 2011, pseudo-galaxies from the data (best fit)

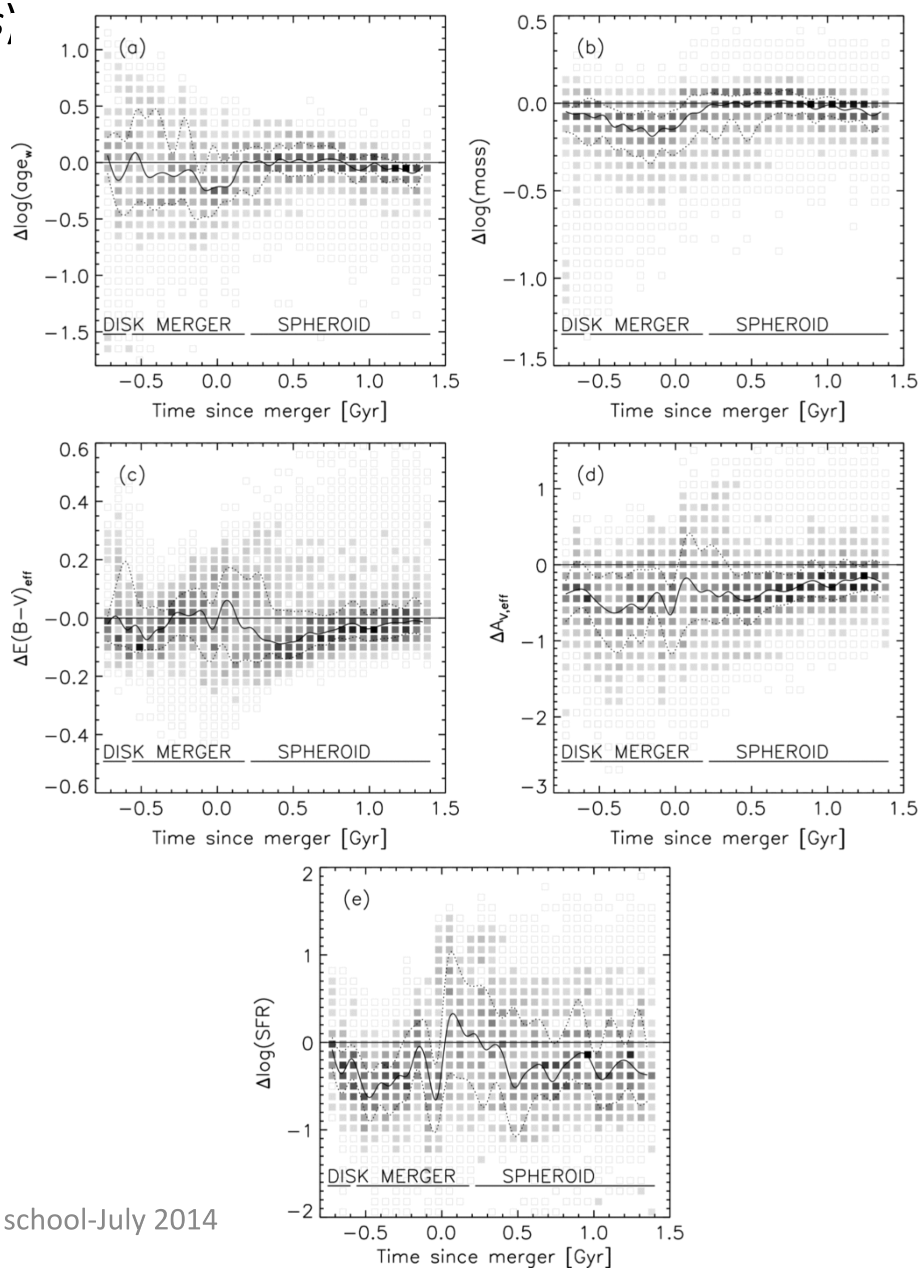
Estimated values of the parameters




Exact values of the parameters

**Catalogues of simulated galaxies from semi-analytical or hydrodynamical simulations**: To test the ability of SED fitting to recover complex objects (*Wuyts et al. 2009, Hydrodynamical simulations*)

