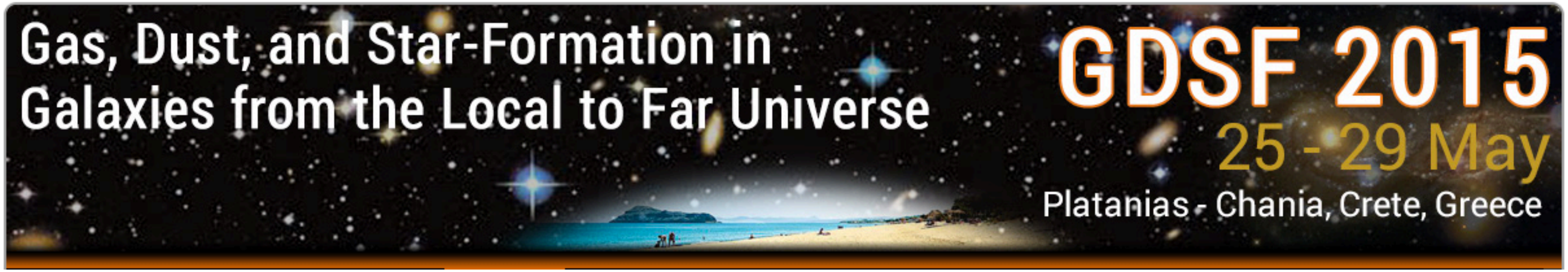

Star formation measurements

Véronique BUAT,
Laboratoire Astrophysique Marseille (LAM)
&
Aix-Marseille University (AMU) , France

Overview

- **General considerations** and calculations, stellar emission and timescales
- **The impact of the star formation history** on SFR determinations

*the different SFH adopted for galaxies at all redshift

*accounting for nebular emission lines.

- **The real world**: **dust absorption & re-emission**

*IR and composite star formation tracers

*Dust attenuation law

*Measuring dust obscuration without IR data

- **SED fitting** to measure SFRs

Some of the topics I will not address

- Tracers other than the stellar light and hydrogen (Hα) recombination lines: [OII]3727, PDR lines [CII]158 [OI]63, radio continuum, gamma ray bursts….
- The impact of varying stellar tracks (rotation, metallicity…), initial mass function

And certainly a lot of other ones……

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A basic equation to derive the SFR (assuming no dust attenuation):

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

$L(\lambda,t)$: Intrinsic luminosity emitted by all the stars of the galaxy

0: t=0 the first stars in the galaxy

$F_\lambda(m,\theta)$: stellar tracks

$SFR(t-\theta)$: Star Formation rate function (M_{sun}/yr)

$\Psi(m)$: Initial Mass Function (IMF) from M_{up} to M_{low},

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- $SFR(t-\theta)$: Star Formation rate function (M_{sun}/yr)
- $\Psi(m)\, dm\, d\theta$: 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:

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

A basic equation to derive the SFR (assuming no dust attenuation):

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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},

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

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

SFR(t)

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)

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

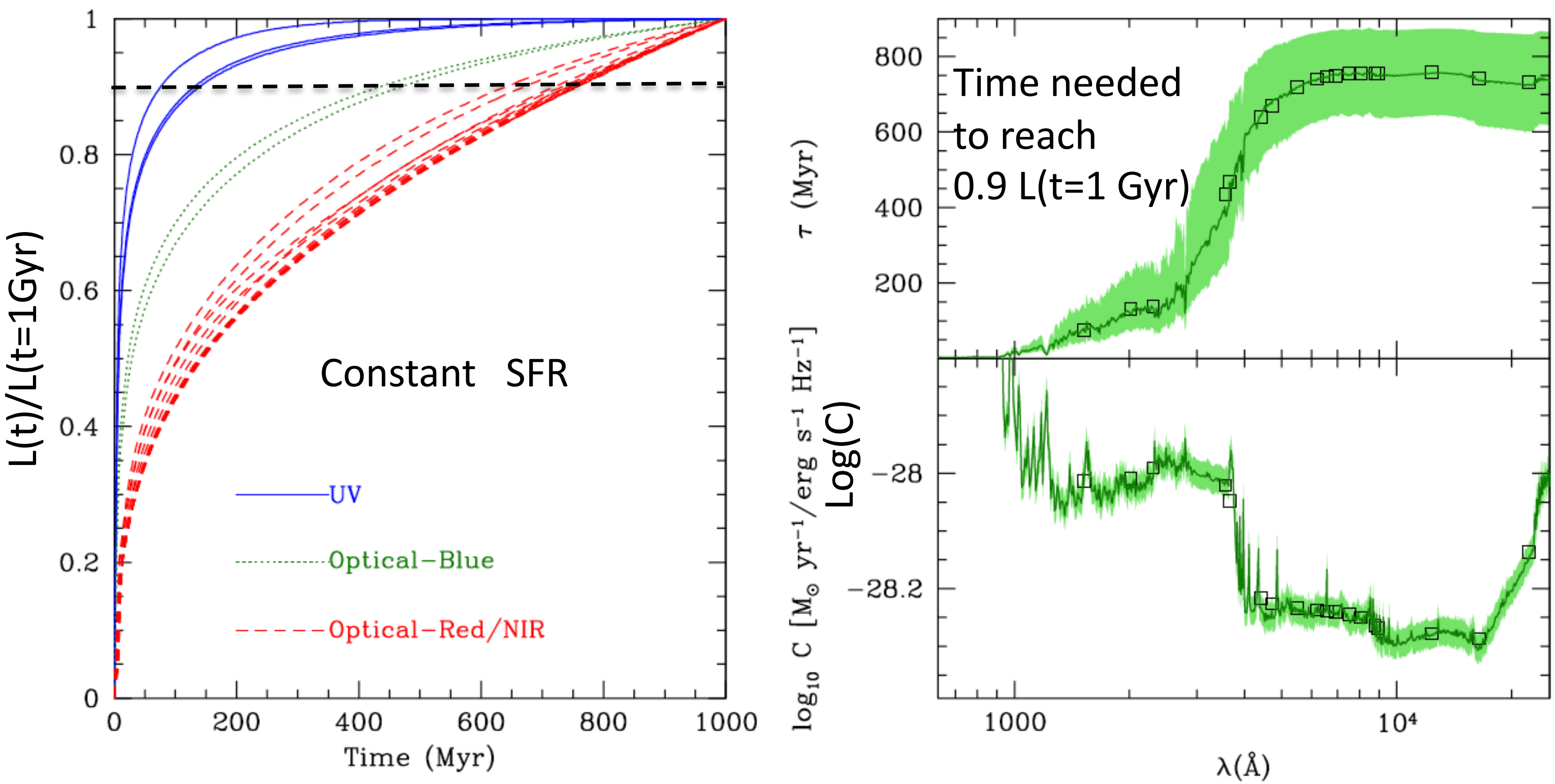
1500-2800 A, Salpeter IMF, >10^8 years of CSFR

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

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

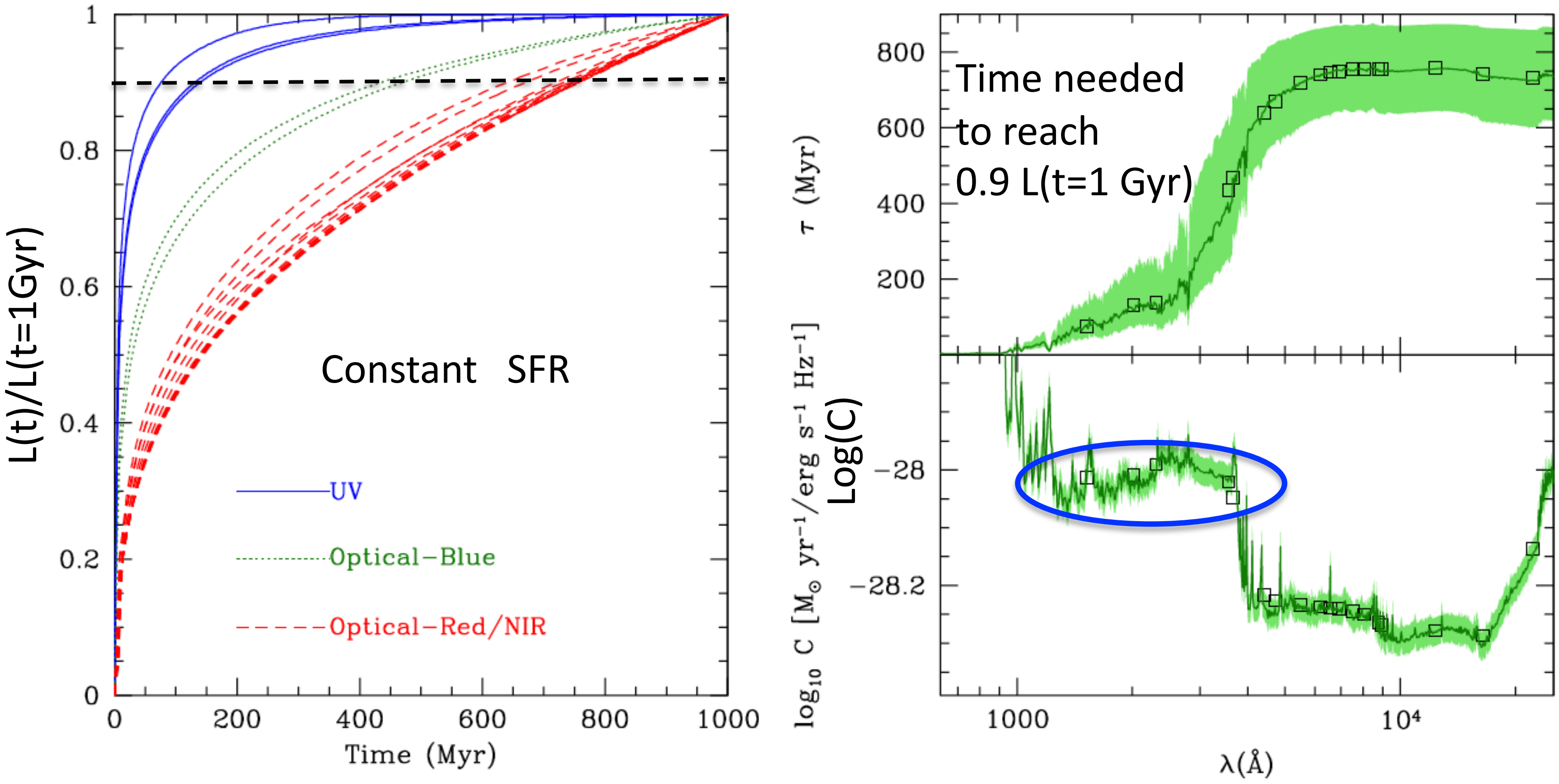
from Kennicutt 1998, ARAA

SFR ($M_\odot$ yr^{-1}) = C L_ν (erg s^{-1} Hz^{-1})



Boissier 2013

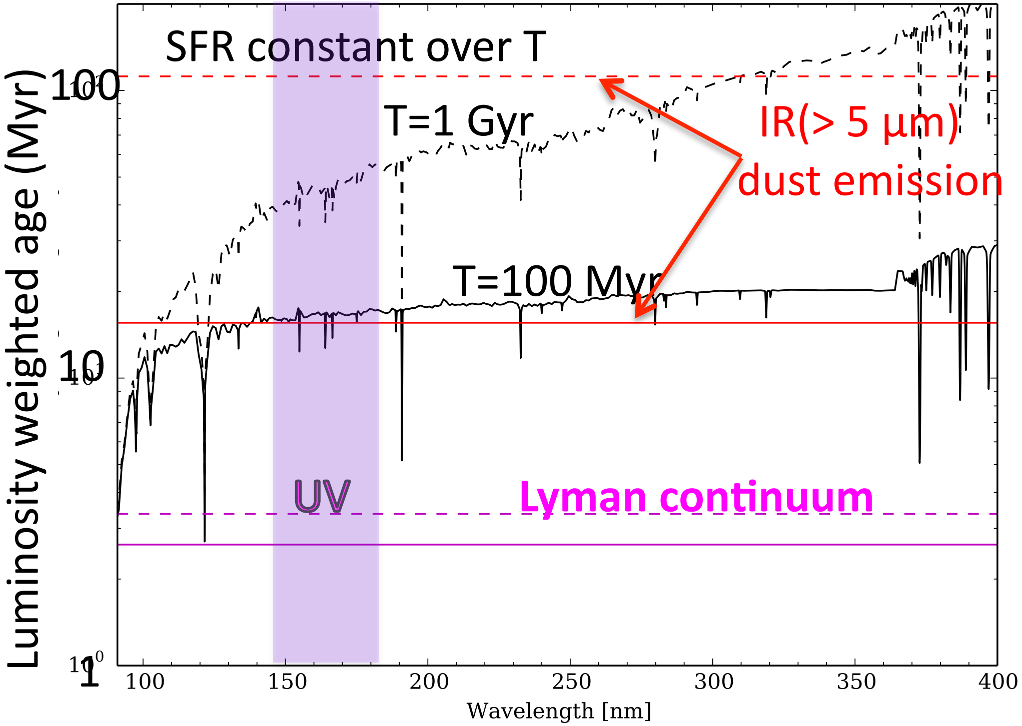
SFR ($M_\odot$ yr^{-1}) = C L_ν (erg s^{-1} Hz^{-1})



Boissier 2013

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

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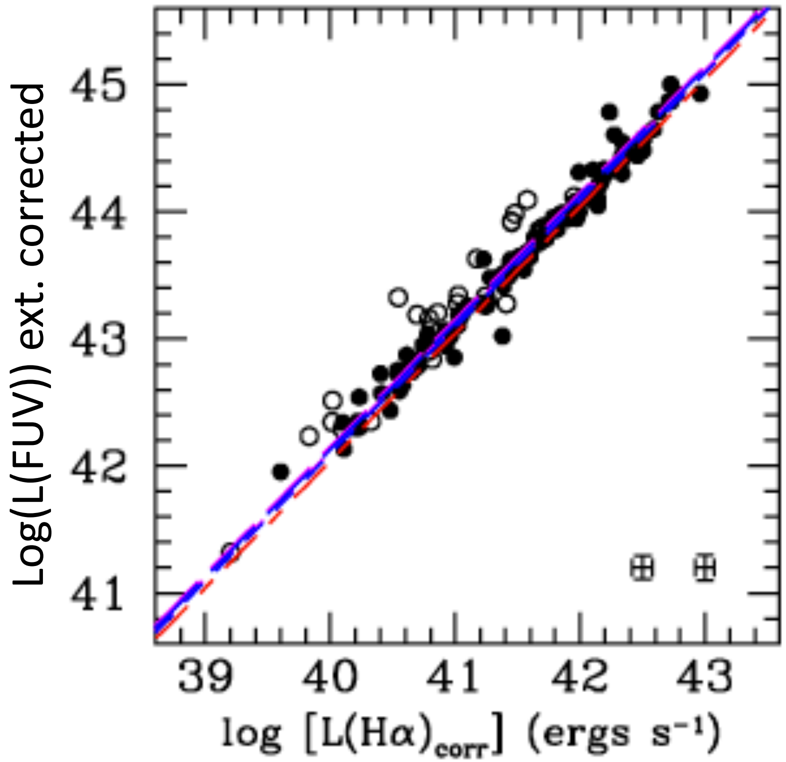
Is a constant SFR a reliable assumption to measure SFR in galaxies?

