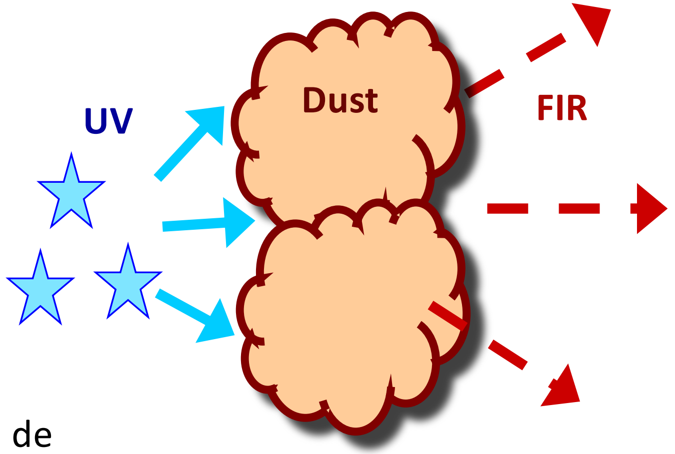
# Dust and stars: an unavoidable and complex interplay

## Dust Obscuration in (distant) galaxies



V. Buat, Laboratoire d'Astrophysique de
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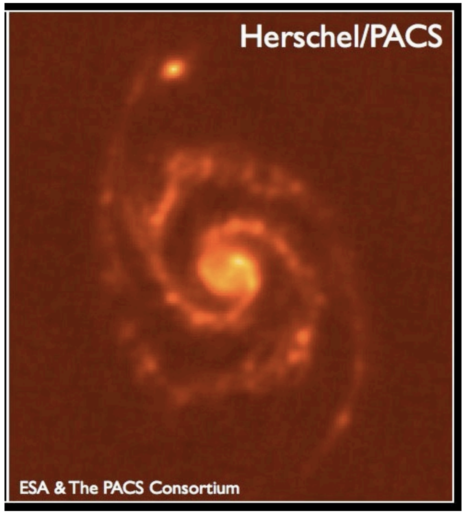
# Dust is present in(almost) every galaxy, from low to high z but with very different distributions

*An excellent and very recent reference: Salim & Narayanan ARAA 2020*

# Dust is present in(almost) every galaxy, from low to high z but with different distributions

*An excellent and very recent reference: Salim & Narayanan ARAA 2020*

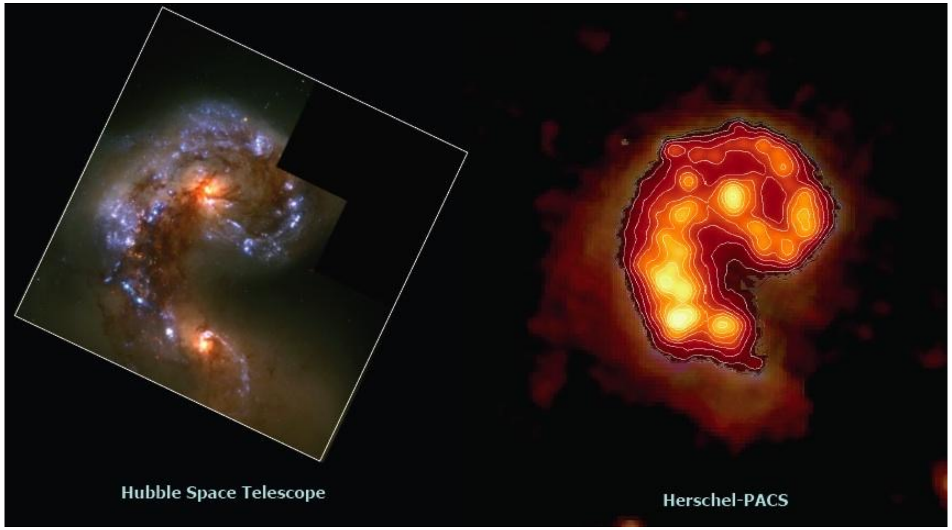
Few examples, from low to high redshift, with more or less complex distributions



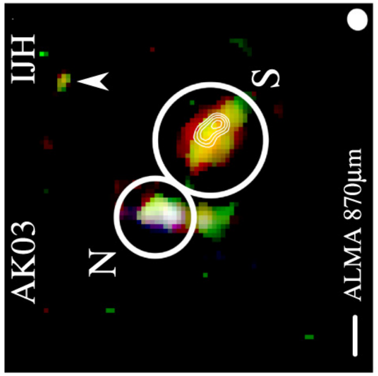
M51: M51A a grand design spiral, with similar global shape for dust and stars

M51B bright in optical and far-IR, very faint in UV

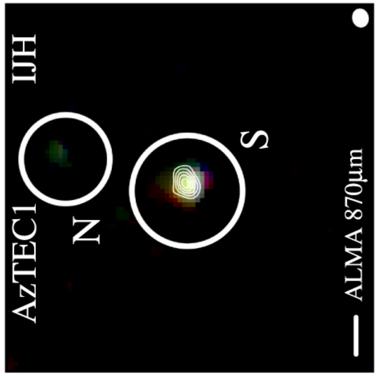
Arp244: very different structure in optical and in IR



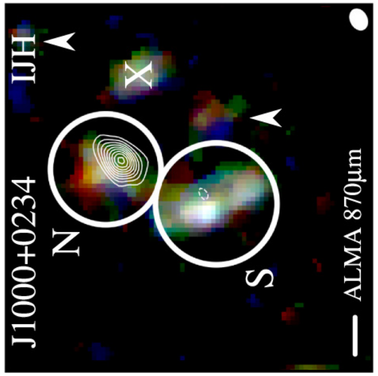
# Submillimeter galaxies (SMG) at z~4.5: HST/ALMA observations: multiple components and minor mergers, stellar and dust disconnection



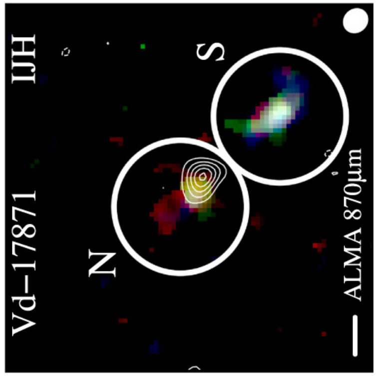
S: $SFR_{IR}$= 120 $M_{sun}yr^{-1}$
$SFR_{UV}$=25 $M_{sun}yr^{-1}$
N: $SFR_{UV}$=53 $M_{sun}yr^{-1}$



S: $SFR_{IR}$= 2400 $M_{sun}yr^{-1}$
$SFR_{UV}$=45 $M_{sun}yr^{-1}$
N: $SFR_{UV}$=8.5 $M_{sun}yr^{-1}$



S: $SFR_{UV}$=148 $M_{sun}yr^{-1}$
N: $SFR_{IR}$= 440 $M_{sun}yr^{-1}$
$SFR_{UV}$=53 $M_{sun}yr^{-1}$



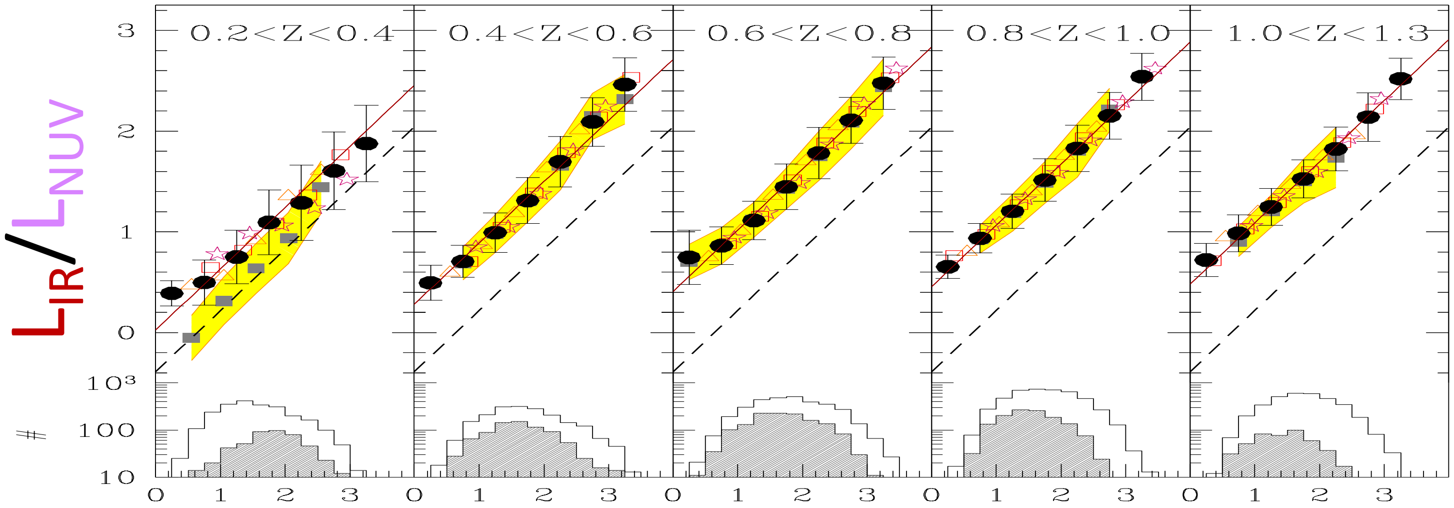
S: $SFR_{UV}$= 59 $M_{sun}yr^{-1}$
N: $SFR_{IR}$= 1120 $M_{sun}yr^{-1}$
$SFR_{UV}$=22 $M_{sun}yr^{-1}$