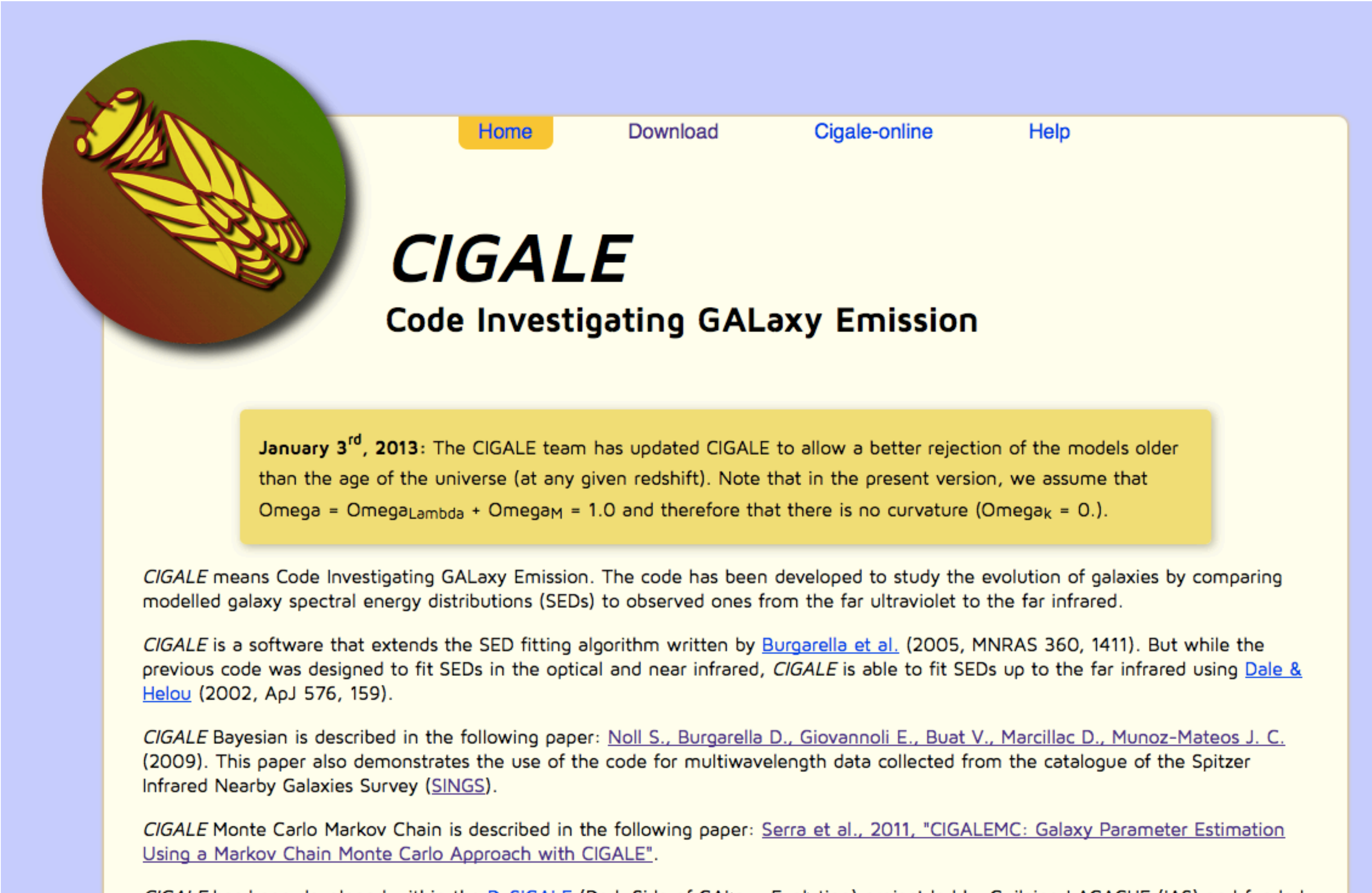


# CIGALE : Code Investigating GALaxy Emission

*P.I. D. Burgarella (Médéric Boquien, Yannick Roehlly)* http://cigale.lam.fr/

New version available soon



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# *CIGALE*

## Code Investigating GALaxy Emission

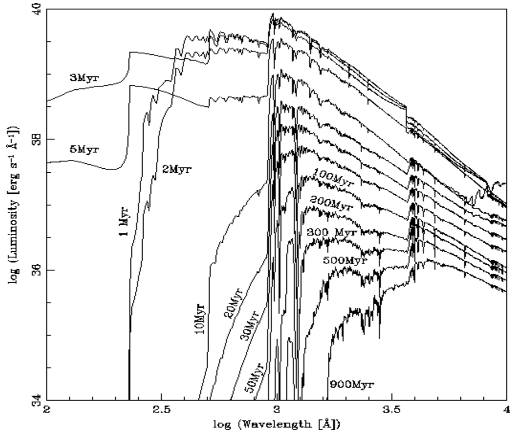
**January 3rd, 2013:** The CIGALE team has updated CIGALE to allow a better rejection of the models older than the age of the universe (at any given redshift). Note that in the present version, we assume that Omega = $\text{Omega}_{\text{Lambda}}$ + $\text{Omega}_{\text{M}}$ = 1.0 and therefore that there is no curvature ($\text{Omega}_{\text{K}}$ = 0.).

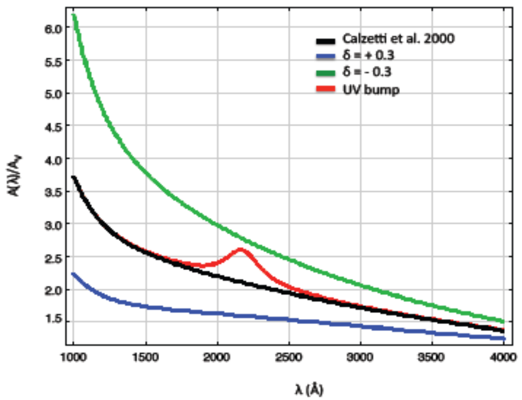
*CIGALE* means Code Investigating GALaxy Emission. The code has been developed to study the evolution of galaxies by comparing modelled galaxy spectral energy distributions (SEDs) to observed ones from the far ultraviolet to the far infrared.