Probably **YES** for the nearby universe

• SINGS
○ MK06



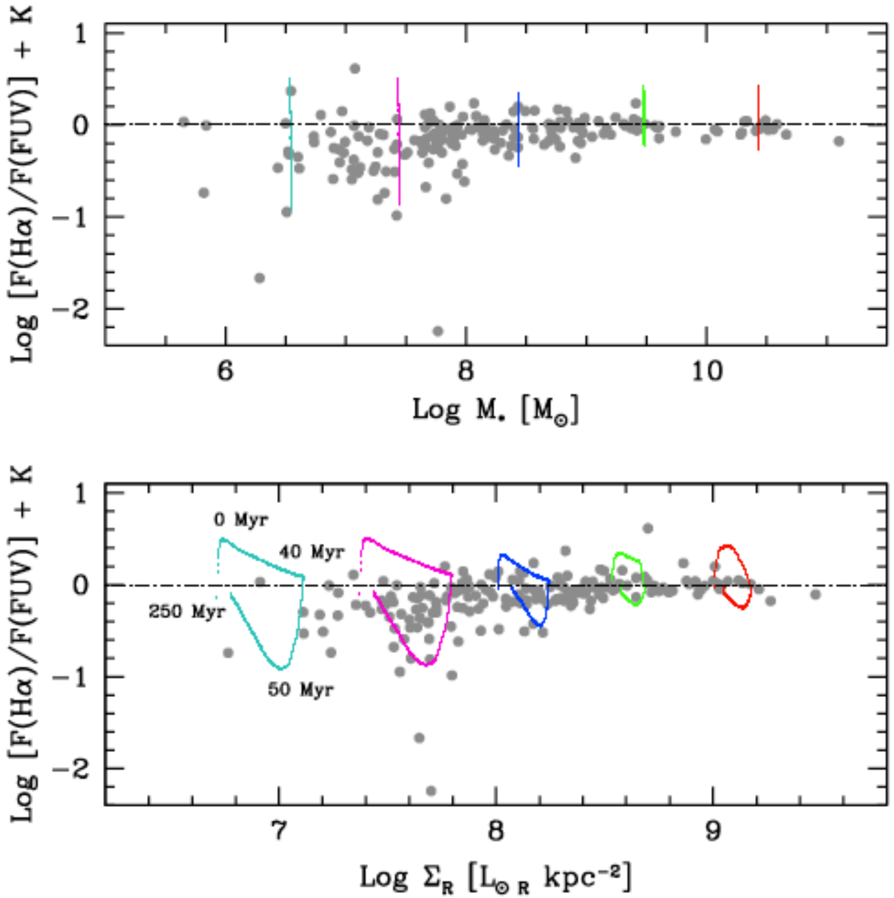
Hao+11

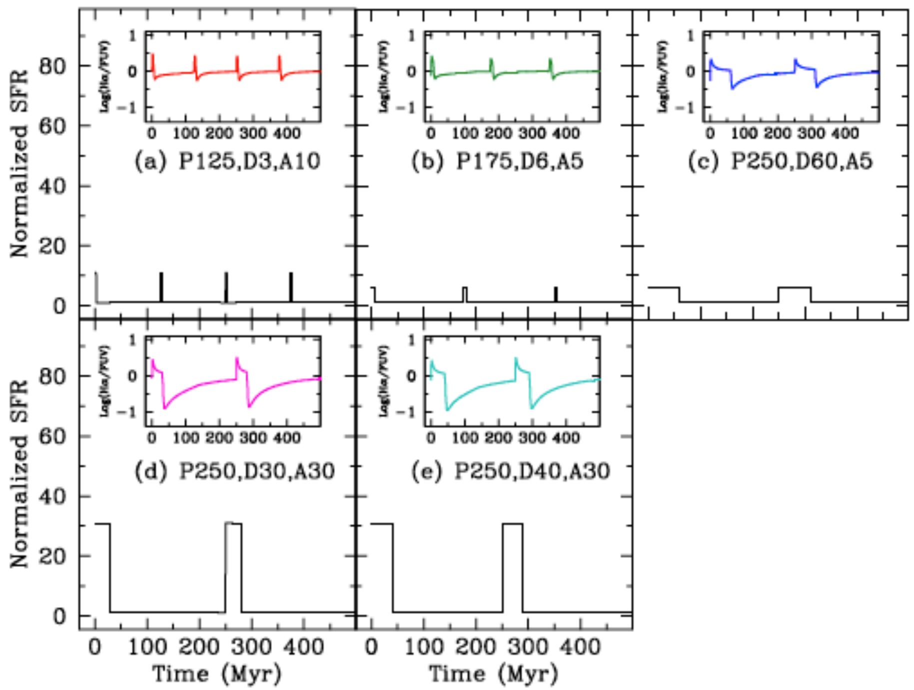
Extinction corrected Hα and FUV luminosities fully consistent with a constant SFR over 100 Myr

But dwarf galaxies: best cases to measure SFH variations,

Weisz+12, Lee+09

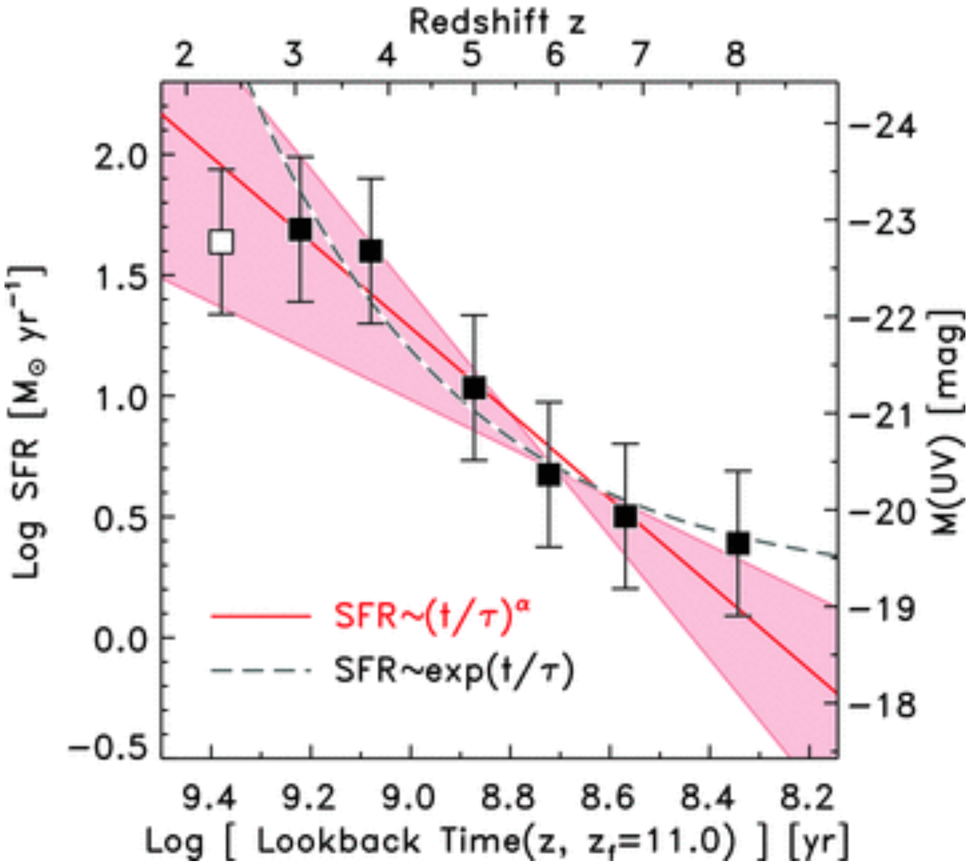
Variations of the SFH seen in Hα/UV ratio:





Star Formation at high z

Some evidence for an increasing star formation at z> 2



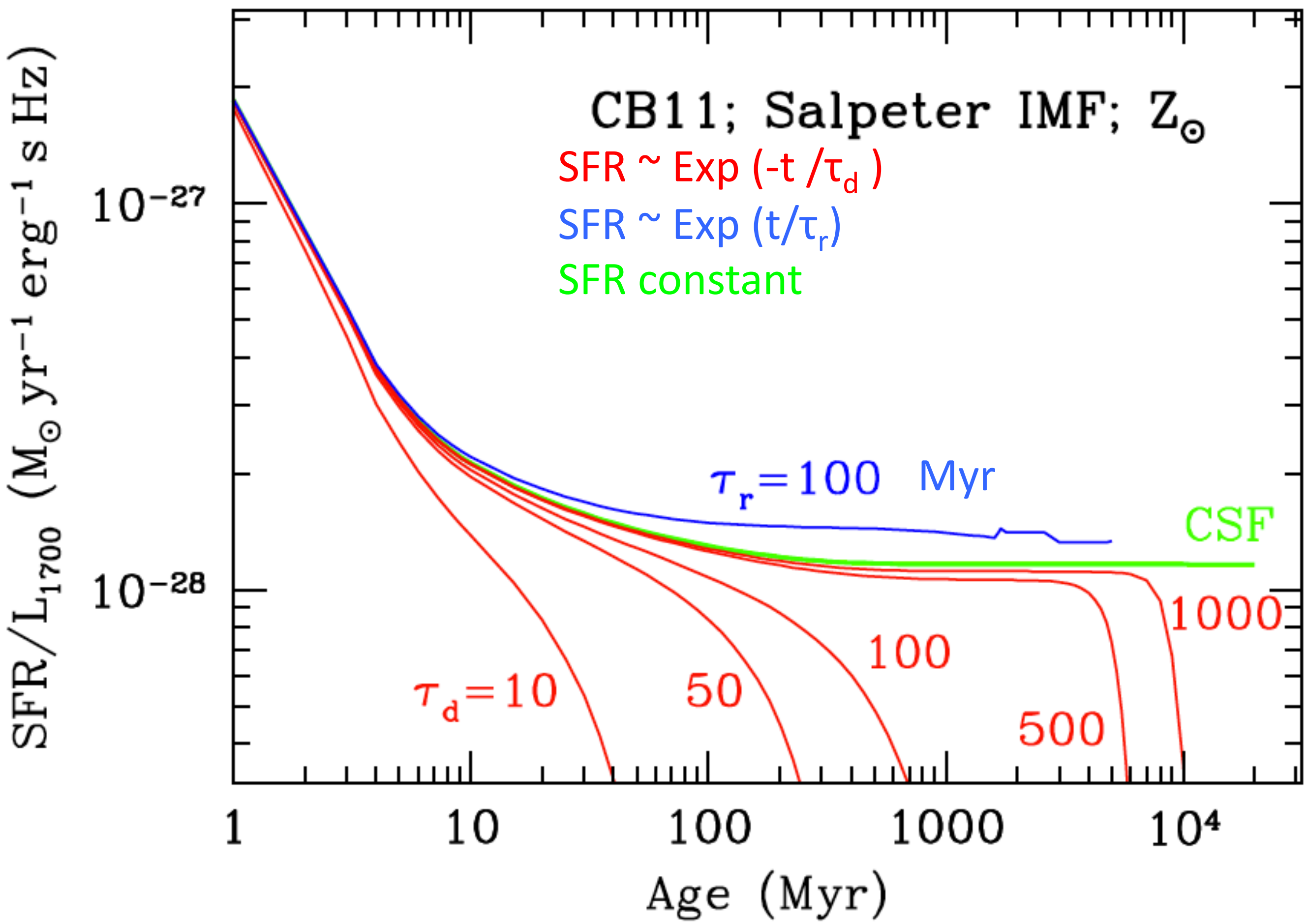
Papovich+11

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)

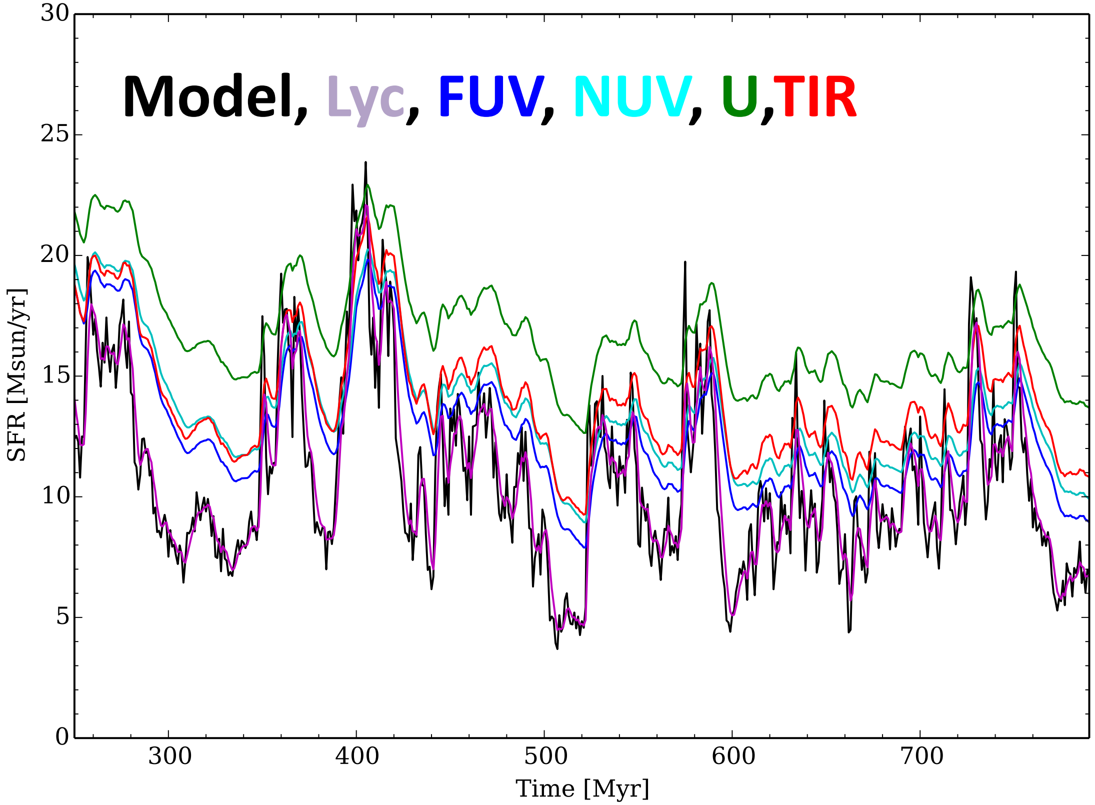
Exponentially decreasing and increasing SFR→ calibration not very different from a CSF for 'realistic' SFH

Reddy+12



Models from MIRAGE hydrodynamical simulations

Boquien, Buat & Perret 2014



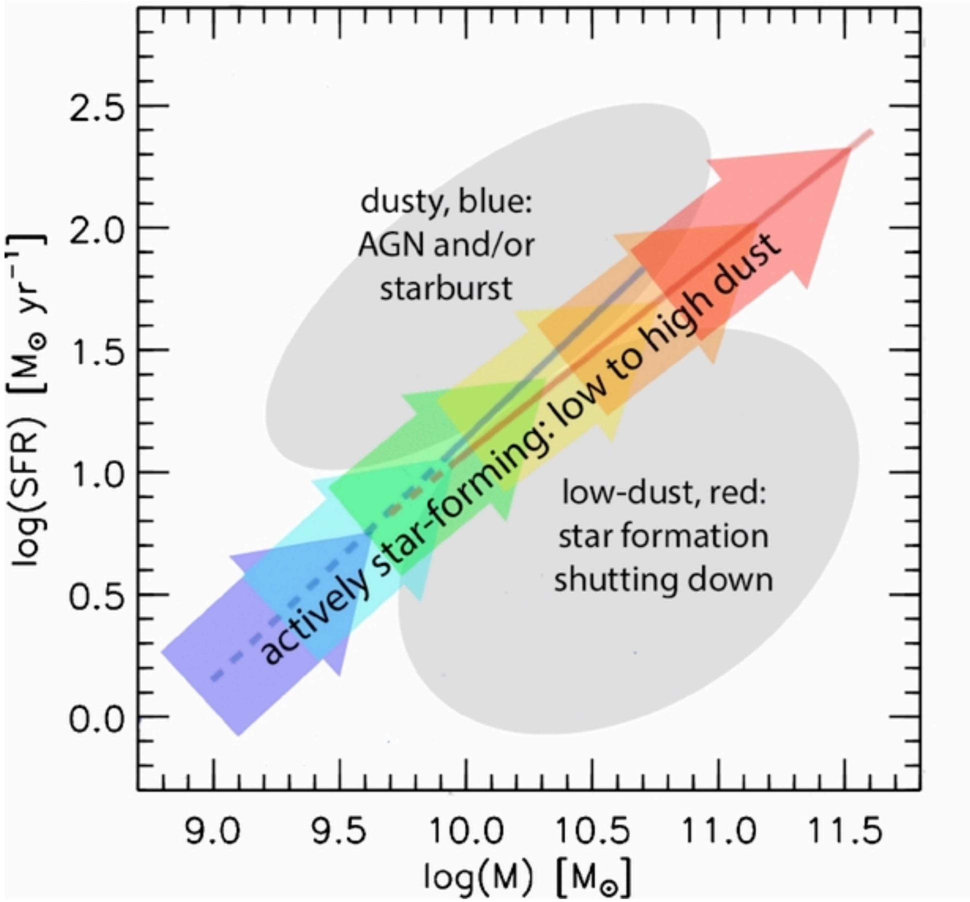
- SFR estimators in **Lyc**, **FUV**, **NUV**, **U**,**TIR,** assuming a **constant SFR over 100 Myr**