$SFR_{IR} >> SFR_{UV}$, dust emission in the reddest (stellar) components

*Gomez-Guijarro+18*

**The IR (~5-1000 µm) emission (i.e. dust emission) can be inferred (in average) from a combination of UV-optical-NIR data (i.e. stellar emission)**

**→ In average no completely hidden stellar emission**



NRK = 0.31*(NUV-r)+0.95(r-K) i.e stellar emission

*Arnouts+13, COSMOS field, 0.2<z<1.3*

# Outline

- ❖Dust and stellar interplay in galaxies: the framework
- ❖Dust attenuation laws
- ❖Amount of Attenuation, empirical relations

# Outline

❖**Dust and stellar interplay in galaxies: the framework**

- Extinction and attenuation

*Definitions and extinction curves*

- The theoretical framework: Radiation Transfer modelling

❖**Dust attenuation laws**

❖**Amount of Attenuation, empirical relations**

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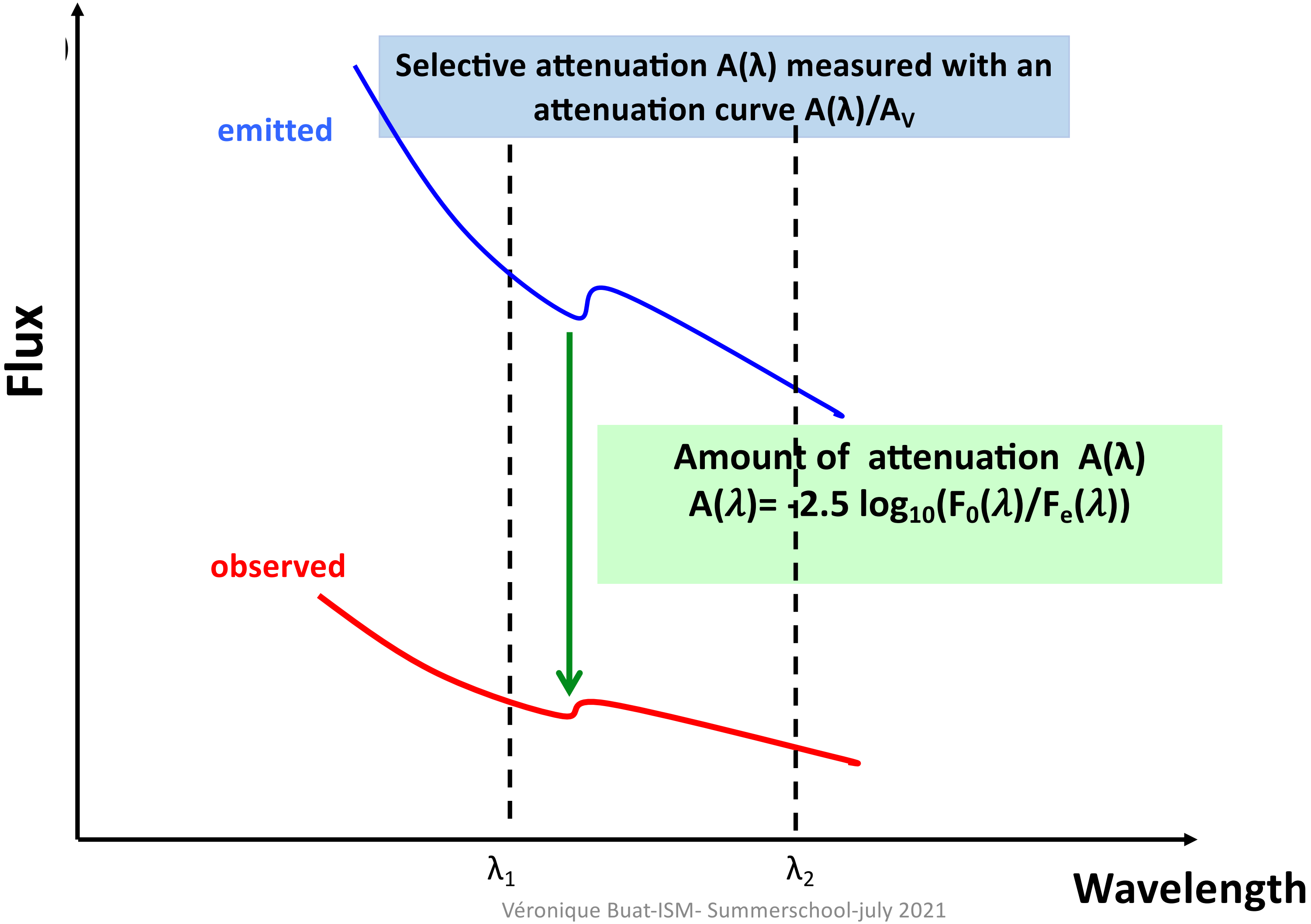
# Dust attenuation: amount of attenuation & attenuation law



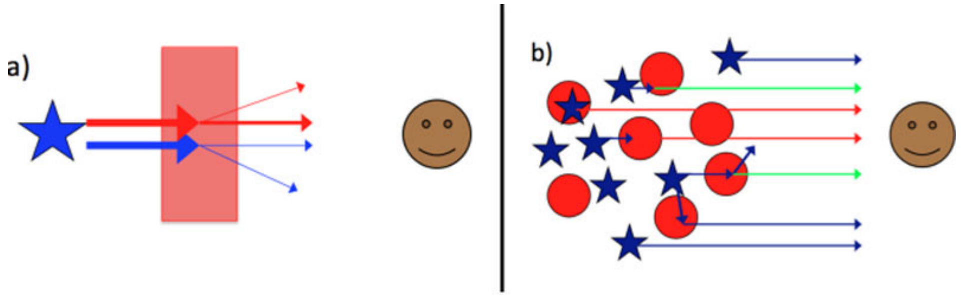
Selective attenuation A(λ) measured with an attenuation curve $A(\lambda)/A_V$

**Amount of attenuation A(λ)**

$$A(\lambda) = -2.5\log_{10}(F_0(\lambda)/F_e(\lambda))$$

# ⚠ Attenuation ≠ extinction in galaxies

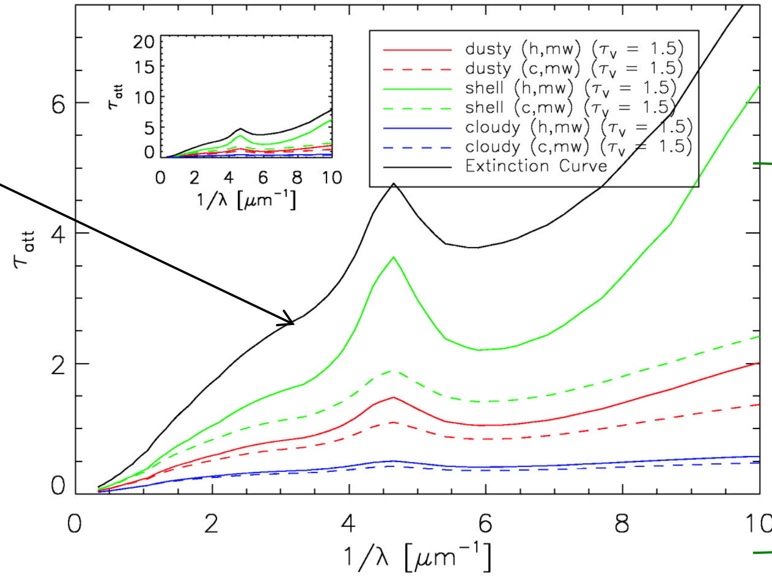
**Line of sight of a star, behind an homogeneous screen**
**→ Extinction law**



**Stars and dust are mixed in different ways**
**→ Attenuation law**

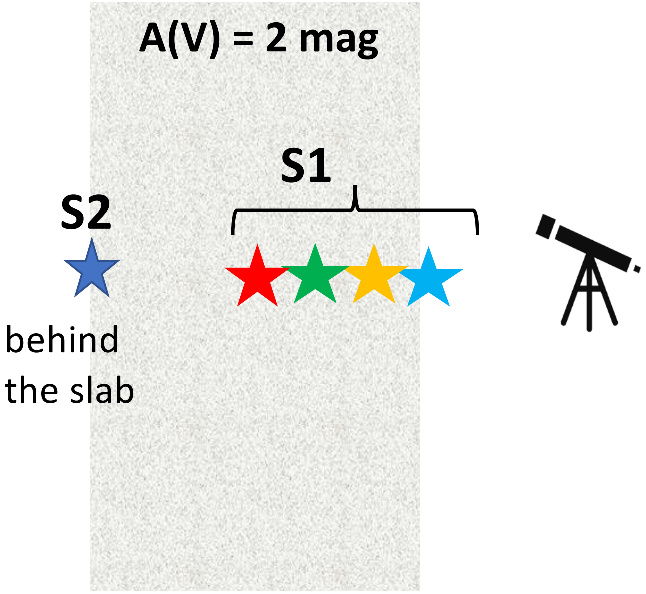
MW Extinction curve along one ligne of sight, depends on dust properties only