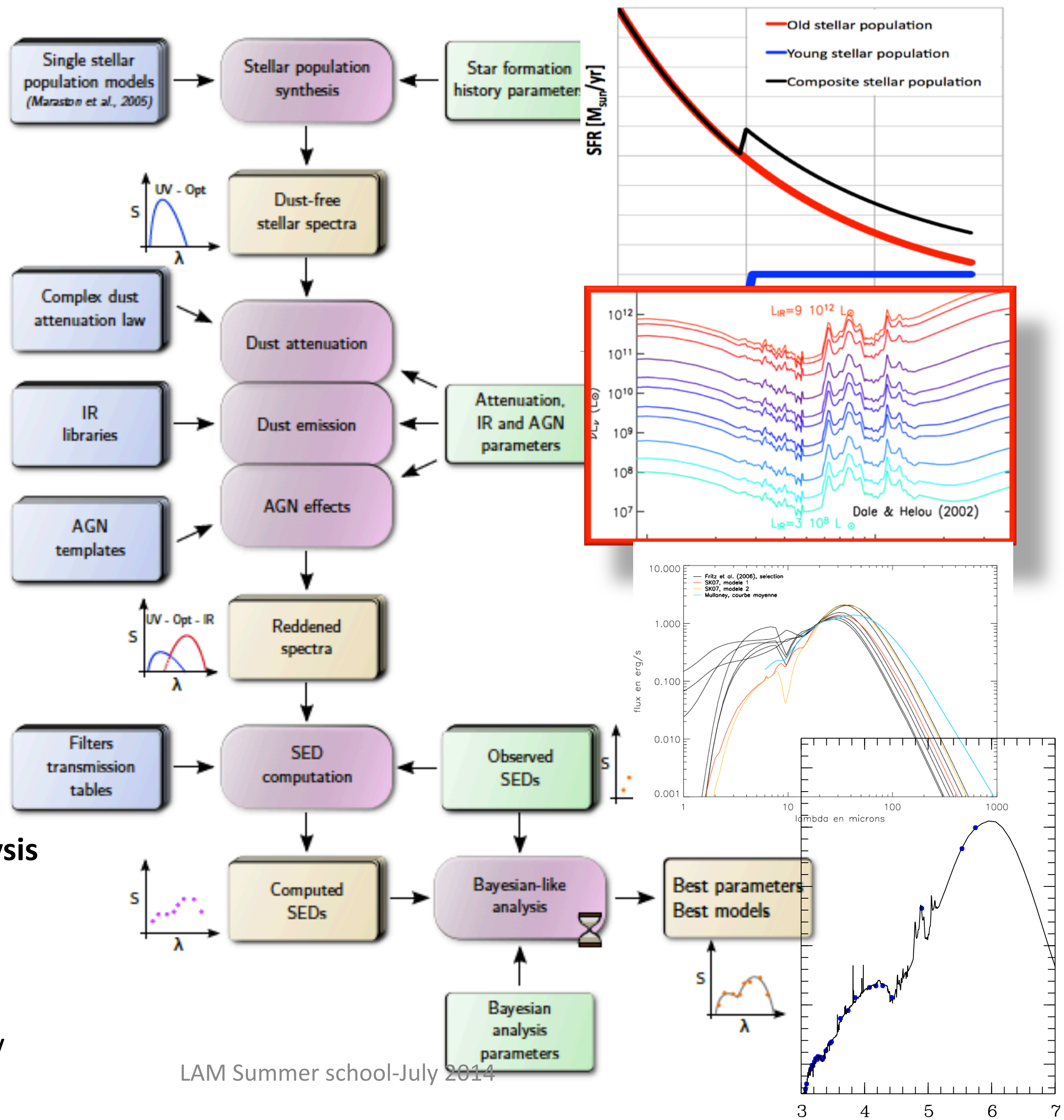
*CIGALE* is a software that extends the SED fitting algorithm written by Burgarella et al. (2005, MNRAS 360, 1411). But while the previous code was designed to fit SEDs in the optical and near infrared, *CIGALE* is able to fit SEDs up to the far infrared using Dale & Helou (2002, ApJ 576, 159).

*CIGALE* Bayesian is described in the following paper: Noll S., Burgarella D., Giovannoli E., Buat V., Marcillac D., Munoz-Mateos J. C. (2009). This paper also demonstrates the use of the code for multiwavelength data collected from the catalogue of the Spitzer Infrared Nearby Galaxies Survey (SINGS).

*CIGALE* Monte Carlo Markov Chain is described in the following paper: Serra et al., 2011, "CIGALEMC: Galaxy Parameter Estimation Using a Markov Chain Monte Carlo Approach with CIGALE".






**OUTPUT PARAMETERS :**

**All based on a Bayesian analysis**

- input parameters
- Stellar Mass
- Dust luminosity
- Amount of obscuration
- D4000 break, slope of the UV continuum....

# References


- Conroy 2013, Modeling the Panchromatic SED of galaxies, ARAA 2013, in press
- Starburst99 http://www.stsci.edu/science/starburst99/docs/default.htm
- Walcher et al. http://www.sedfitting.org/SED08/Welcome.html
- Gawiser, 2009, Spectral Energy Distributions fitting: application to Lyα emitting galaxies, New Astronomy reviews, vol 53
- Kennicutt & Evans, 2012, Star formation in the Milky Way and Nearby Galaxies, ARAA vol 50
- Boissier, S. 2012, Star formation in Galaxies, Planets, Stars and Stellar systems, vol 6
- Calzetti 2012, Secular Evolution of Galaxies, XXIII Canary Islands Winter School of Astrophysics

# $F_{H\alpha}/F_{UV}$ : a theoretical diagnostic to study the IMF?

Boselli et al. 2001)