- **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

Impact of the SFH on the Main Sequence (SFR-M_{star} relation)

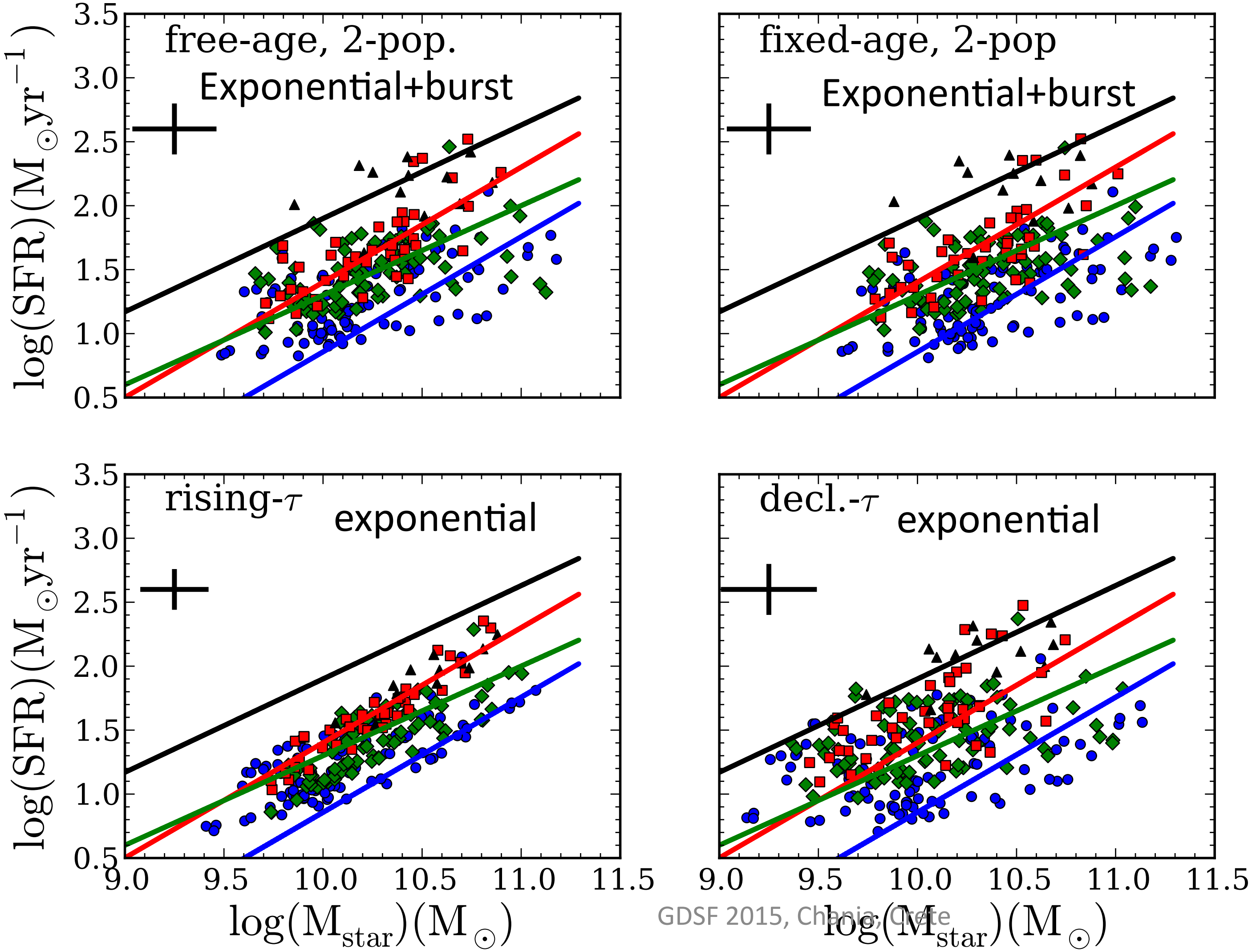


Whitaker+12

The Main Sequence (SFR-M* relation) argue for a smooth evolution of the star formation, only starburst galaxies, above the Main Sequence, may experiment short bursts

Choosing different Star Formation Histories to derive the SFR-M_{star} relation in a consistent way: Impact of the SFH

Buat +14

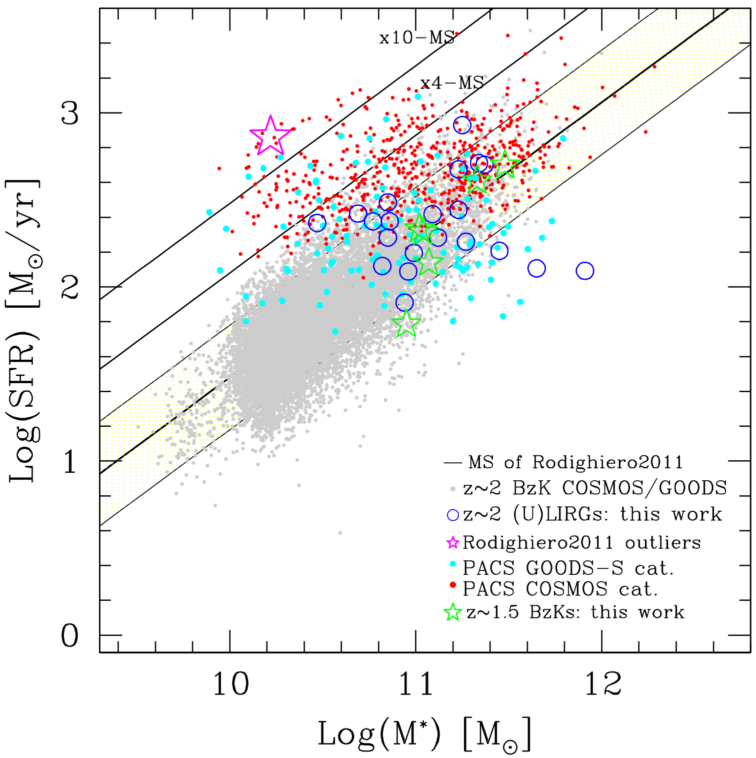


Data:
1<z<1.2:
1.2<z<1.7
1.7<z<2
z>2

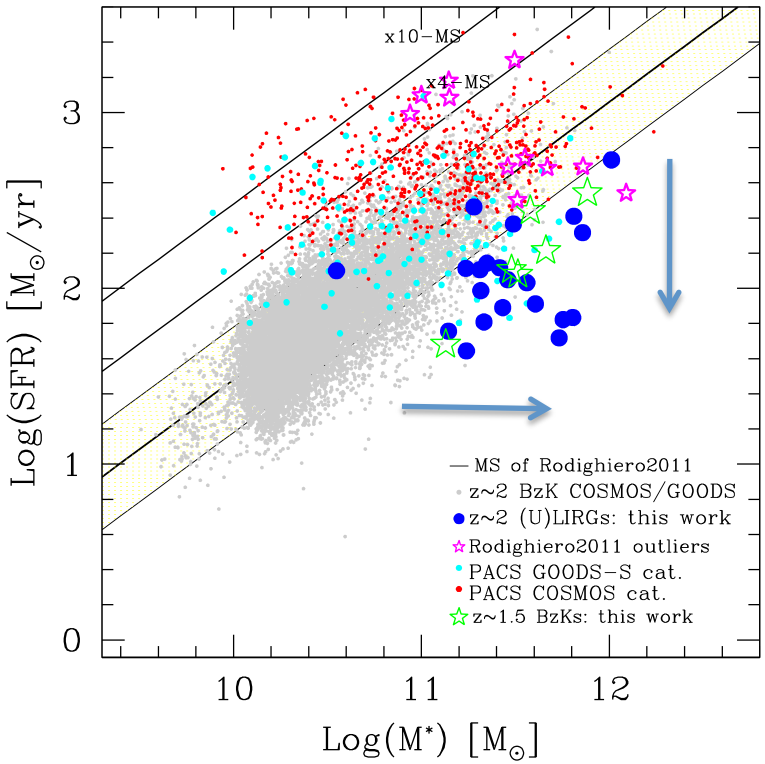
Lines:
Elbaz+07, z=1
Heinis+13 z=1.5
Daddi+07,z=2
Heinis+13; z=3

(U)LIRGs at z~2 analysed with the GRASIL code

Lo Faro (2013/14)