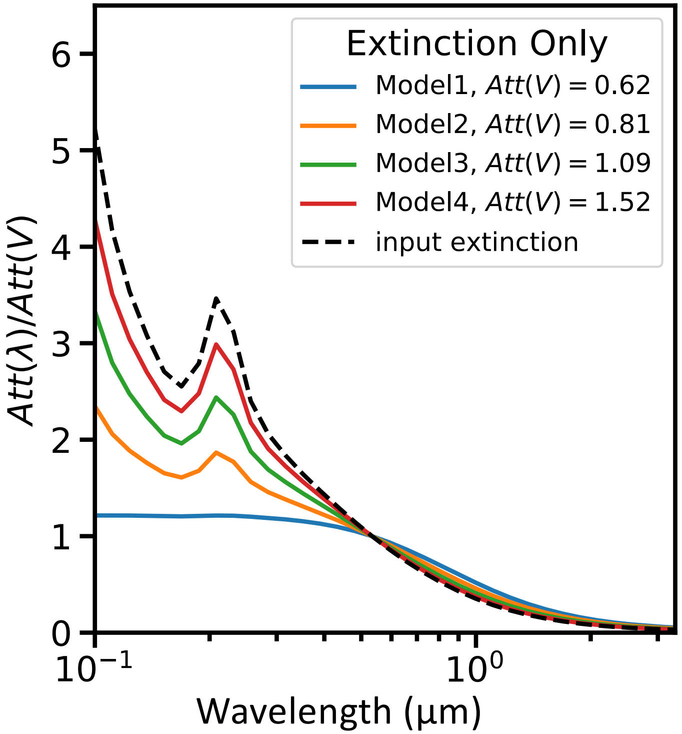
*Witt & Gordon 2000*



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

★1: S2 almost completely attenuated, S1 dominates
→ flat attenuation curve,
★2 ★3 ★4: optical depth for S1 increases
→ steeper attenuation curve



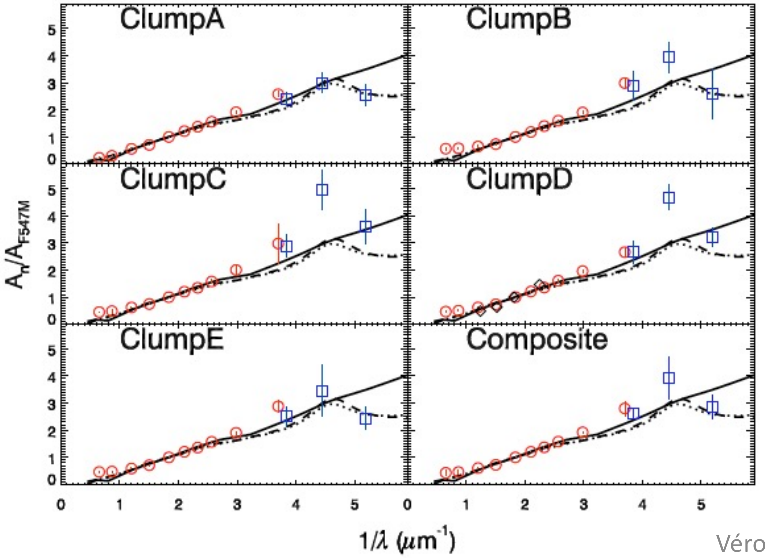


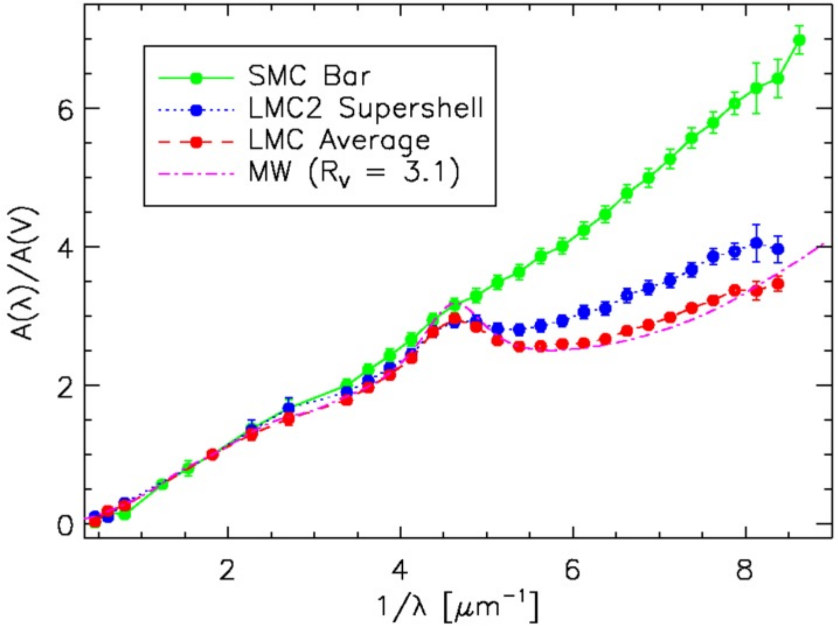
*Adapted from Gordon, 2021, in Star Formation Rates in Galaxies, CUP*

# Extinction curves

- MW, SMC, LMC
- Very few nearby galaxies
- Higher z: AGN,QSO, GRB, SN

**Clumps in the central part of M31, Dong+14**

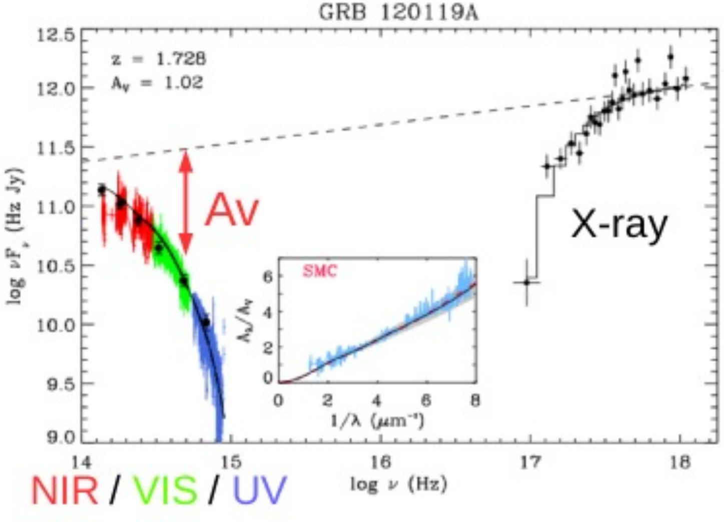




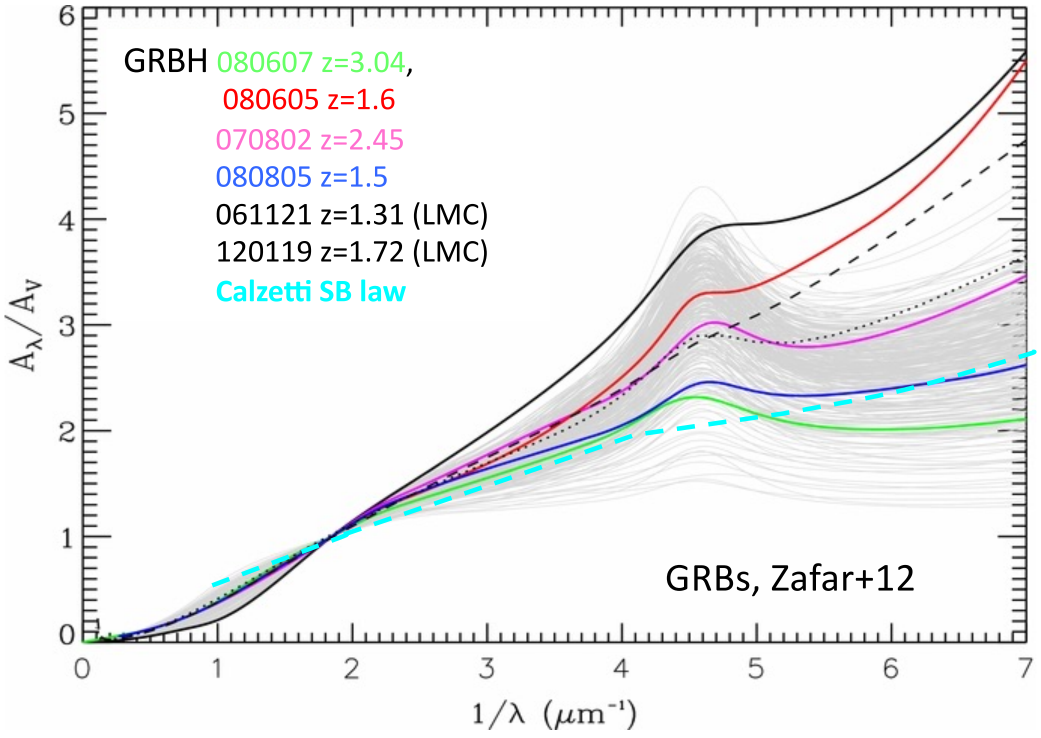
Average laws
LMC, SMC, MW, Gordon+03

# Extinction curves measured in galaxies hosting $\gamma$-rays bursts

*Zafar+18*



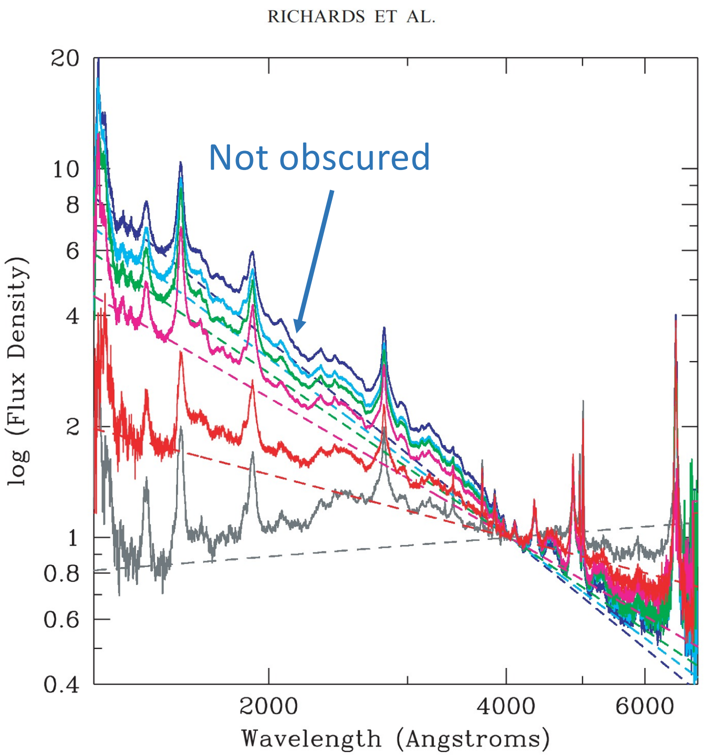
The afterglow is modelled by a single or double power-law: any deviation is due to dust extinction