TABLE 4

ADOPTED IMF PARAMETERS

| IMF Slope | IMF Cutoff | $K_{H\alpha}(\alpha, M_{up})^a$ | $K_{UV}(\alpha, M_{up})^b$ | $\log [K_{H\alpha}(\alpha, M_{up})/K_{UV}(\alpha, M_{up})]$ |
|---|---|---|---|---|
| 1.5…… | 80 | $1/(1.61 \times 10^{42})$ | $1/(2.01 \times 10^{40})$ | 1.903 |
| 2.5 | 40 | $1/(5.41 \times 10^{40})$ | $1/(3.18 \times 10^{39})$ | 1.231 |
| | 80 | $1/(1.16 \times 10^{41})$ | $1/(3.54 \times 10^{39})$ | 1.514 |
| | 120 | $1/(1.60 \times 10^{41})$ | $1/(3.66 \times 10^{39})$ | 1.640 |
| 3.5…… | 80 | $1/(5.53 \times 10^{38})$ | $1/(1.67 \times 10^{38})$ | 0.520 |

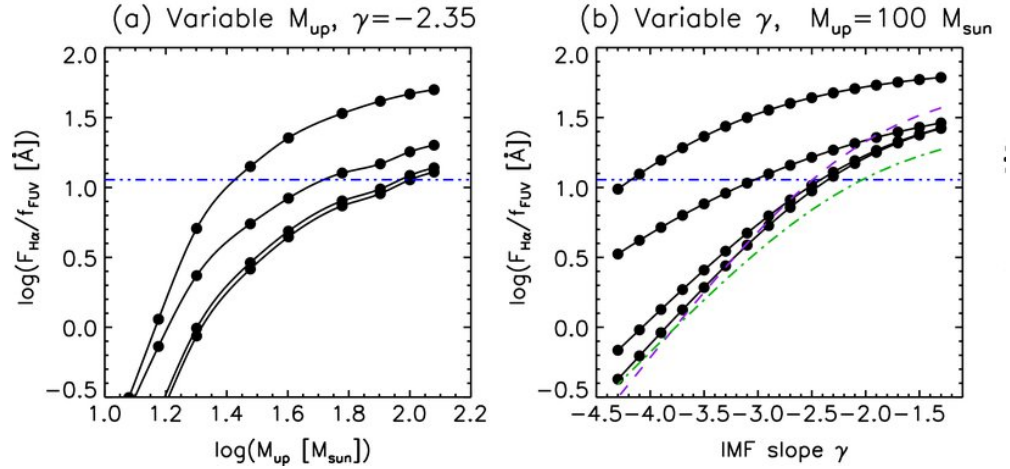
[a] From Charlot & Fall 1993, for $M_{low} = 0.1\ M_\odot$, in units of $(M_\odot\ \mathrm{yr}^{-1})(\mathrm{ergs\ s}^{-1})^{-1}$.

[b] From S. Charlot 1996, private communication, for $M_{low} = 0.1\ M_\odot$, in units of $(M_\odot\ \mathrm{yr}^{-1})(\mathrm{ergs\ s}^{-1}\ \text{Å}^{-1})^{-1}$.

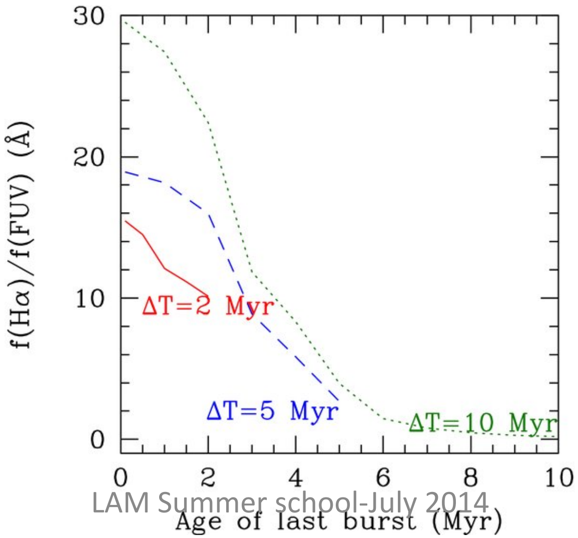
**Assumption: a constant star formation, a steady state in the production of UV and Hα light**