SFR from Kennicutt 98 recipe
M* from HYPERZ

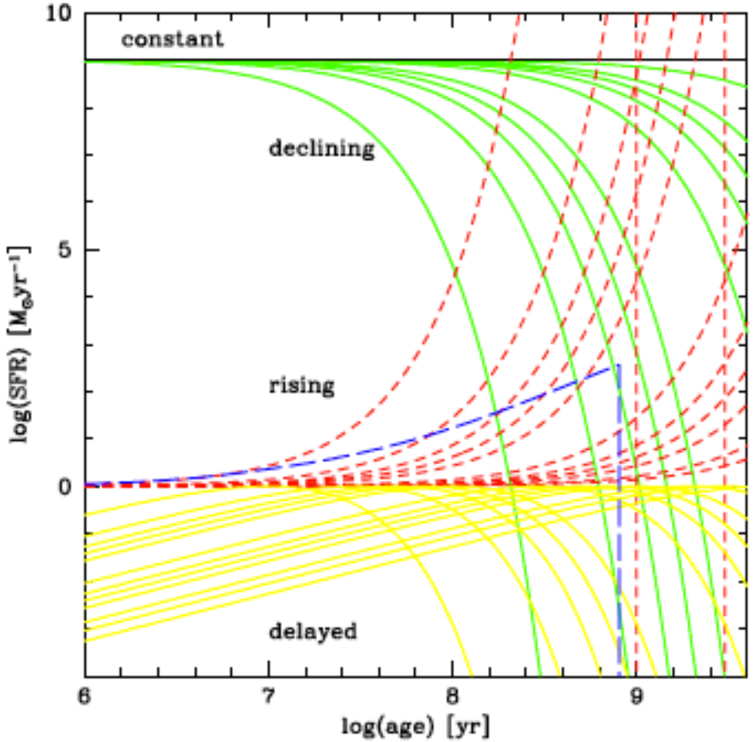


SFR and M* with GRASIL

Star formation history: simple modeling versus 'realistic' simulations

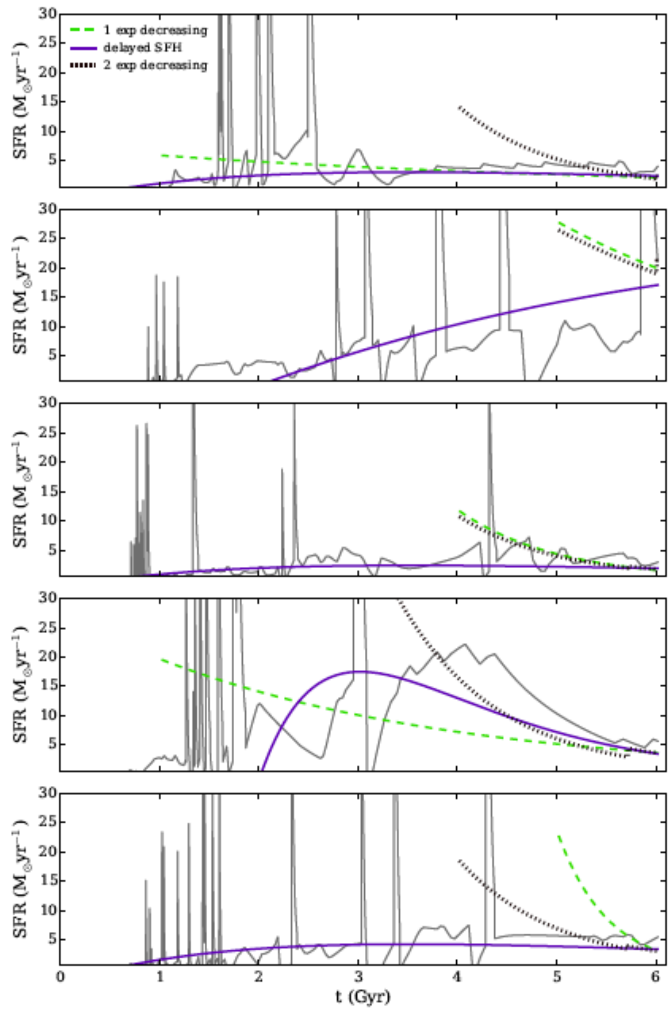
Simple models are usually assumed

Schaerer+14



SFH from numerical models, compared to simple models

Ciesla+15



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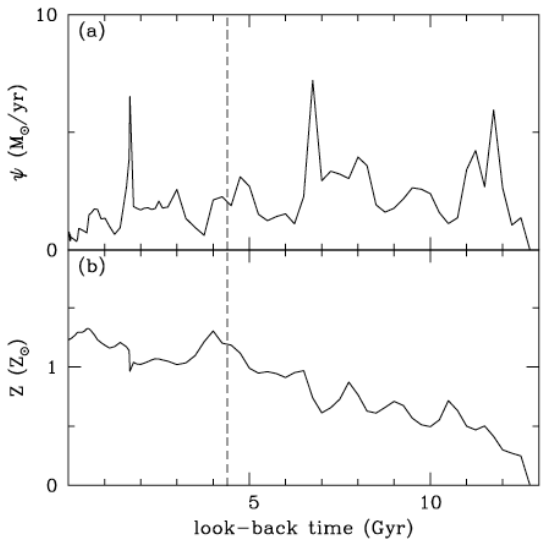
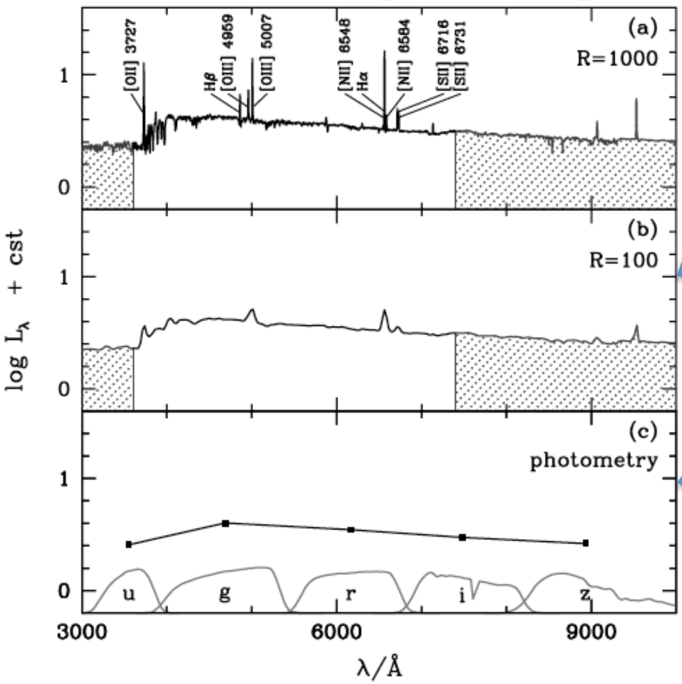
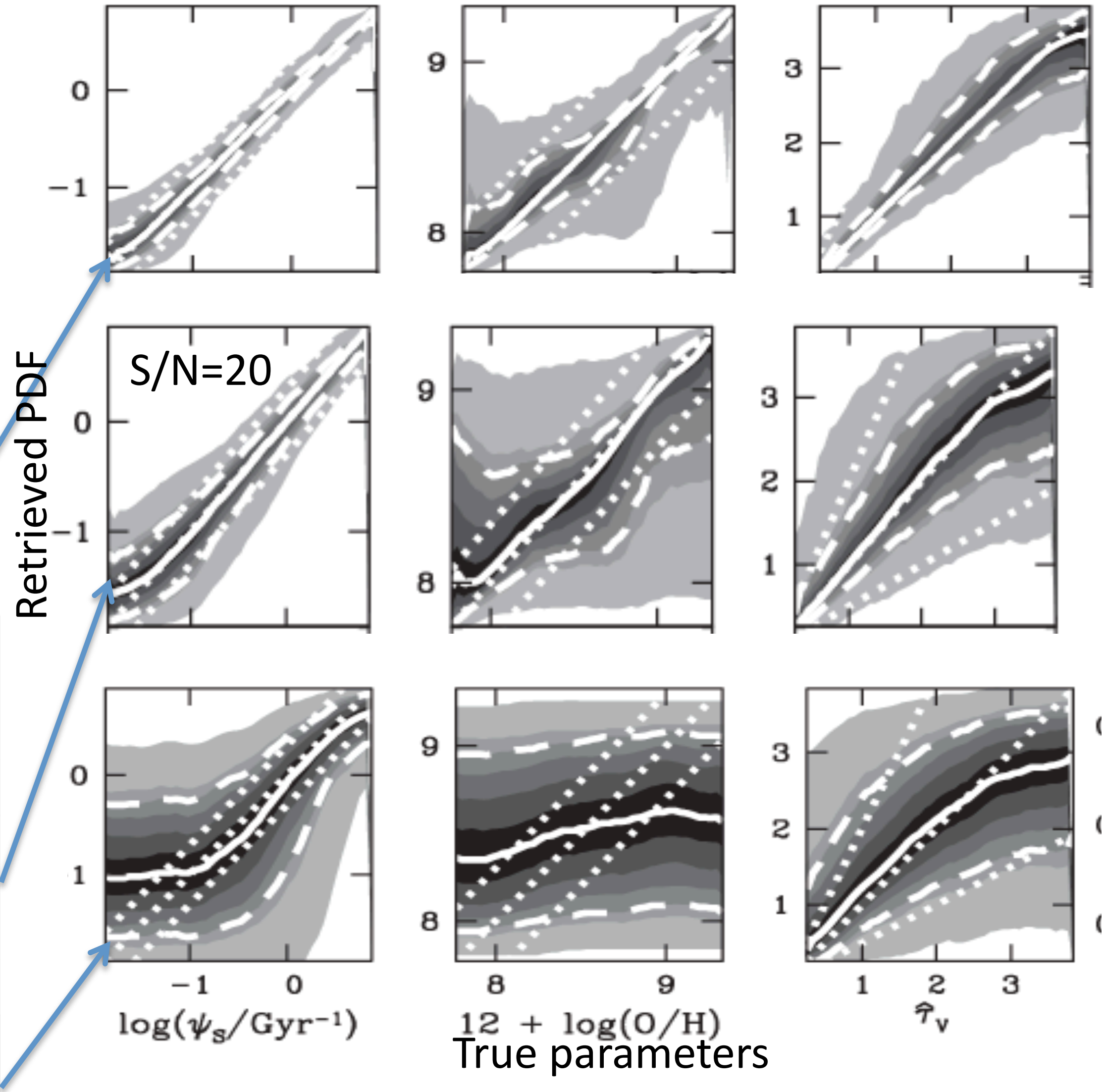
Pacifici+12, **pseudo-observations from Millenium simulations, analysis of SEDs**

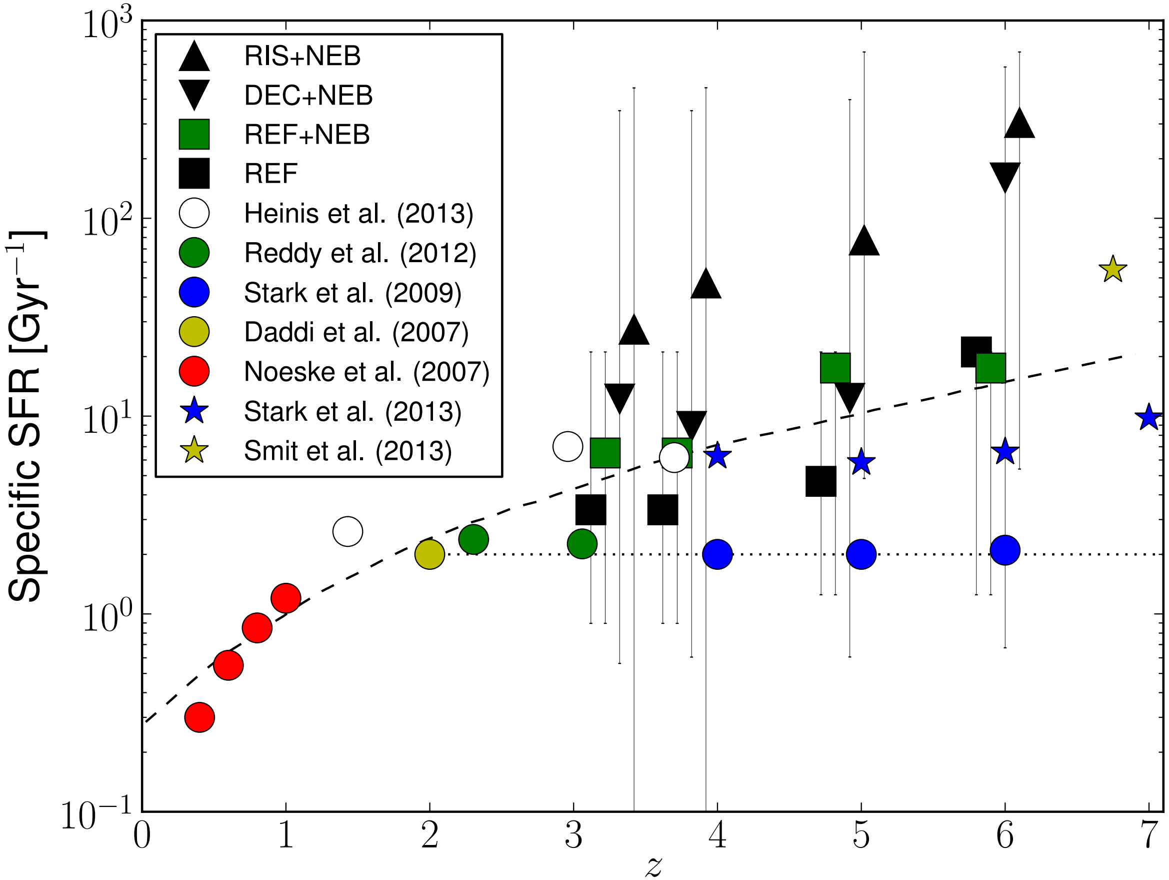






Combining stellar and nebular emissions to fit the data: including nebular emission strongly constrain the estimates

Photometric data at high redshift :
the **presence of emission lines** in the band may strongly modify the measure of the SFR



de Barros+14, see also Stark+13, Gonzalez+13

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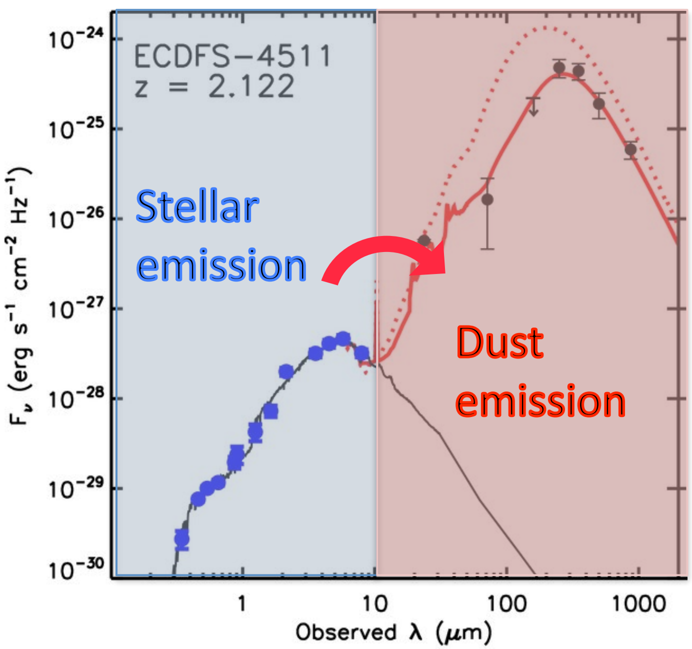
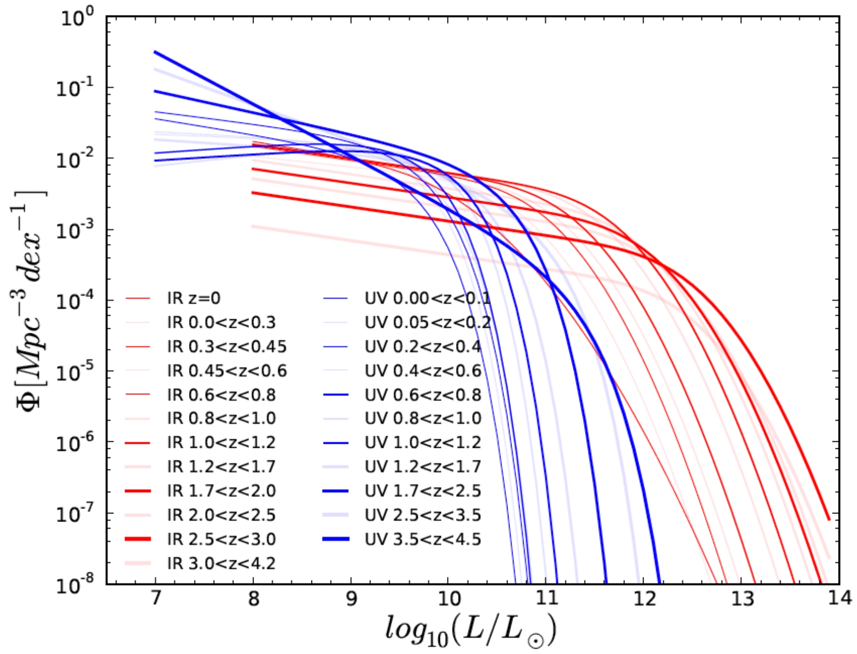
Dust absorption and re-emission in galaxies: general context



Adapted from Muzzin+10

UV and IR luminosity functions strongly differ



Gruppioni+13, Cucciati+12, Burgarella+13

At least half of the SFR is locked in IR at z=0
and the fraction increases with z (up to z~2)
(Takeuchi+06, Burgarella+13)

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

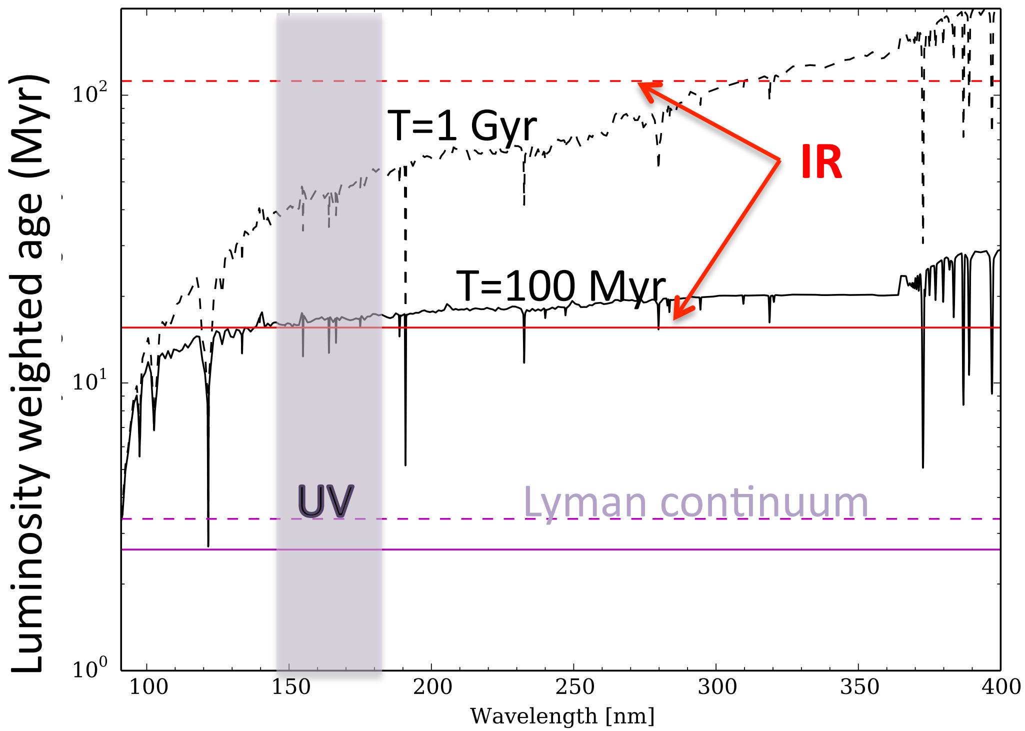
A very strong hypothesis:

complete dust obscuration, dust heating fully due to young stars

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

L_{IR} = L_{bol} (*Kennicutt 98)*

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



Composite tracers: stellar and dust emissions

(Hirashita+04, Iglesias-Paramo+07,Kennicutt+09, Calzetti+07,09,Hao+11, Kennicutt & Evans12, Leroy+09,+12, Zhu+08, Elbaz+07, Daddi+07, Wuyts+11 etc…)

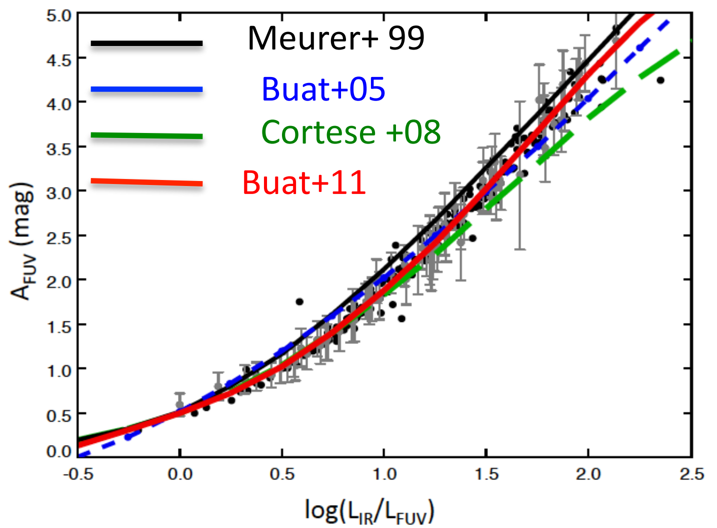
Combining L_{IR} and L_{FUV} would give the total light from young stars.
In a very simplified way we can write:

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

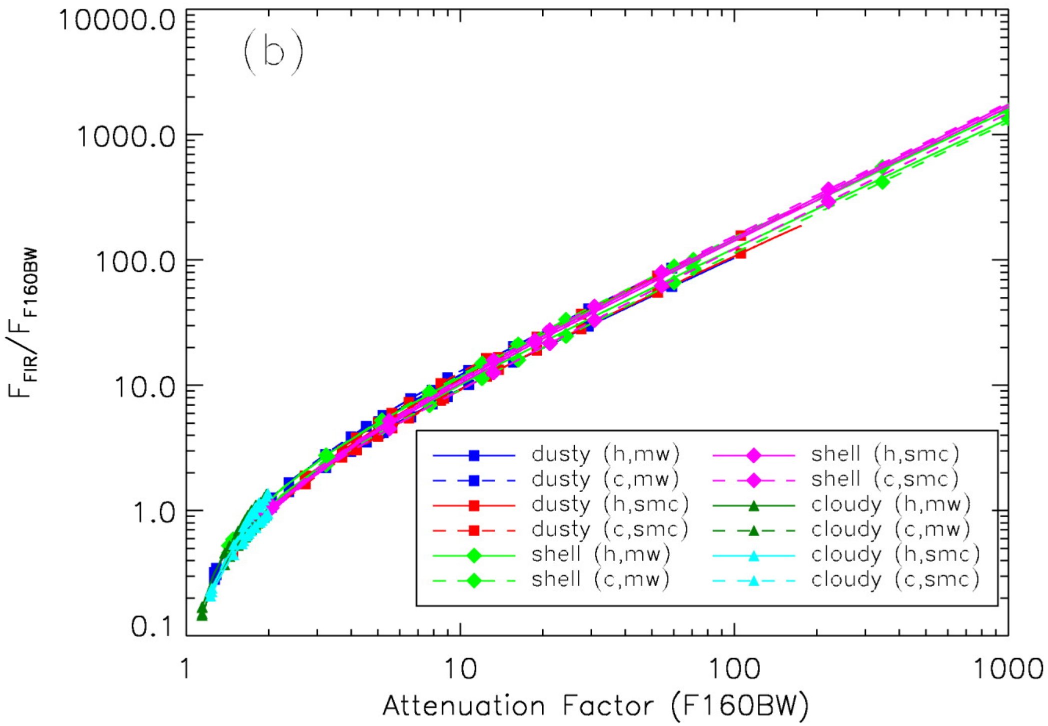
→ $A_{FUV} = f(IRX)$, $IRX = L_{IR}/L_{FUV(obs)}$

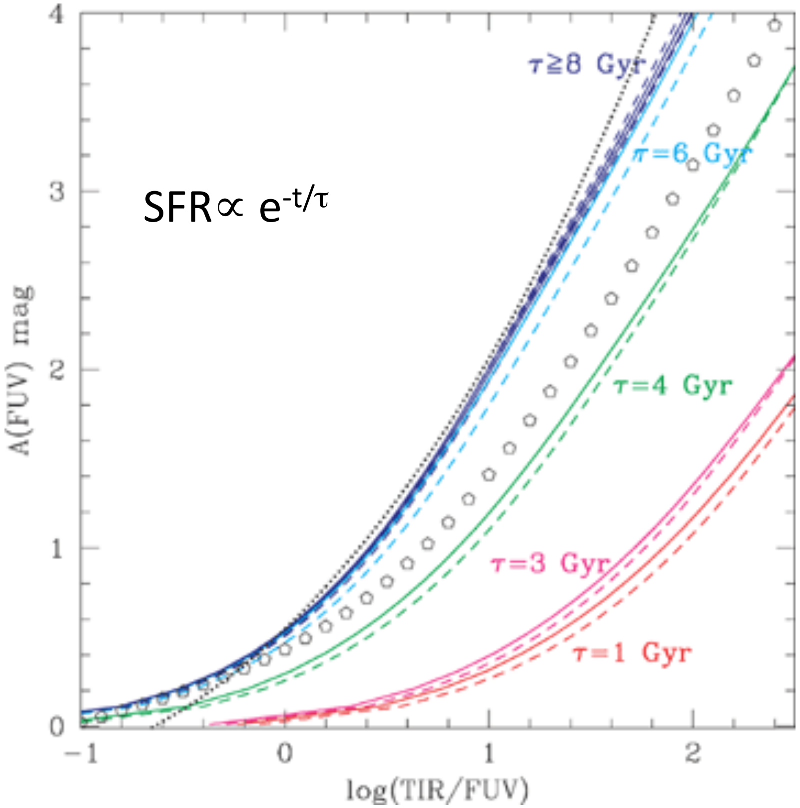
with L_{IR} : 5-1000 μm, $L_{FUV} = \nu.F\nu$ at 150 nm
(e.g. Meurer et al. 99, Buat+05,+11, Cortese+08, Hao et al. 11, Kennicutt & Evans 12)

→ **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

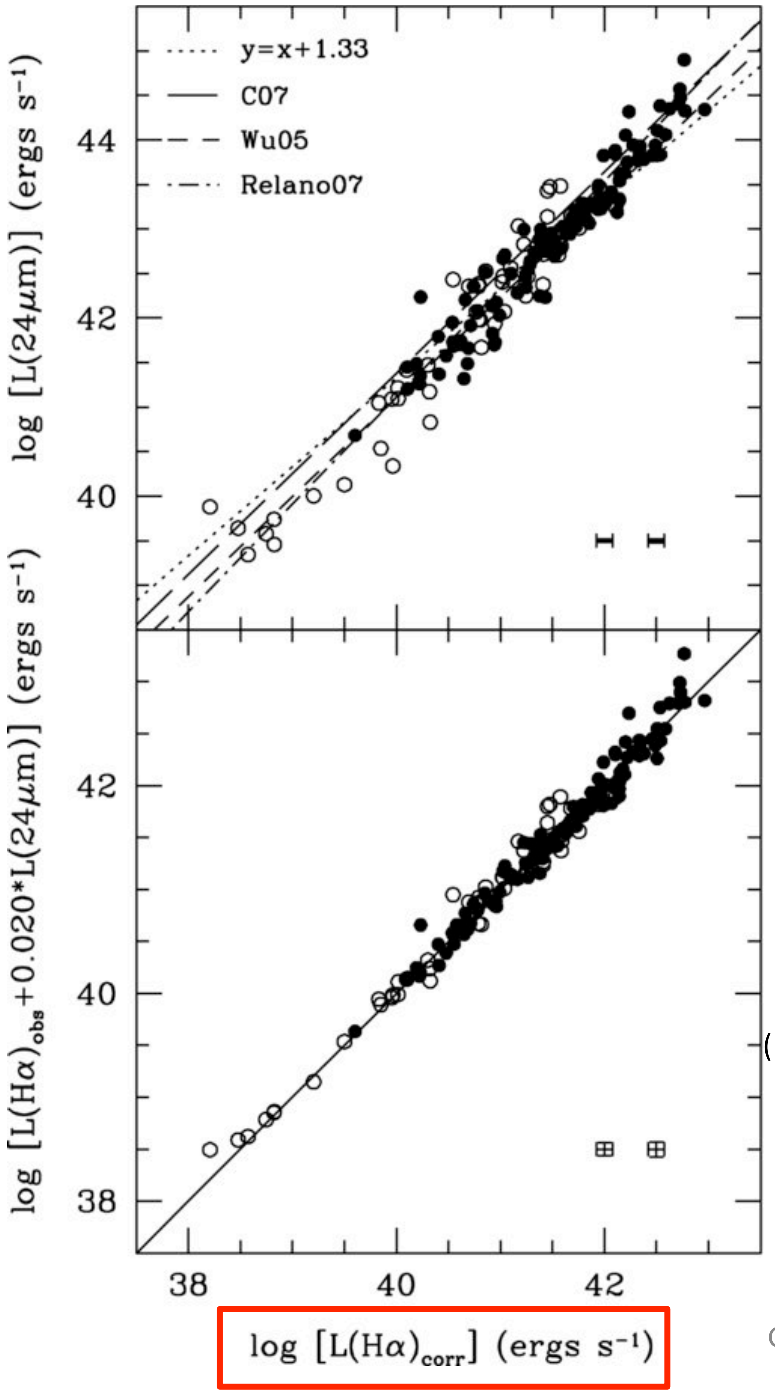




Star forming galaxies and various geometries/dust properties
Gordon et al. 2000

Cortese et al. 08

The calibration depends on the star formation history



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)

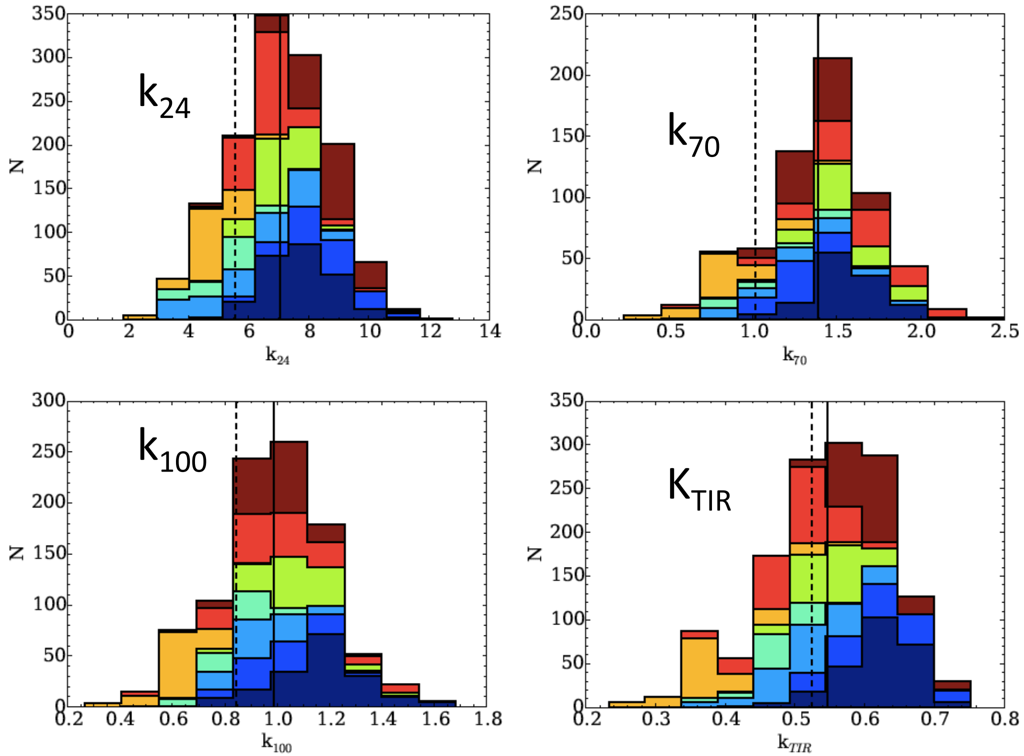
Composite tracer*s: Kennicutt & Evans, 2012, see also Calzetti+07, Zhu+08, Hirashita+03, Bell03, Leroy+08,12*
Monochromatic IR tracers*: Calzetti+05,07,09; Wu+05, Zhu+08, Rieke+09*

Variations of the calibration of composite tracers inside galaxies

Boquien et al, in prep

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

IR=TIR, 24, 70 and 100 μm



k_{IR} increases with sSFR

Values in agreement with measurements of Hao+11 for luminosity weighted means

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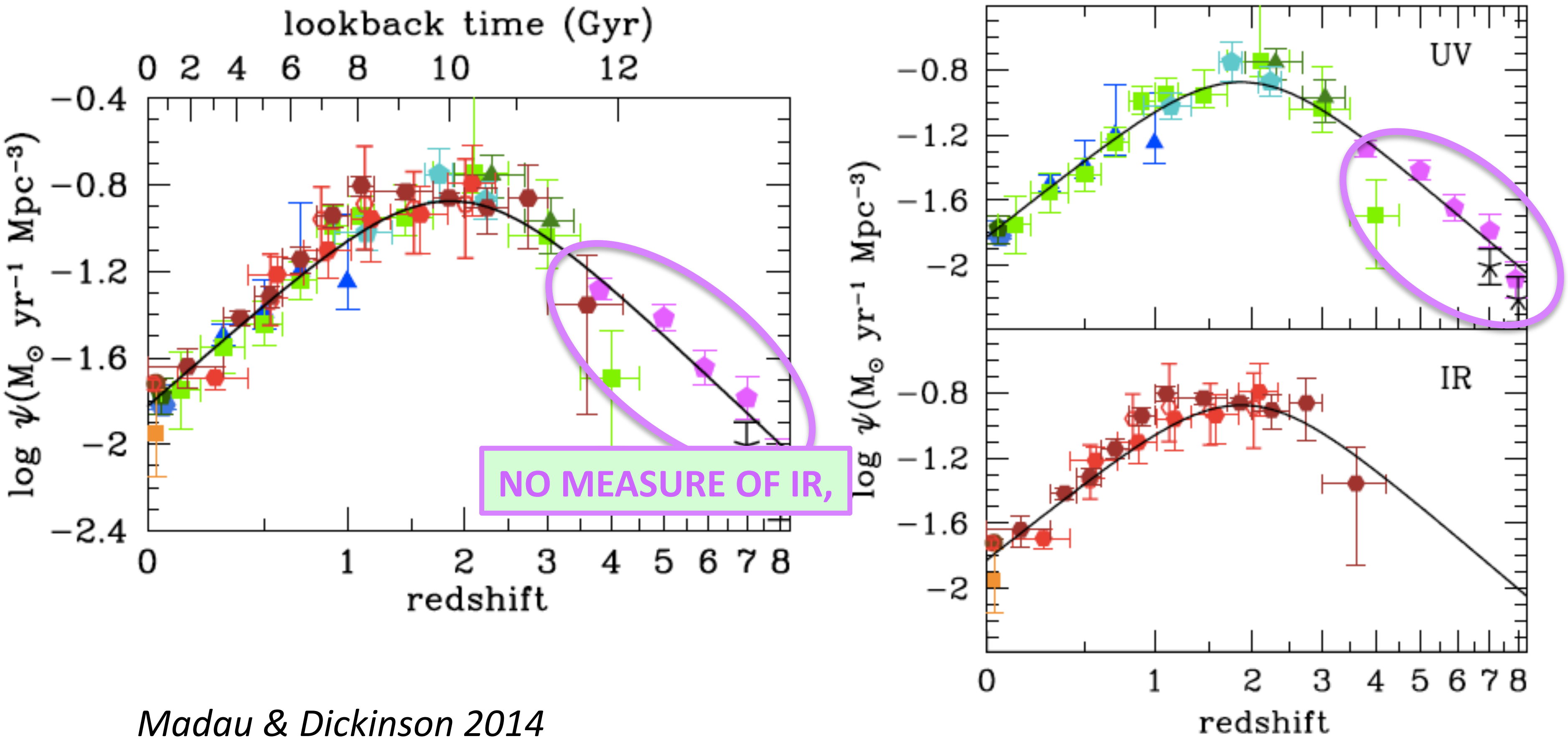


Madau & Dickinson 2014

Measuring dust attenuation without IR data : the slope of the UV continuum

Meurer (+95,+99)

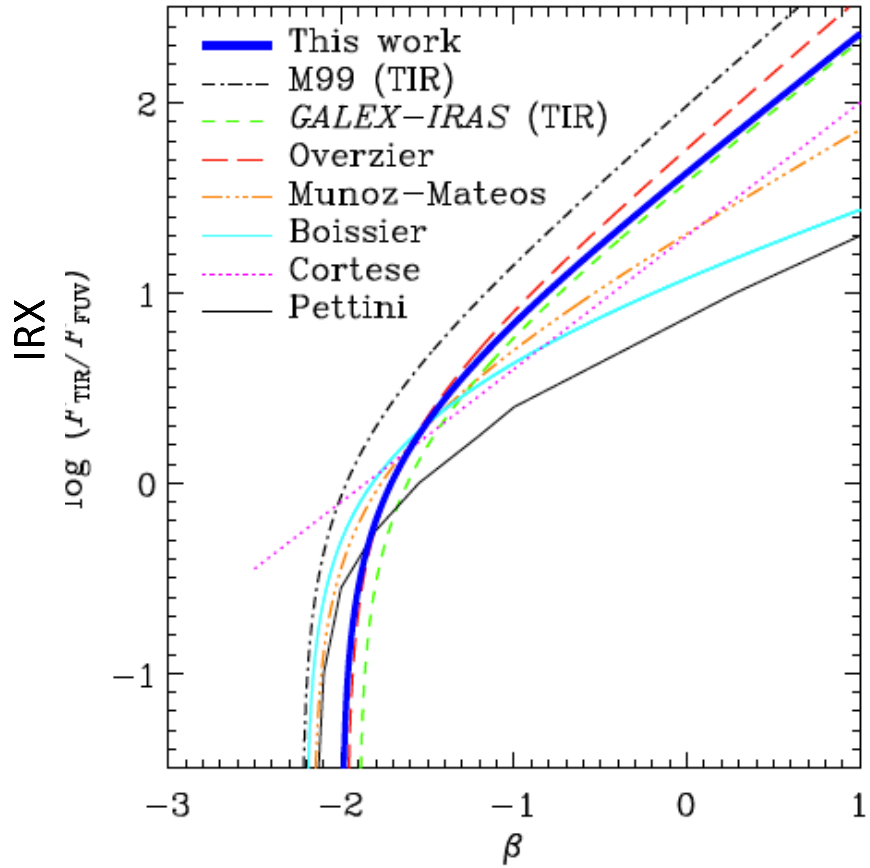
$F_\lambda = \lambda^\beta$ (1200<λ<~2500 A)

IRX for local starburts

Normal star forming galaxies found below the SB law

LIRGs and ULIRGs above the SB law: various ages for the UV emitting populations and/or dust properties?