GRBs, Zafar+12

# Extinction curves measured in obscured quasars

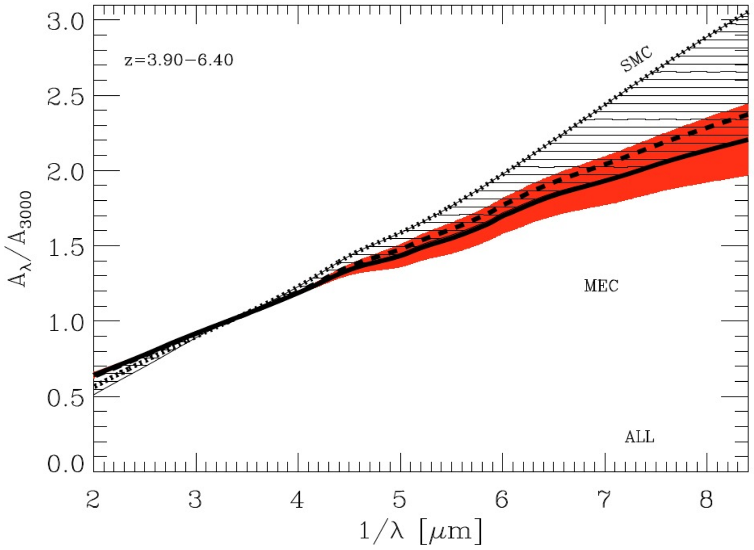
- Similar non obscured spectra: any deviation due to extinction



Not obscured

Richards+03, SDSS quasars→SMC curve

Gallerani+10: high z quasars: flatter curves→ constraints on dust production



# Outline

❖**Dust and stellar interplay in galaxies**

- Extinction and attenuation
- The theoretical framework: Radiation Transfer modelling

*Short presentation and few very useful results*

❖**Dust attenuation laws**

❖**Amount of Attenuation, empirical relations**

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# Radiation Transfer modeling to understand the main features of dust attenuation

- **Dust models**: **optical properties, chemical composition, grain size distribution**

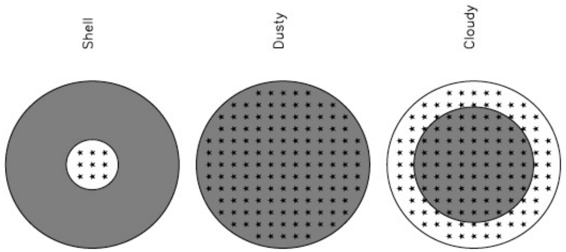
  ***Most of the time, a single model → a single extinction curve***

- **RT codes**: **interaction between photons and dust particles.** Monte-Carlo methods (TRADING, SKIRT) or/and ray-tracing (DartRay)
- **Stellar radiation field**: **theoretical** population synthesis models **or from observations** (commonly used for the old stellar population)
- **Dust/star geometry**: **distribution** homogeneous/ **clumpy**, **geometry**: shell/mixture, spherical/slab/bulge+disk

# Radiation transfer modeling: different configurations

- **Simple global geometry and stellar content**: to test dust properties and distributions

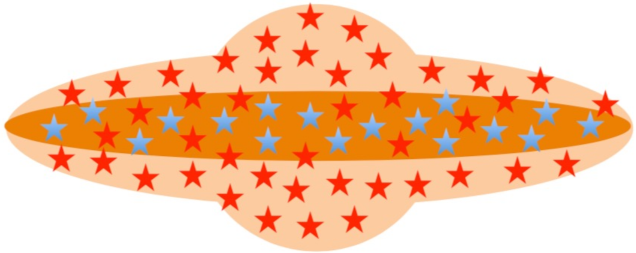
*(e.g. Witt & Gordon 00, Seon and Draine 17, Law+18)*



Spherical geometry,
Homogeneous stellar
Populations
*Witt&Gordon00*

- **Galaxy-like simplified geometries,** to produce libraries or fit **for nearby galaxies,** applied to sample of galaxies or to individual galaxies

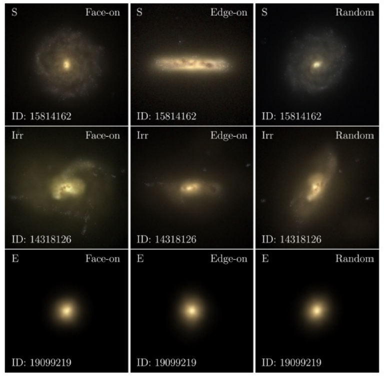
(*e.g. Pierini+04, Silva+98, Tuffs+04,deLooze14, Law+20 Nersenian+19)*



Non spherical
geometry,
different stellar
populations,
**dustpedia sample**
*deLooze+14*

- **Post-processing Applied to simulated galaxies**: hydrodynamical simulations to explore different galaxy types (isolated, mergers) and provide statistical analyses

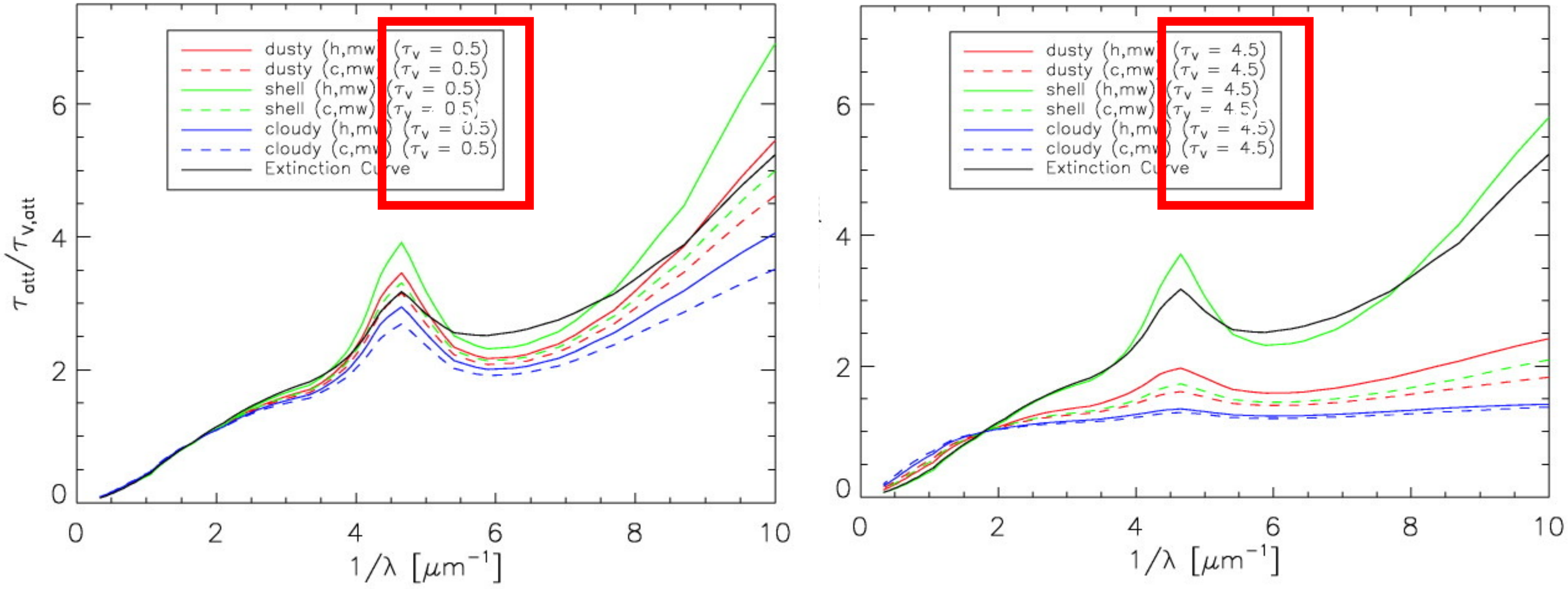
(*e.g.Trayford+17, 20, Narayanan+ 18*)

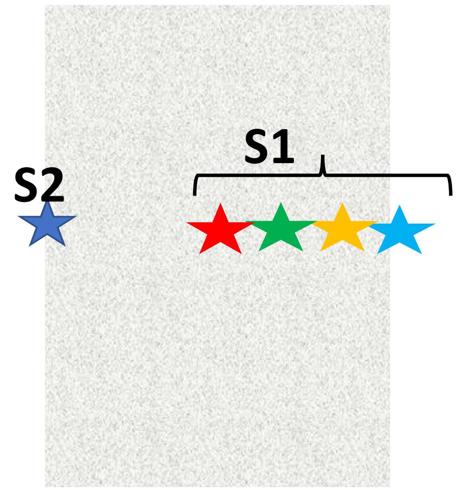


Eagle simulations+
SKIRT modeling
Trayford+17

# 1. RT modeling: Flattening of the attenuation curve & decrease of the UV bump amplitude when attenuation increases

**Embedded dust optically thick up to V or NIR**
**→ only least extincted stars contribute**





Witt & Gordon, 00 See also Seon & Draine 2016

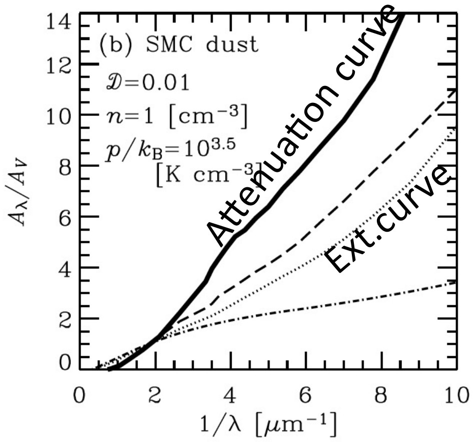
# 2. RT modeling: with different stellar populations and dust/stars geometry: Age selective attenuation → steeper attenuation law.