# $F_{H\alpha}$ /$F_{UV}$ : influence of the upper end of the IMF AND of the short term variations of the SF

*Meurer+09*: upper end variations of the IMF in Low Surface Brightness Galaxies

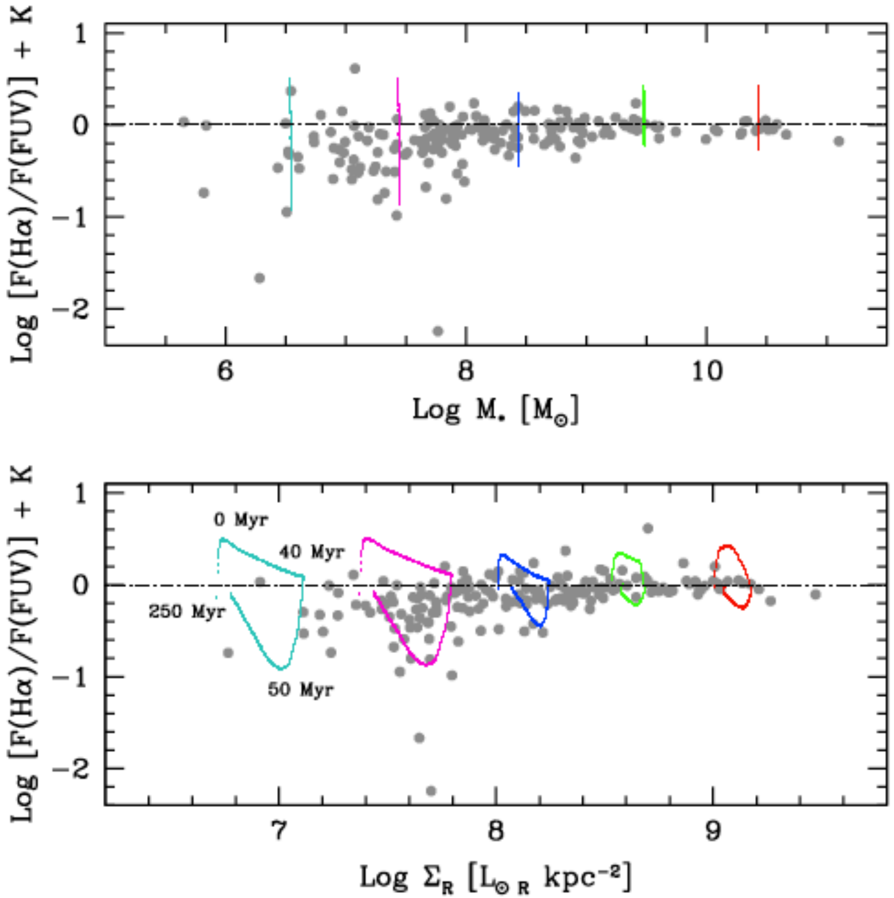


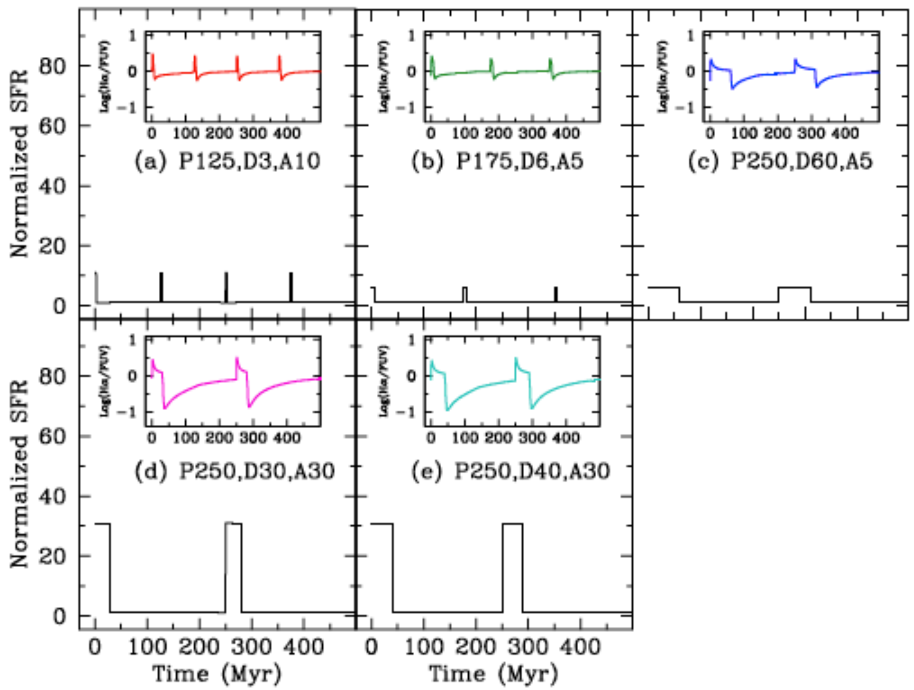

*Boselli+09*: Micro-history in low mass galaxies



**Dwarf galaxies**: best cases to measure SFH variations, Lee+09

Variations of the SFH explains the Hα/UV variations and dispersion: Weisz+12, Lee+09