APERTURE EFFECTS also affect the original relation (Overzier+11, Takeuchi+12)



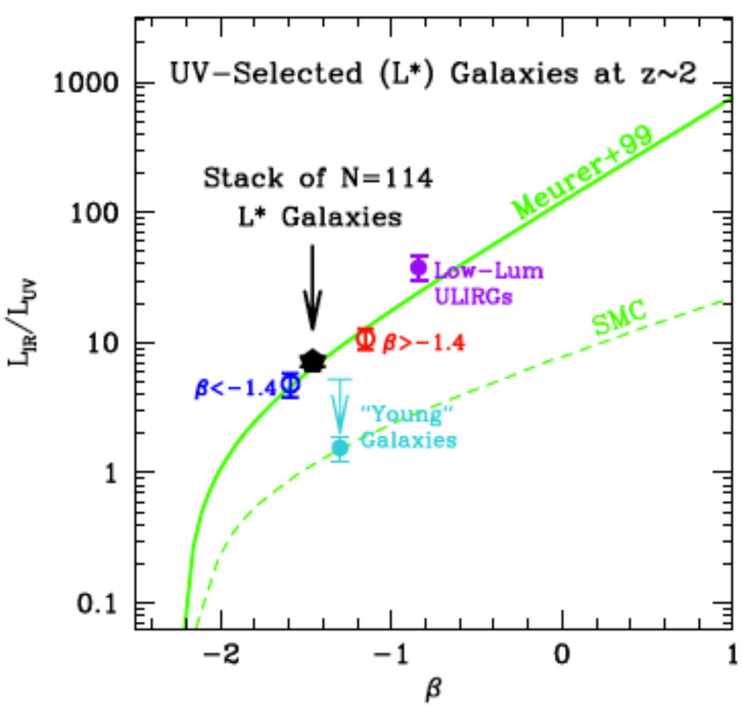
Takeuchi+12

e.g. Meurer+99, Dale+07, +09, Boissier+07, Munoz-Mateos+09, Hao+11, Howell+10, Goldader+02, Buat+05, Overzier+11, Casey+14 etc..

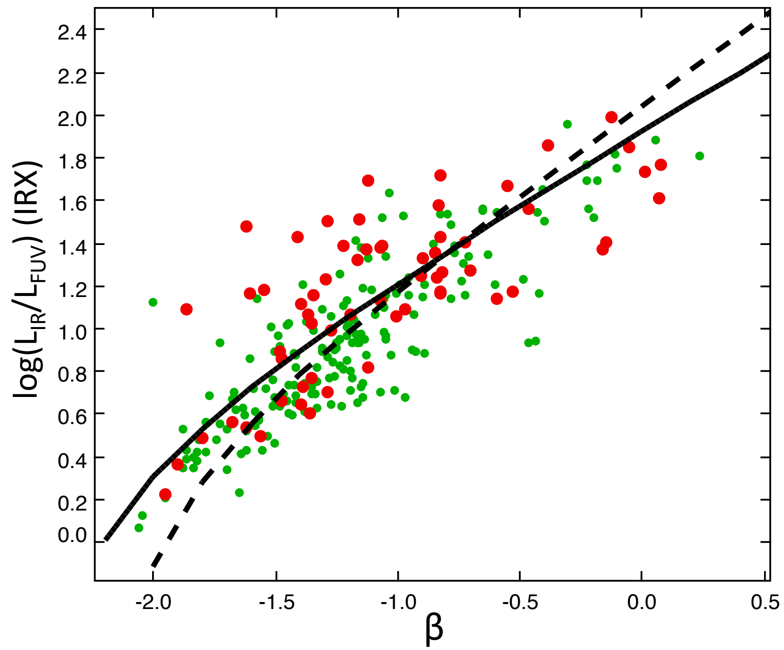
UV selected galaxies at high z

Herschel/PACS data
GOODS-Herschel project

Reddy+12, z=2



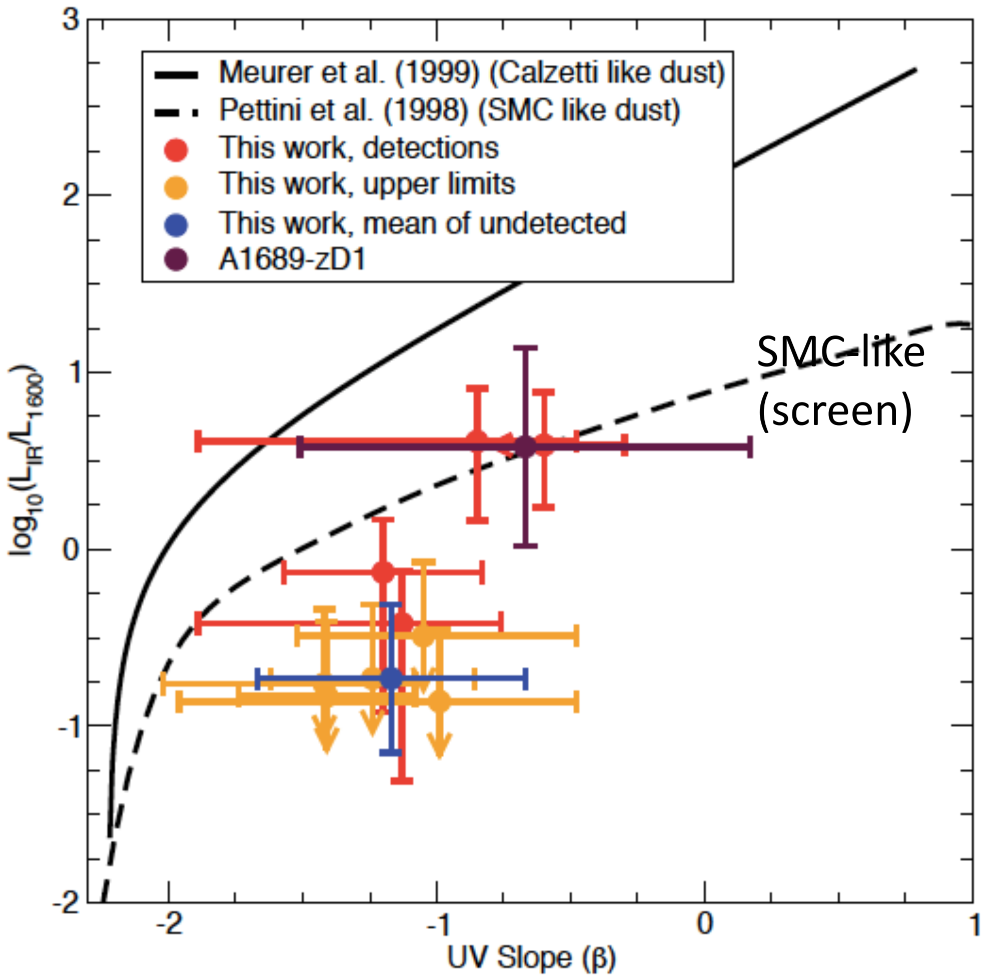
Buat+12 1<z<2



See also *Burgarella+07, Reddy+08*

Capak+15, ***Nature, in press***

Lyman Break Galaxies at z=5-6 observed with ALMA with a very low dust content and not very blue colors……

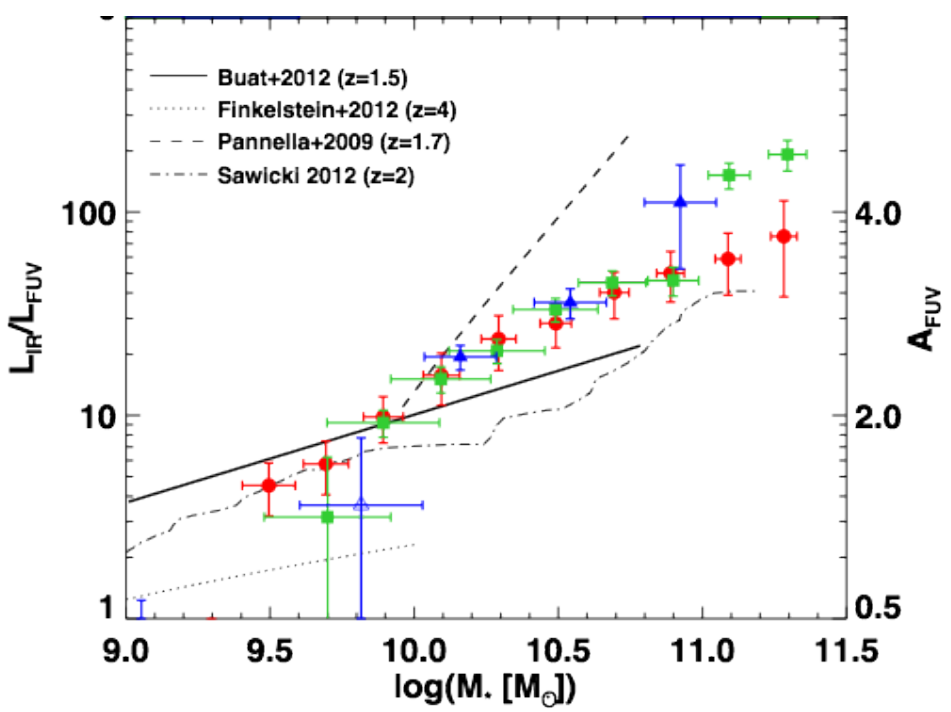


Using the SMC extinction curve instead of the Meurer law

→SFR lower by a factor 2-4 in individual objects (40% for the SFRD)

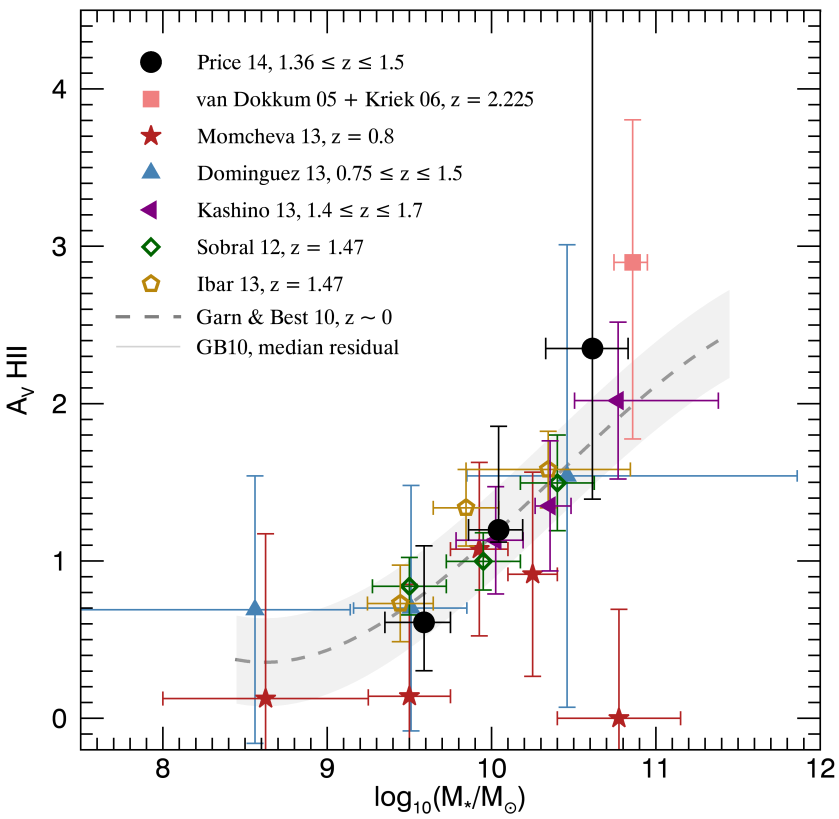
Is there a universal Attenuation-Stellar mass relation?

UV continuum



Heinis+14, see also Pannella +14

Nebular lines



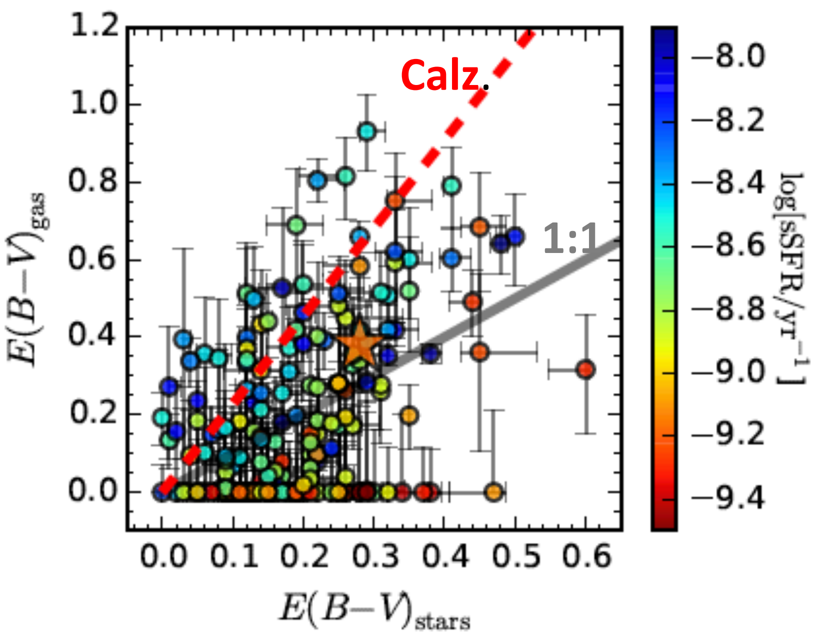
Price+14

Linking the amount of attenuation in the emission lines and the stellar continuum

A differential attenuation in galaxies:
ionized gas more attenuated than stellar continuum

$\boldsymbol{E(B\text{-}V)_s = 0.44\, E(B\text{-}V)_g}$ *Calzetti 97, Calzetti 01*

Various estimates at high redshift, inhomogeneous methods used to apply the Calzetti's recipe (*Kashino+13, Price+14, Reddy+15*)



Reddy+15

Large scatter…
$E(B\text{-}V)_{gas}$-$E(B\text{-}V)_{star}$ may vary with SFR (increase), sSFR (Reddy+15, Price+14)

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- **The impact of the star formation history** on SFR determinations

*the different SFH adopted for galaxies at all redshift

*accounting for nebular emission lines.