Youngest stars in dusty clumps & older stars in a smoooth dust distribution

Emission at short wavelengths comes from young stars embedded in a dusty medium: higher attenuation in the UV and **steeper attenuation laws**

**Standard age limit for birth clouds : 10 Myr**

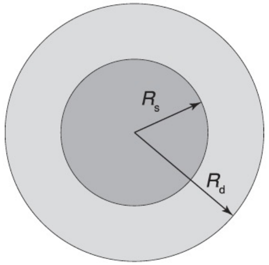
*(Charlot & Fall 2000, Granato+06, Panuzzo+07, Inoue 2005)*

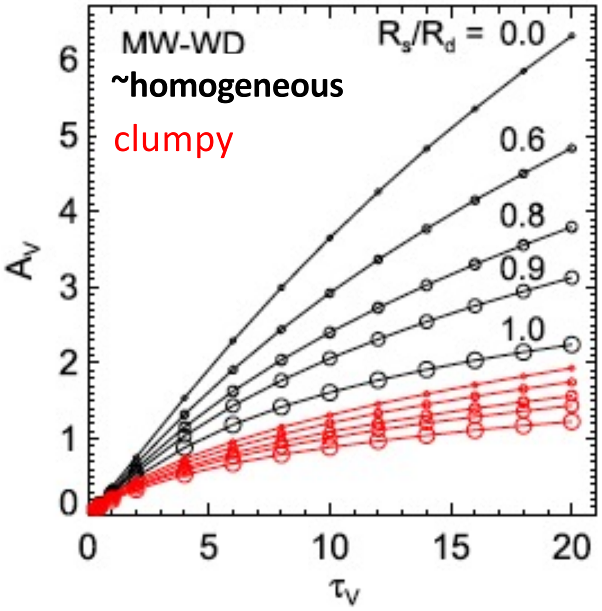


Inoue+05: plane parallel geometry, clumpy medium for young stars

# 3. RT modeling: a clumpy medium leads to a less effective optical depth than an homogeneous medium for the same dust column density and the attenuation curve flattens

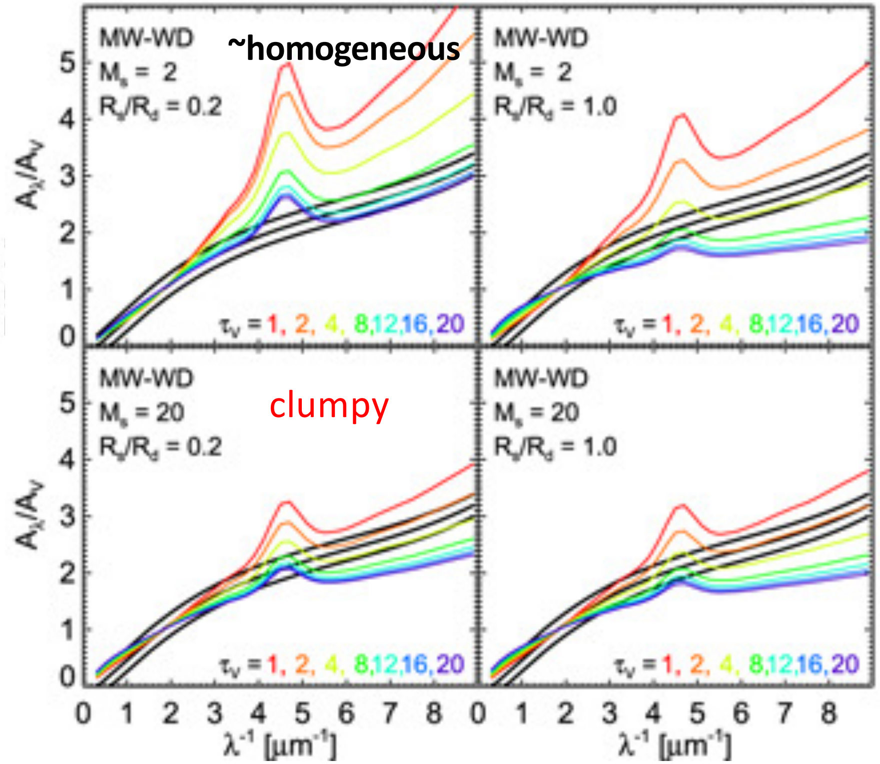
*Seon & Draine 2016*





~homogeneous

clumpy



~homogeneous

clumpy

# Application of RT models on nearby galaxies
# M51 De Looze+14, SKIRT code
# M31: Viaene+ 17

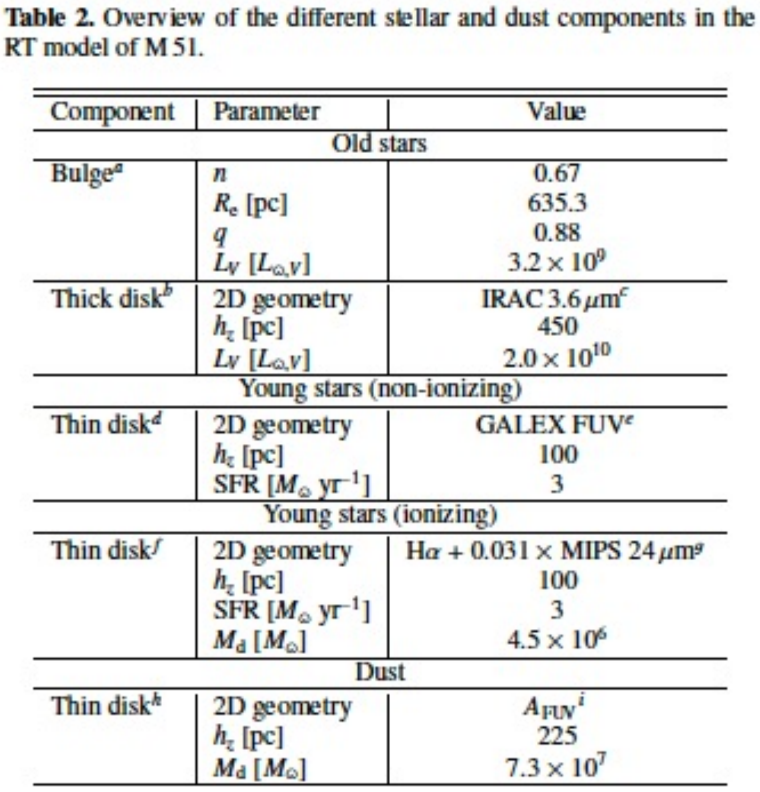
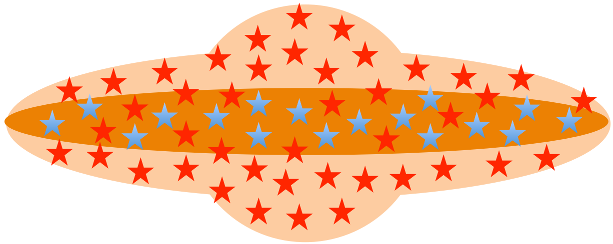
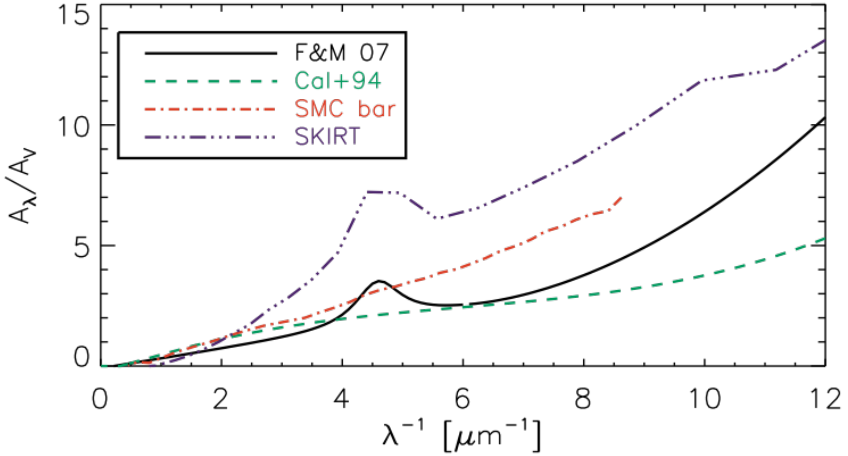