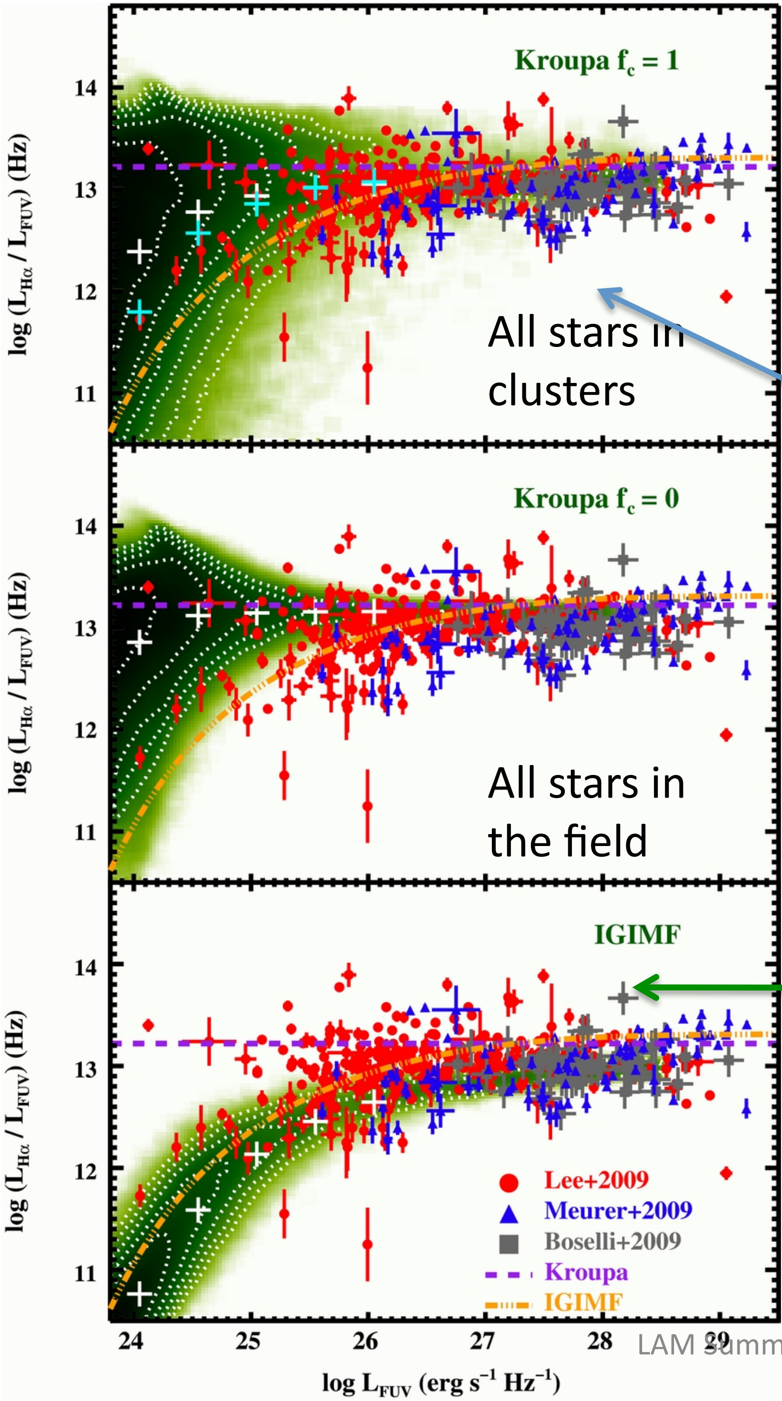



# IMF variations?

Steeper IMF or lower $M_{up}$ (Meurer+09) (see before)

Or other solutions?

*Fumagalli+11*




*Fumagalli+11*:
Joint effects of SFH, Cluster Mass Function and IMF with stochastic sampling
→ Seems to reproduce the dispersion of the data

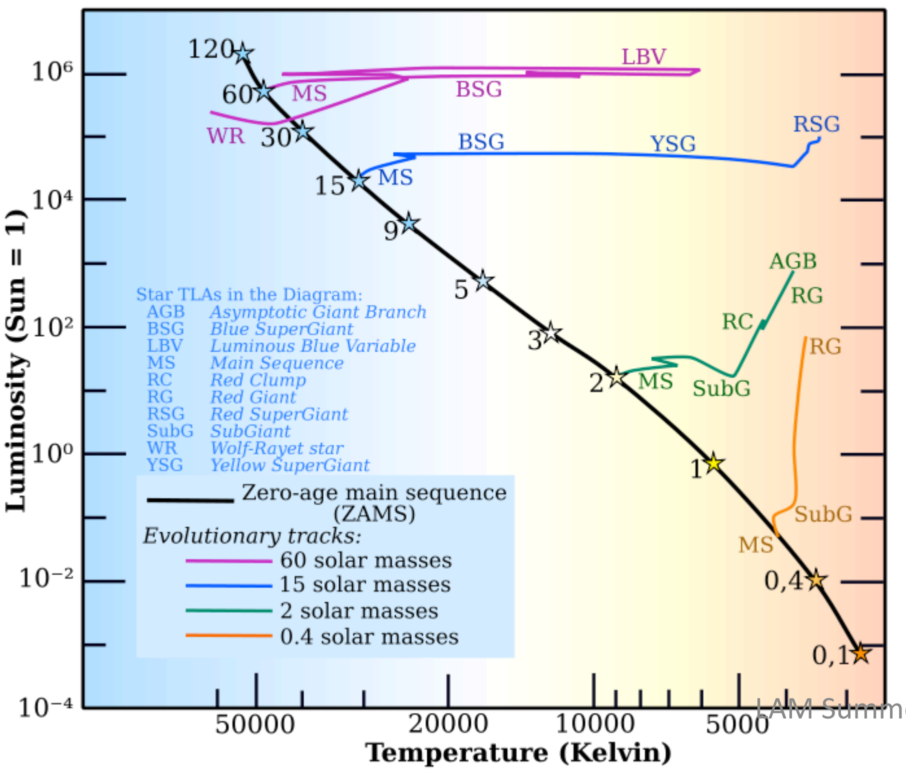
Integrated galactic initial mass function (IGIMF) *(Pflamm-Altenburg+07,+09)*

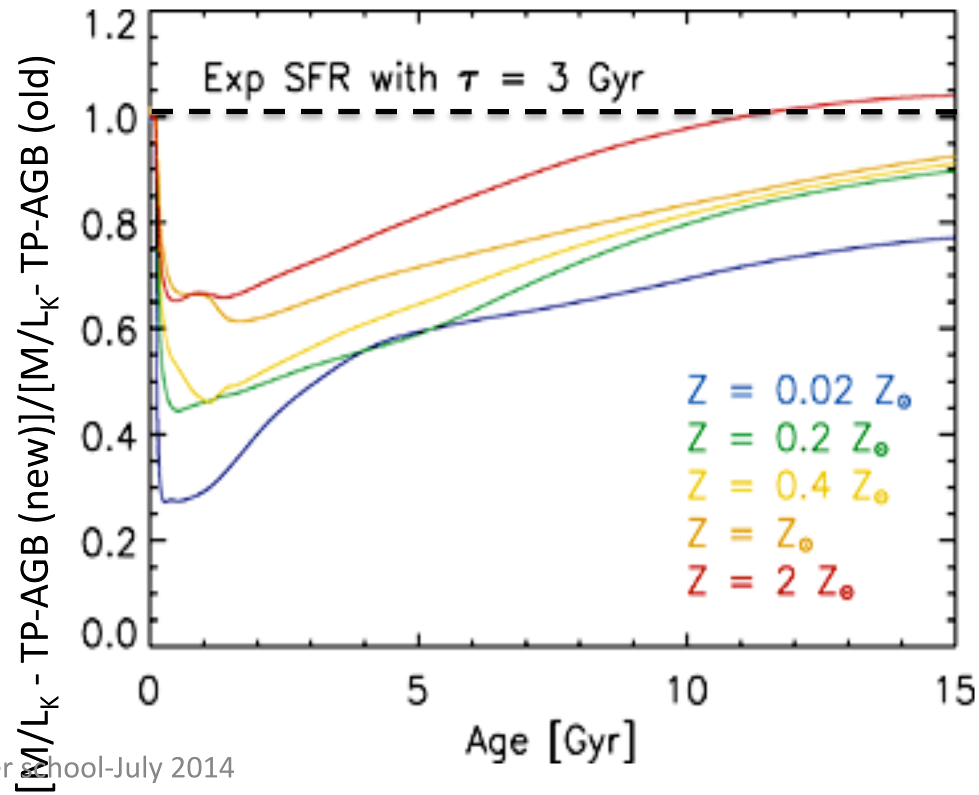
IGIMF: truncation of the IMF and of the Cluster Mass Function:
$M_{max} = f(M_{cl})$ and $M_{cl,max} = f(SFR)$
→ seems to predict too low Hα luminosities