- **The real world: dust absorption & re-emission**

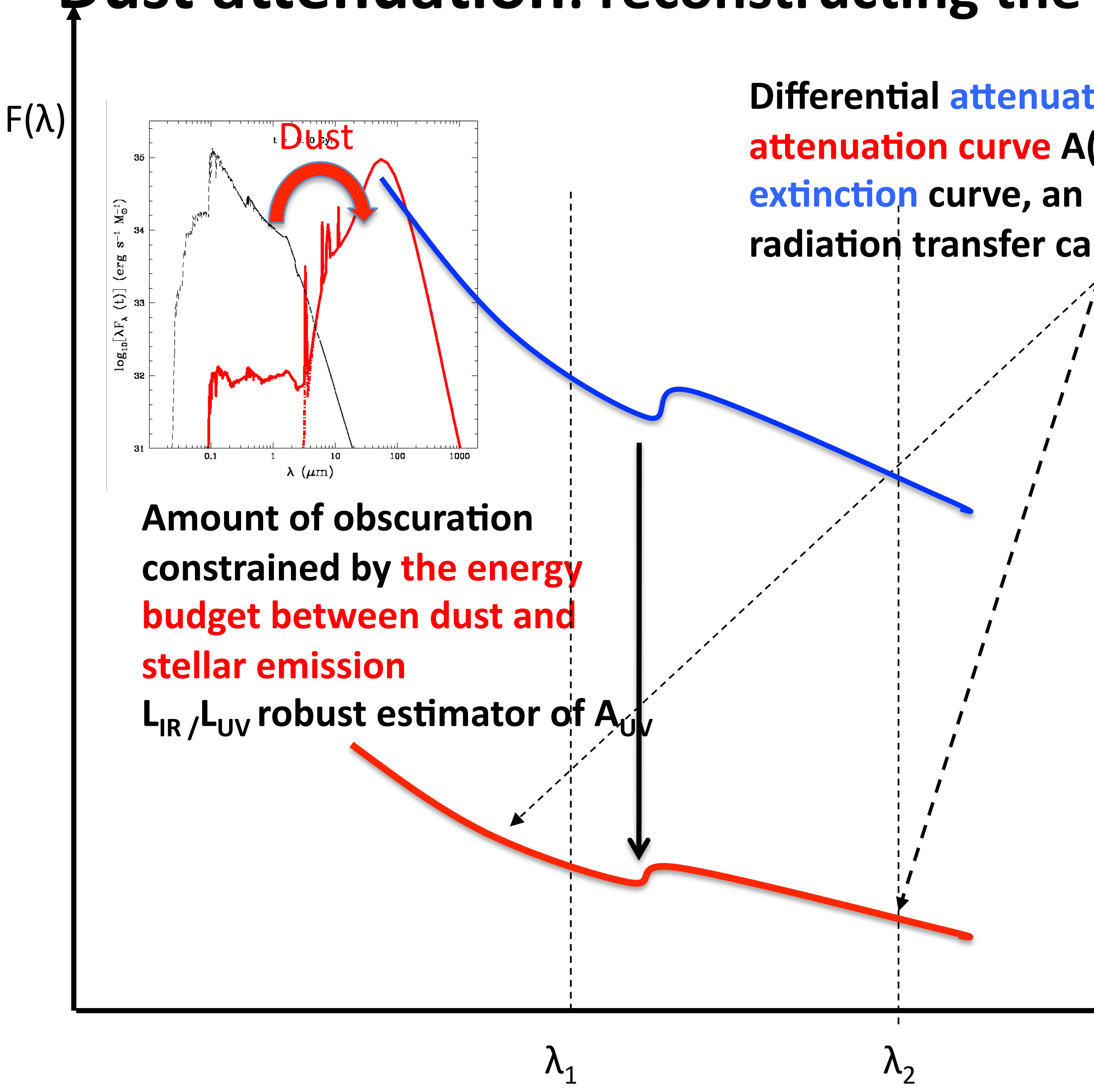
*IR and composite star formation tracers

*Measuring dust obscuration without IR data

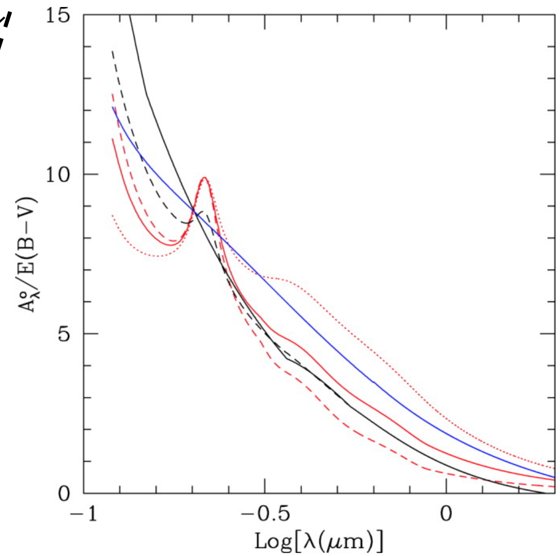
***Dust attenuation law**

- **SED fitting** to measure SFRs

Dust attenuation: reconstructing the SED (mainly in UV)



Differential attenuation characterized by the attenuation curve A(λ)/E(B-V) or an extinction curve, an adopted geometry and radiation transfer calculations



Calzetti 01

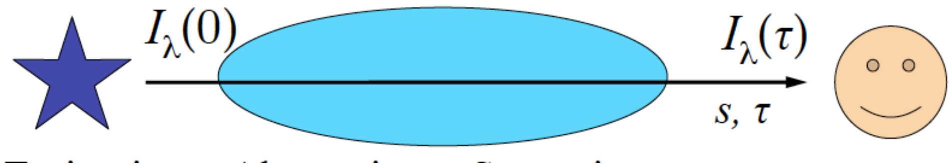
Amount of obscuration constrained by the energy budget between dust and stellar emission

L_{IR}/L_{UV} robust estimator of A_{UV}

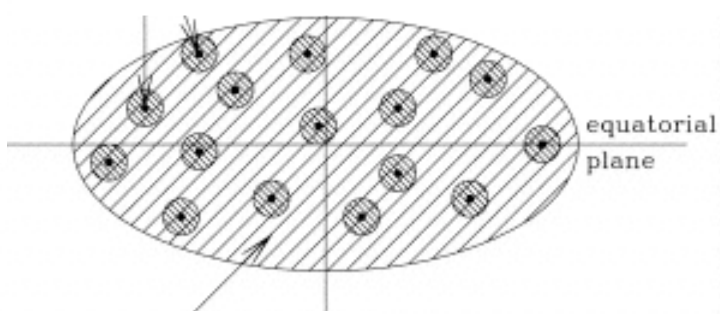
Attenuation & extinction laws in galaxies

They are different because of absorption & scattering of photons

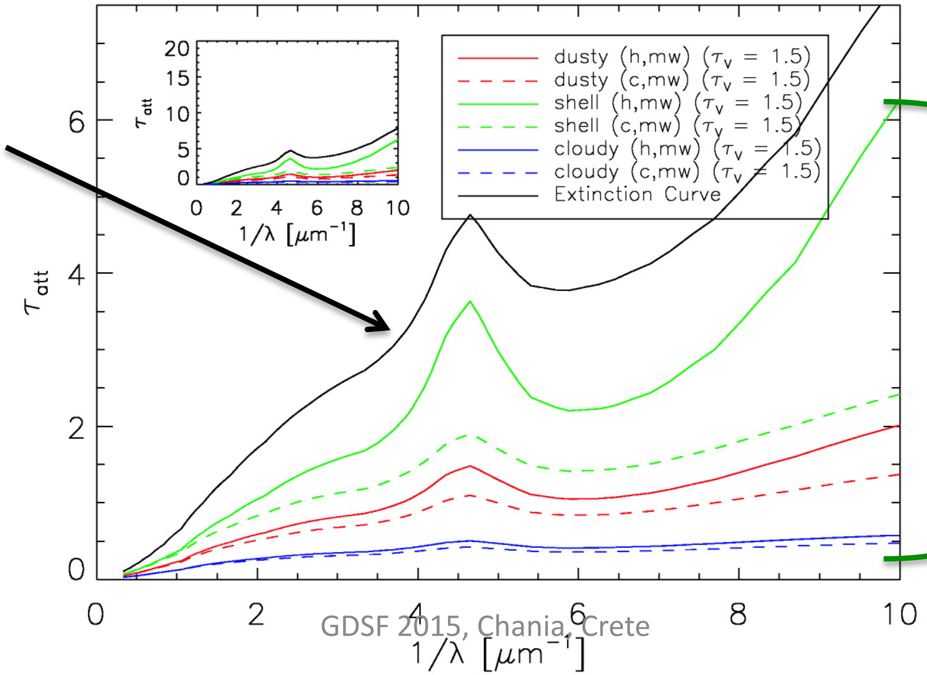
Extinction Only (UV, Opt, NIR)



Attenuation in a galaxy, stars and dust are mixed

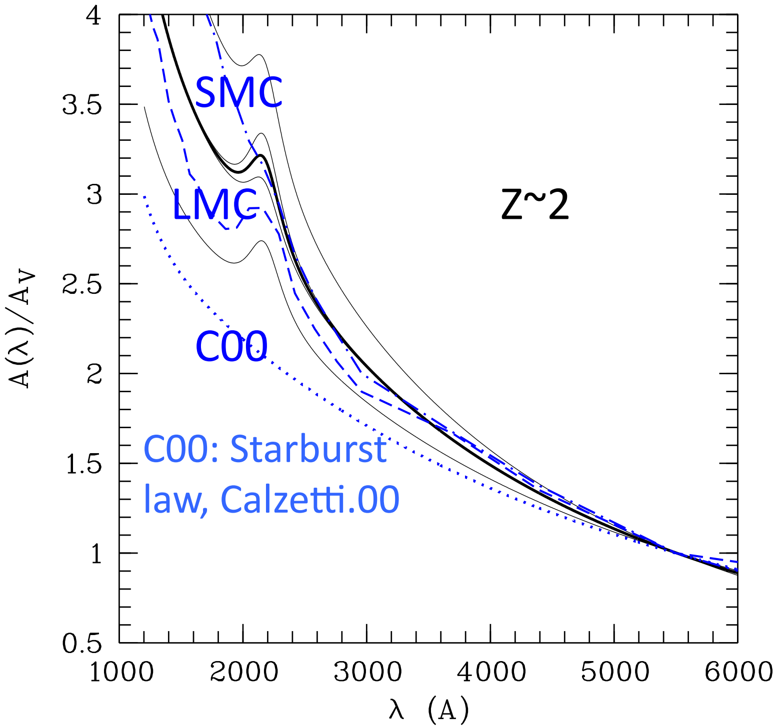


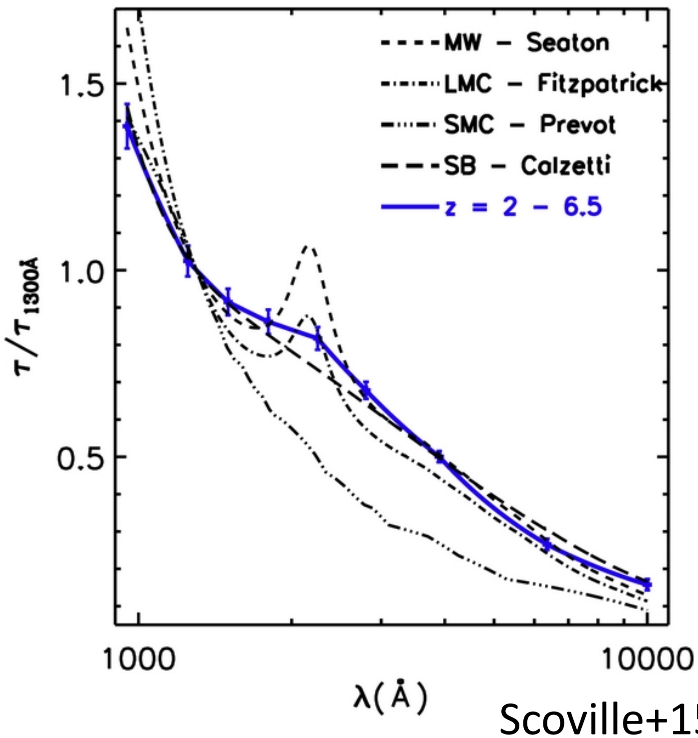
MW Extinction curve along one ligne of sight, depends on dust properties only