**Table 2.** Overview of the different stellar and dust components in the RT model of M 51.

| Component | Parameter | Value |
|---|---|---|
| Old stars | | |
| Bulge[a] | $n$ | 0.67 |
| | $R_e$ [pc] | 635.3 |
| | $q$ | 0.88 |
| | $L_V$ [$L_{\odot,V}$] | $3.2 \times 10^9$ |
| Thick disk[b] | 2D geometry | IRAC 3.6 $\mu$m[c] |
| | $h_z$ [pc] | 450 |
| | $L_V$ [$L_{\odot,V}$] | $2.0 \times 10^{10}$ |
| Young stars (non-ionizing) | | |
| Thin disk[d] | 2D geometry | GALEX FUV[e] |
| | $h_z$ [pc] | 100 |
| | SFR [$M_\odot$ yr$^{-1}$] | 3 |
| Young stars (ionizing) | | |
| Thin disk[f] | 2D geometry | H$\alpha$ + 0.031 × MIPS 24 $\mu$m[g] |
| | $h_z$ [pc] | 100 |
| | SFR [$M_\odot$ yr$^{-1}$] | 3 |
| | $M_d$ [$M_\odot$] | $4.5 \times 10^6$ |
| Dust | | |
| Thin disk[h] | 2D geometry | $A_{FUV}$[i] |
| | $h_z$ [pc] | 225 |
| | $M_d$ [$M_\odot$] | $7.3 \times 10^7$ |



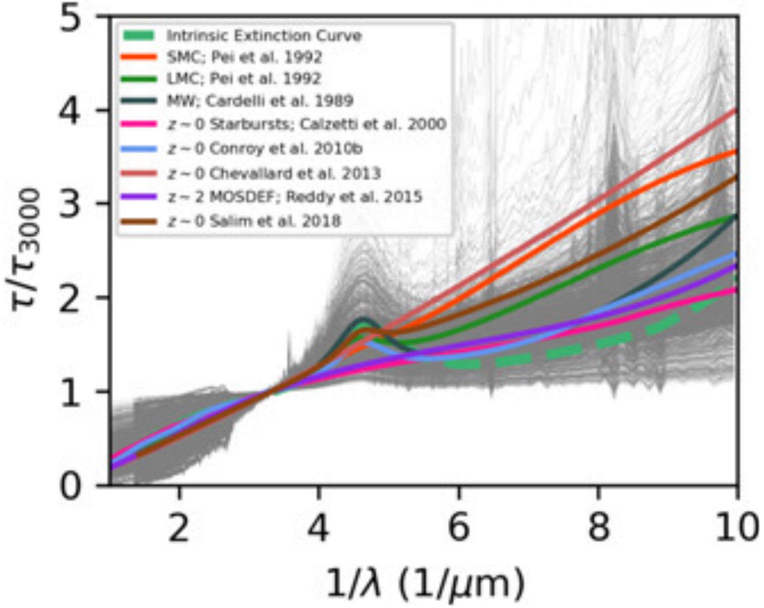


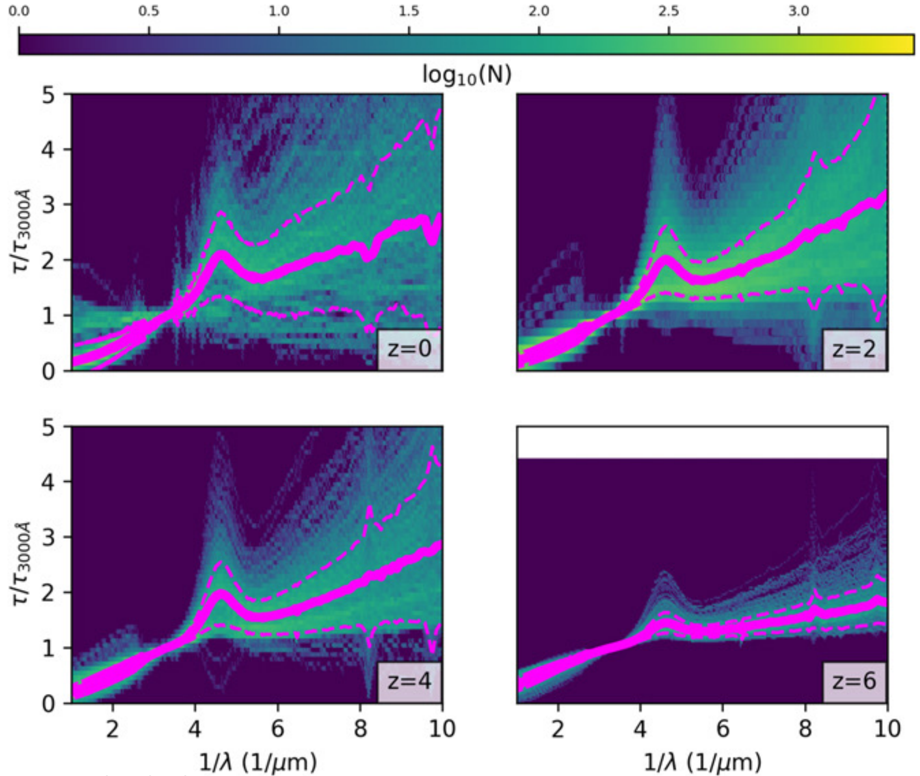
# Radiation transfer modeling on simulated galaxies: more complex geometry, coupled with galaxy evolution