# The case of the TP-AGB
# (Thermal-pulsing asymptotic giant branch) stars

The story: in 2006, Maraston et al. underlined the uncertainty about the TP-AGB phase and the consequences on stellar mass derivations.

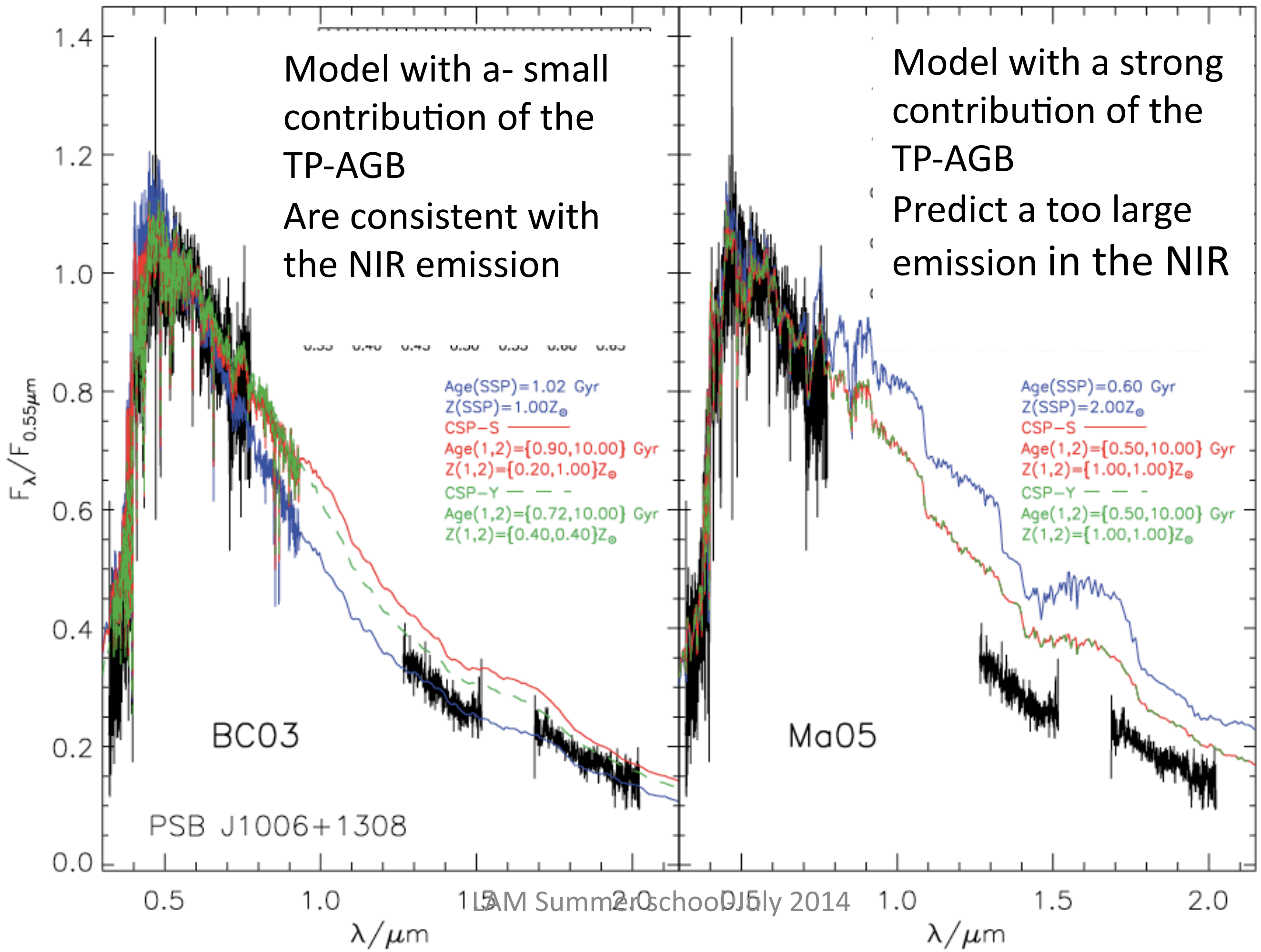
→TP-AGB much more luminous than previously thought for ages between 3 $10^8$ to 2 $10^9$ years
→ may imply lower stellar mass of galaxies by a factor ~2, particularly when NIR data are included (where TP-AGB emit most of their energy)