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

Witt & Gordon 2000



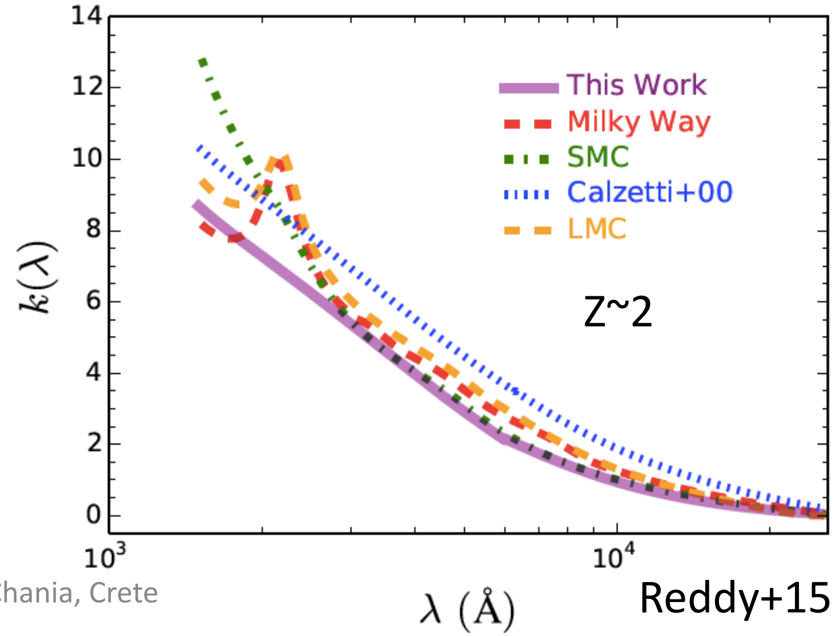


Scoville+15

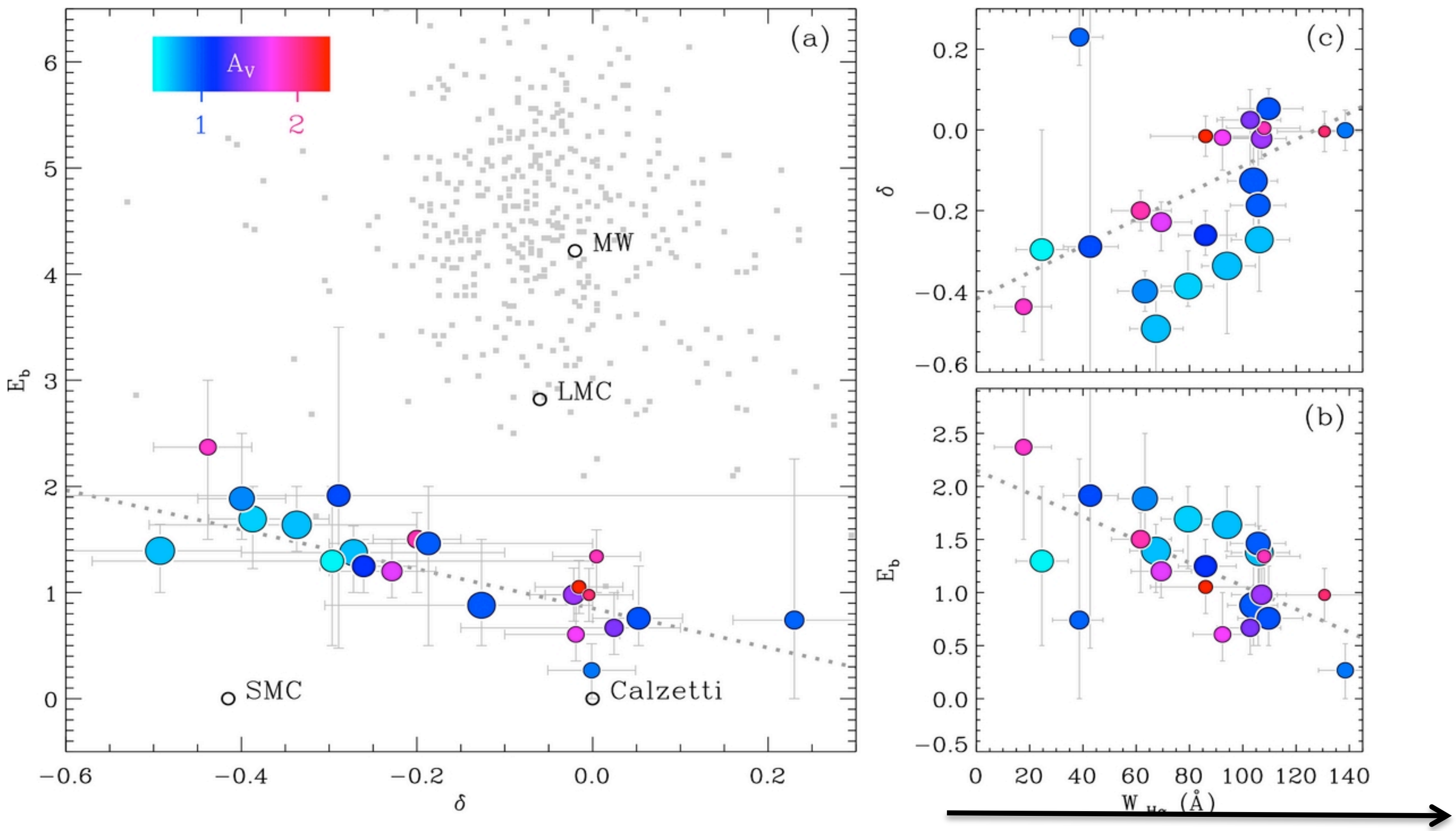
$$k(\lambda) = \left(\frac{A(\lambda)}{E(B-V)} + \frac{E_b \lambda^2 \gamma^2}{(\lambda^2 - \lambda_0^2) + \lambda^2 \gamma^2} \right) \left(\frac{\lambda}{\lambda_V} \right)^{\delta}$$

E_b= 1.6 +/- 0.4 δ = -0.27 +/- 0.17

Buat+11,12



Reddy+15



sSFR

Kriek & Conroy 13 :
Shallower curves and weaker bumps for large sSFR

Shallower curves for higher attenuation (Tuffs+04, Pierini+04, Wild+11
UV bumps detected in GRB hosts (e.g. Liang&Li, 10,11)

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

Intrinsic luminosity emitted by all the stars of the galaxy

t=0 the first stars in the galaxy

stellar tracks

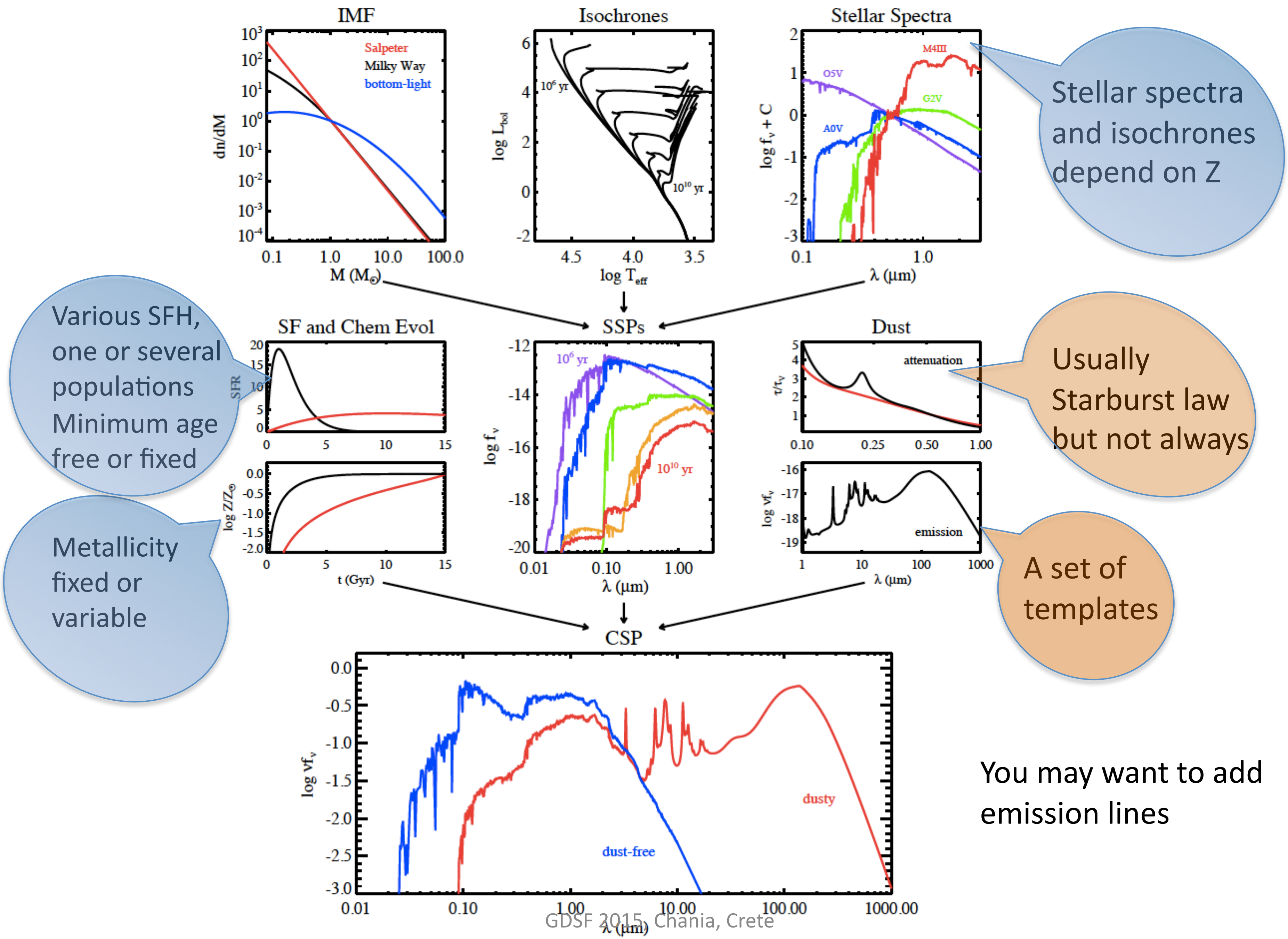
Star Formation rate function (M_{sun}/yr)

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

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

SFR(t) but not only

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



You may want to add emission lines

Parameter estimation

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

  To compare models: **reduced χ^2** degree of freedom is sometimes difficult to estimate

- **Probability distribution functions (PDF)** for each parameter built by marginalizing over all the other parameters:

  <u>→ mean, median, dispersion, quartiles of the PDF</u>

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

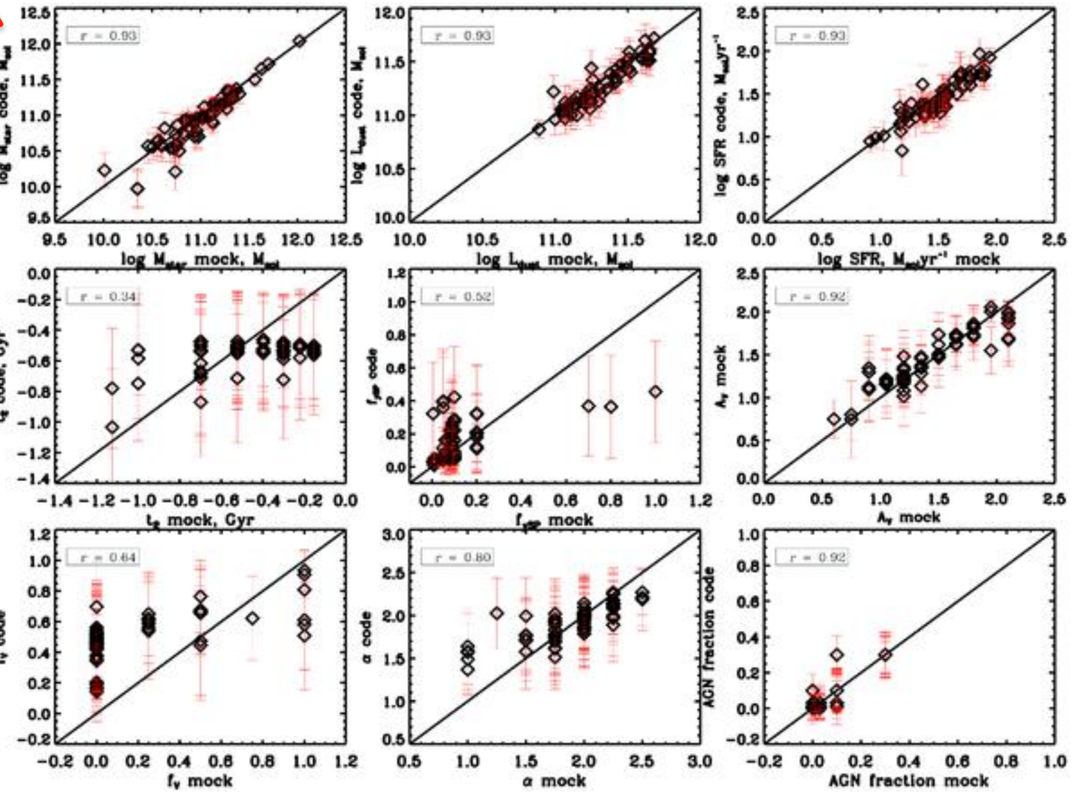
http://www.sedfitting.org/SED08/Welcome.html

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

Giovannoli et al. 2011, pseudo-galaxies and data drawn from the best fit models (Walcher+08, daCunha+08)

Estimated values of the parameters



Exact values of the parameters

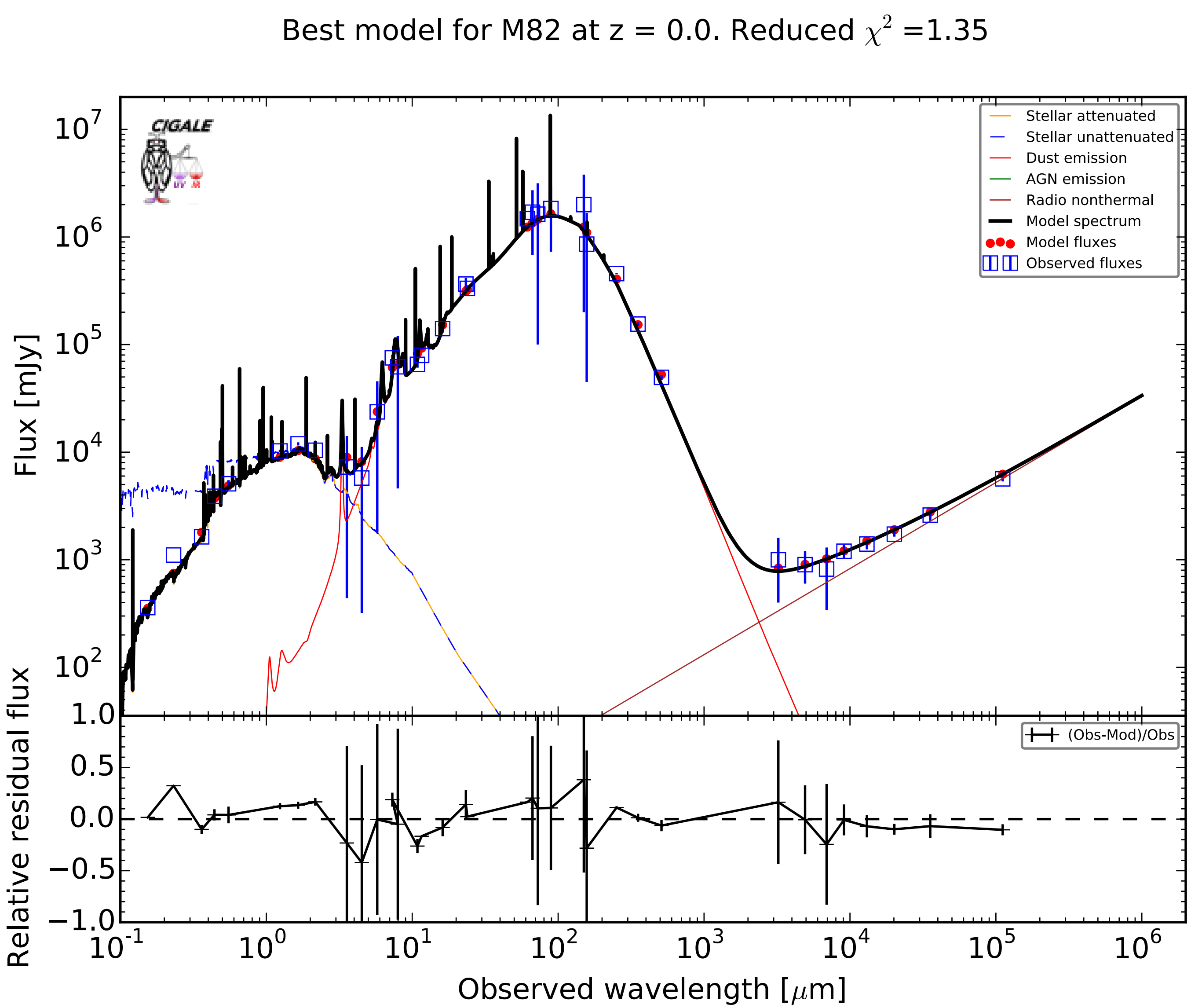
The new CIGALE code (cigale.lam.fr)

Noll+09, Burgarella+15, Boquien+15, in prep

- Written in **PYTHON**, users can add their own modules
- Star formation histories, standard or provided by the users
- Stellar populations models: Bruzual & Charlot 03, Maraston+05
- Attenuation curves with free parameters (with or without a bump, differential attenuation (old/young stars)
- IGM attenuation
- Dust emission models: Draine & Li 07, Dale+14, Casey 12
- Nebular lines: HII regions only
- AGN modules: Fritz+06 models
- Non detections and upper limits accounted for
- Very fast on multicore computers (8 cores = ~1000 models/s)

Creation of artificial catalogues: generates SEDs for any star formation histories

can be coupled with the output of theoretical models (Semi-analytical models, hydrodynamical models (*Boquien+14, Cousin+ in prep)*



Burgarella +15, in prep.

A very short summary

- Accurate measurements of the SFR: a difficult task
- Classical recipes are derived under specific prescriptions, the users must check their validity for their own study.
- The star formation history can be critical, SFR and stellar masses have to be derived in a consistent way
- SED fitting methods with appropriate SFHs are likely to be reliable
- Dust attenuation: very difficult to estimate in the absence of IR data…

Thank you