*(e.g. Baes+19, Camps+16,18, Trayford+20)*

**MUFASA+GIZMO simulations & HYPERION RT** *(Narayanan+18)*

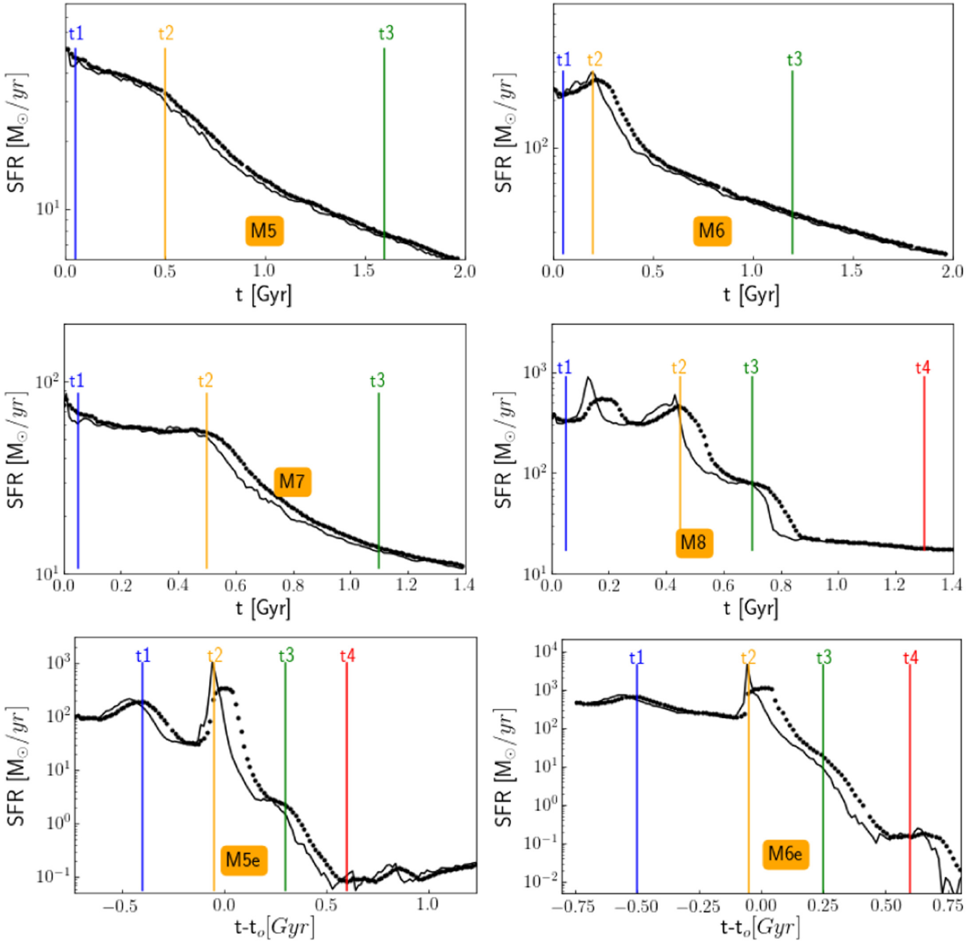
A single MW-like extinction curve

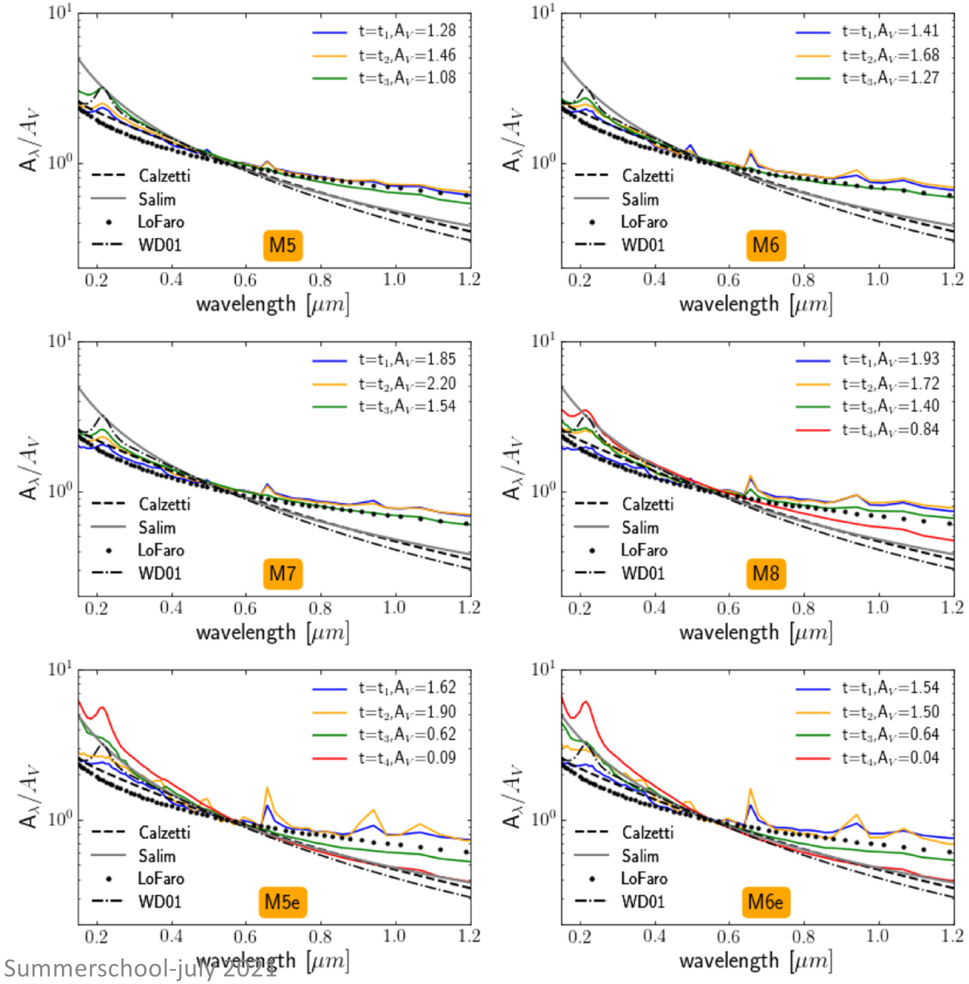




# Gadget-2 simulations +SUNRISE post process

## Roebuck+19





# Key points to remember about RT analyses

(useful for this lecture)

- Clumpy medium usually as a diffuse ISM+more opaque clumps

*less efficient than an homogeneous medium to absorb photons*

- Models of galaxies with an age selective attenuation: steepens the effective attenuation curve
- A single extinction curve (single dust model) is assumed
- Attenuation curve become flatter when the attenuation increases.
- When the UV bump is present in the extinction curve, its amplitude decreases when attenuation increases

# Outline

- ❖Dust and stellar interplay in galaxies: the framework
- ❖**Dust attenuation laws**
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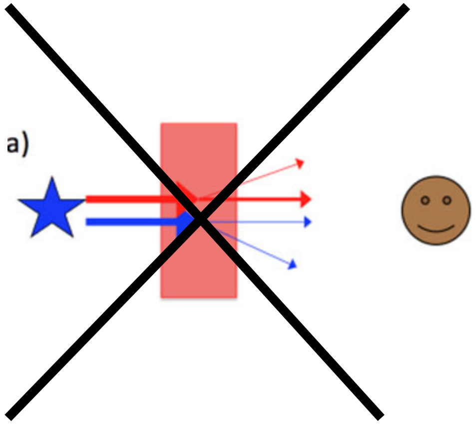
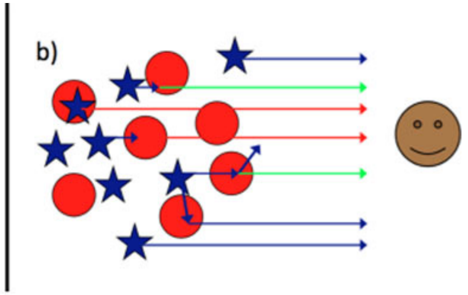
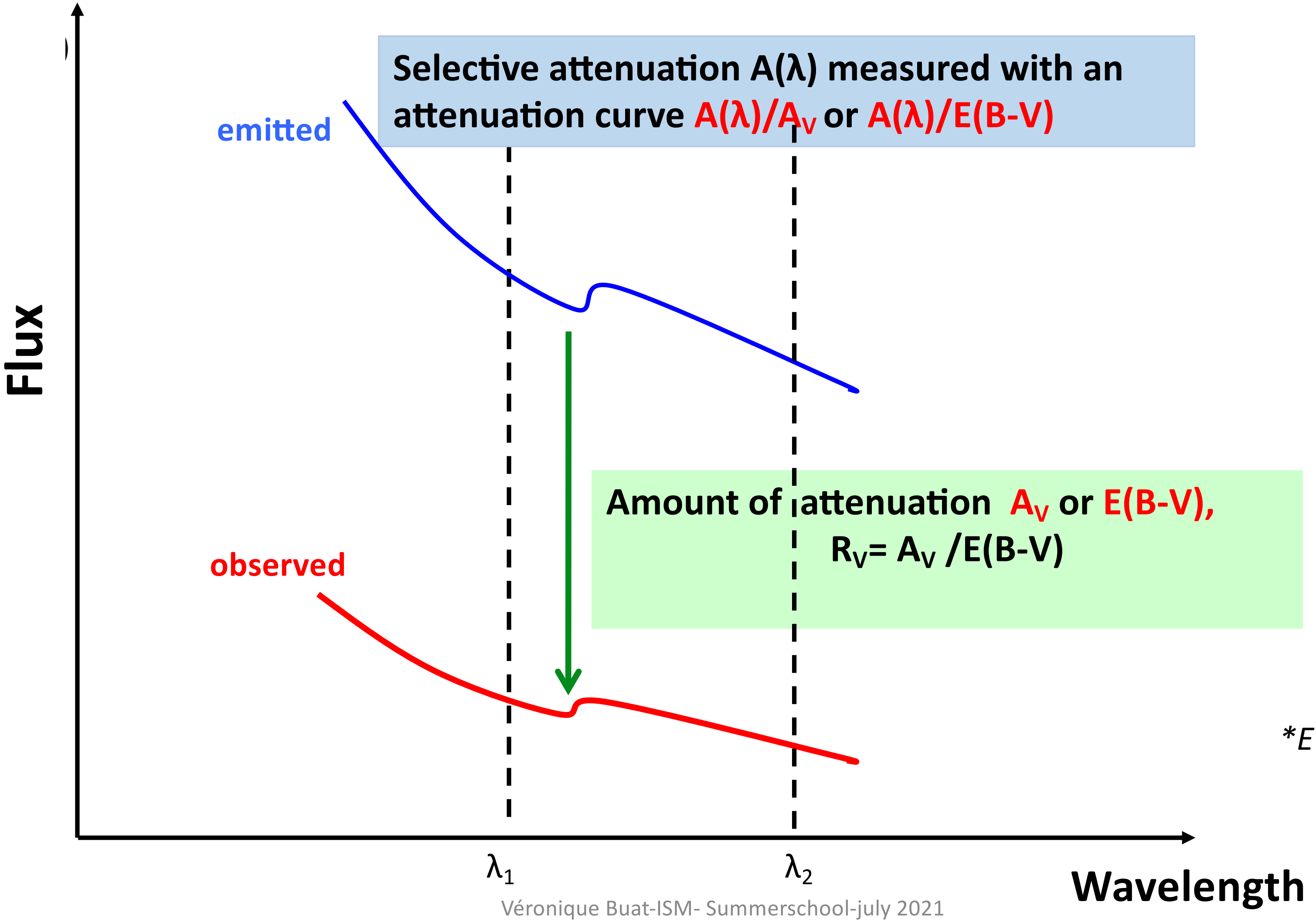


Extinction along the line of sight:
extinction law



Attenuation: complex geometry
‘effective’ attenuation law

# (too many..) important/useful definitions



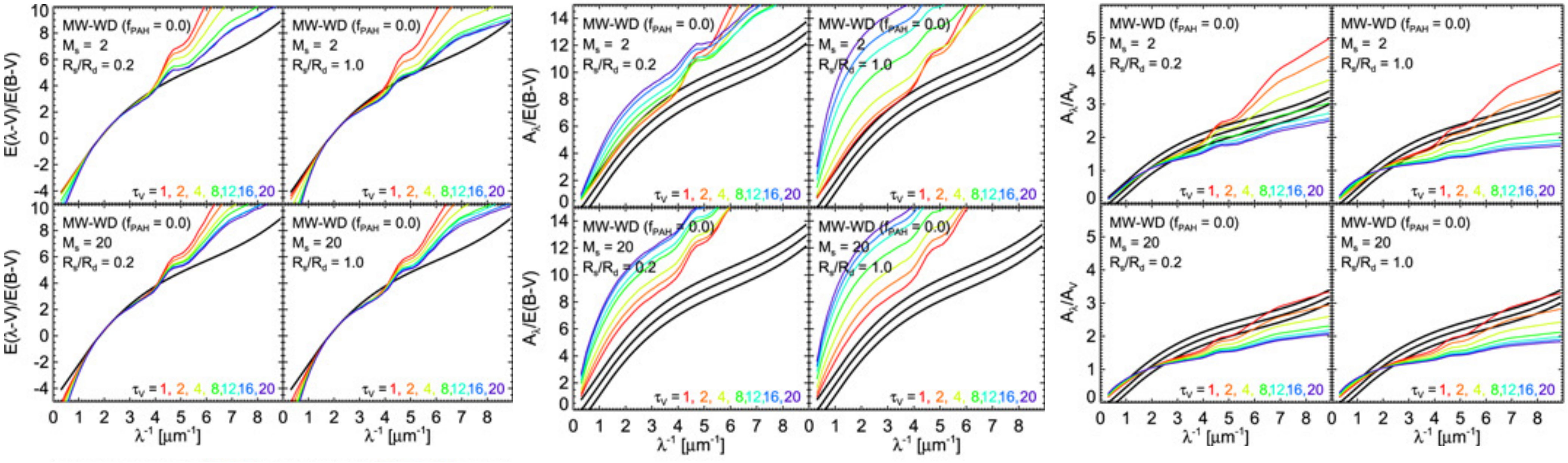
**Selective attenuation $A(\lambda)$ measured with an attenuation curve $A(\lambda)/A_V$ or $A(\lambda)/E(B-V)$**