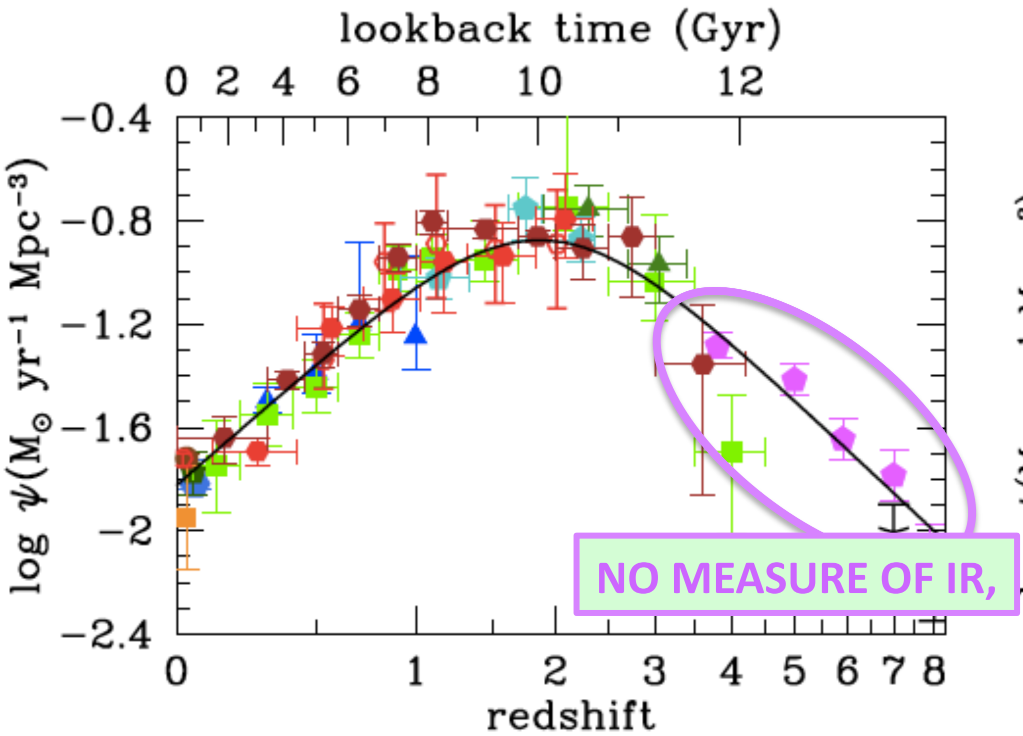



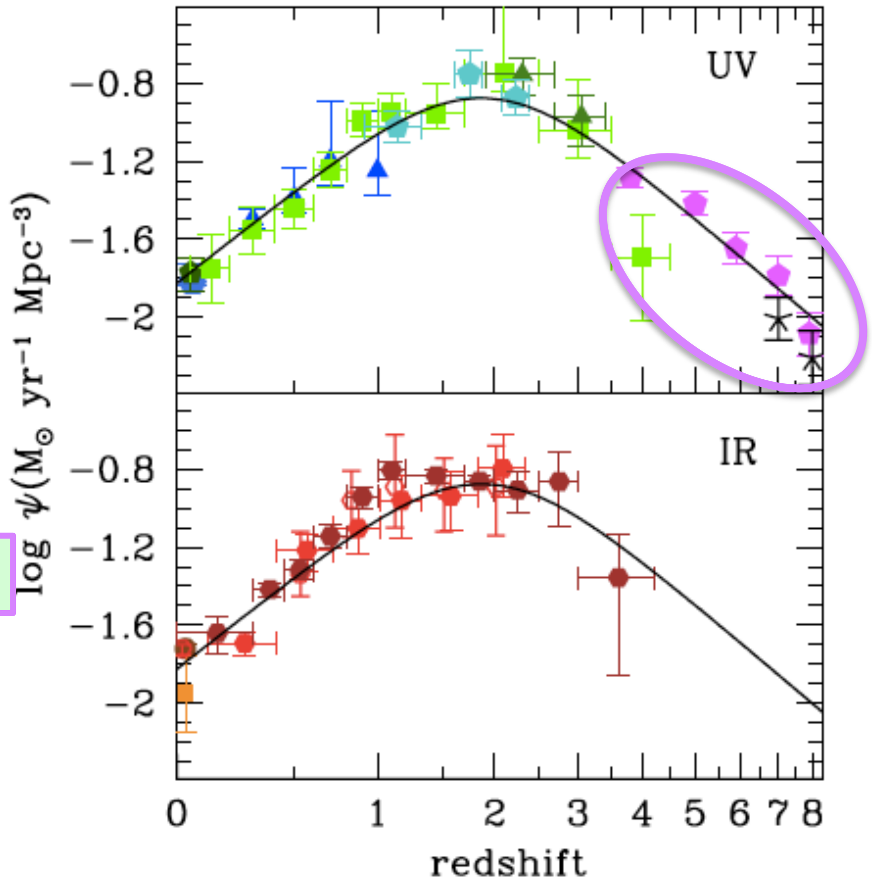
**Post-starburst galaxies: a laboratory to test the influence of TP-AGB**

Galaxies with a recent (< 2 Gyr) burst → no flux boosting in the NIR, prior models with a low contribution of TP-AGB (e.g. Bruzual & Charlot 2003) is now preferred




Zibetti+13




*Madau & Dickinson 2014*