**Amount of attenuation $A_V$ or $E(B-V)$,**

**$R_V = A_V / E(B-V)$**

*$E(B-V) = A(B) - A(V)$

# The representation of the attenuation laws strongly depends on the quantities considered



*Seon & Draine 2016*

# Outline

❖Dust and stellar interplay in galaxies: the framework

❖**Dust attenuation laws**

- The ‘Calzetti’ law and direct measurements
- Formalisms and shape of the attenuation law
- Attenuations laws from numerical simulations
- Attenuations laws from observations

*SED fitting methods, variation of attenuation laws*

- The case of dusty IR luminous galaxies

❖**Amount of Attenuation, empirical relations**

# The original attenuation law of Calzetti et al. 1994→2000

**It is an empirical law, then models were developped to understand its shape**

**It was measured on a sample of central starbursts in nearby galaxies :**

UV (IUE) spectra and Balmer decrements H$\alpha$/H$\beta$

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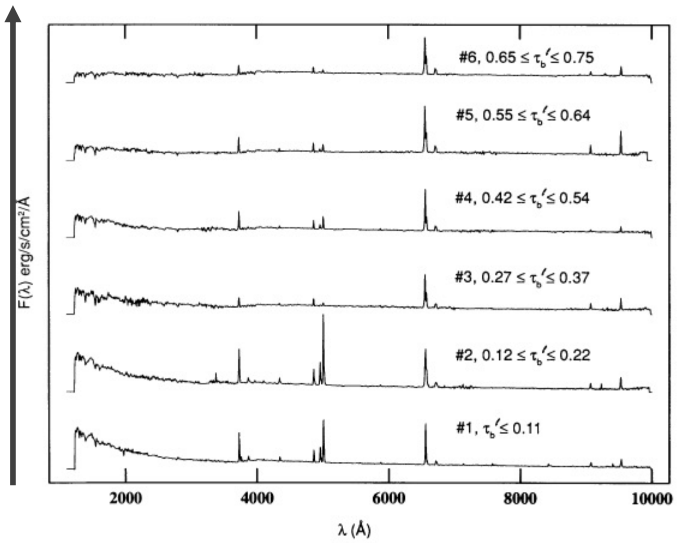

Extinction in the lines increases

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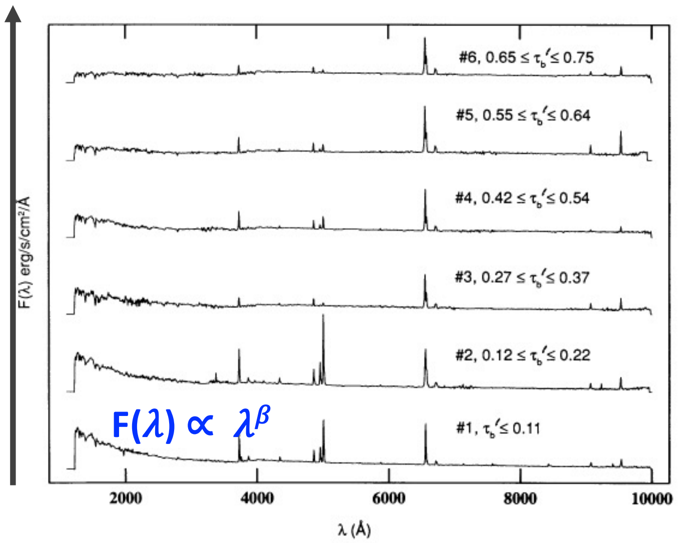
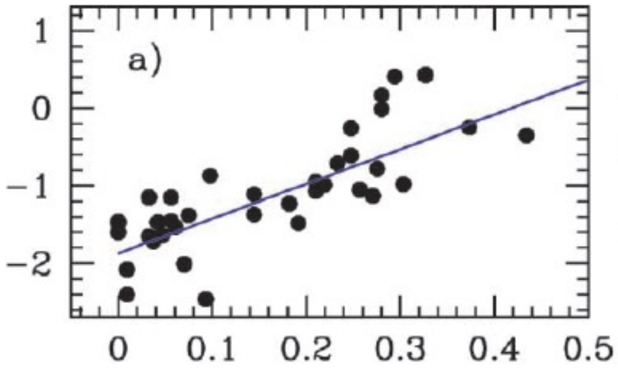
Galaxies ordered in bins of extinction in the lines

Extinction in the lines increases



**$F(\lambda) \propto \lambda^{\beta}$**

$\beta$ increases with extinction



$\beta$

~F(Hα)/F(H$\beta$)~ extinction in line

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**It was measured on a sample of central starbursts in nearby galaxies :**

UV (IUE) spectra and Balmer decrements Hα/H$\beta$

✓Galaxies ordered as a function of their obscuration measured with Hα/H$\beta$

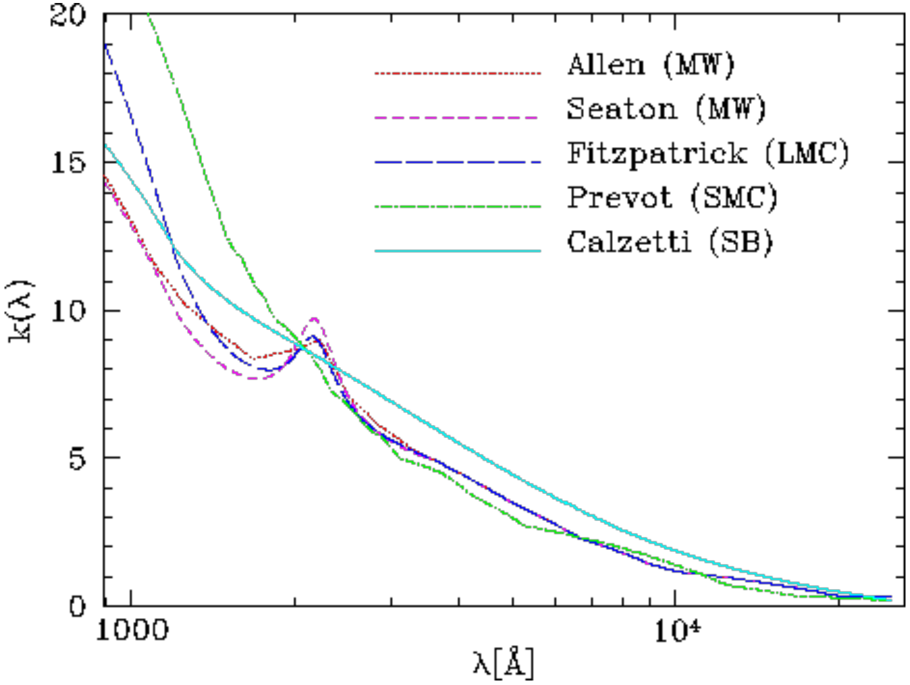
✓The UV-visible spectrum is supposed to ONLY vary with dust reddening

→ $k(\lambda_1)-k(\lambda_2)= (A(\lambda_1)-A(\lambda_2))/E(B-V)_{gas}$

→ implies $\mathbf{E(B-V)_{stars} = 0.44\ E(B-V)_{gas}}$

✓ The absolute calibration is performed with dust emission (Calzetti+2000)

# The shape of the Calzetti-Starburst law



- The **Calzetti attenuation law** is compared to **extinction laws for the MW, LMC, SMC**
- **The Calzetti attenuation law IS NOT an extinction law** **even if it** is expressed as an extinction law and routinely compared to a few of them.
- **No UV bump**, a general shape similar to the MW extinction curve, and grayer (flatter) than the LMC & SMC extinction curves

# Other Attenuation laws are derived from observations

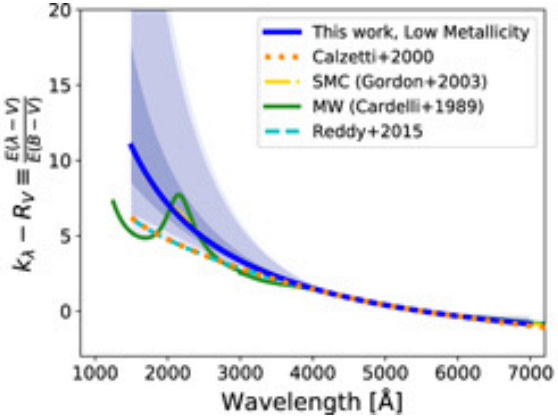
## with Calzetti-like methods:

Balmer optical depth to quantify attenuation, comparison of UV spectra or photometric spectral energy distributions

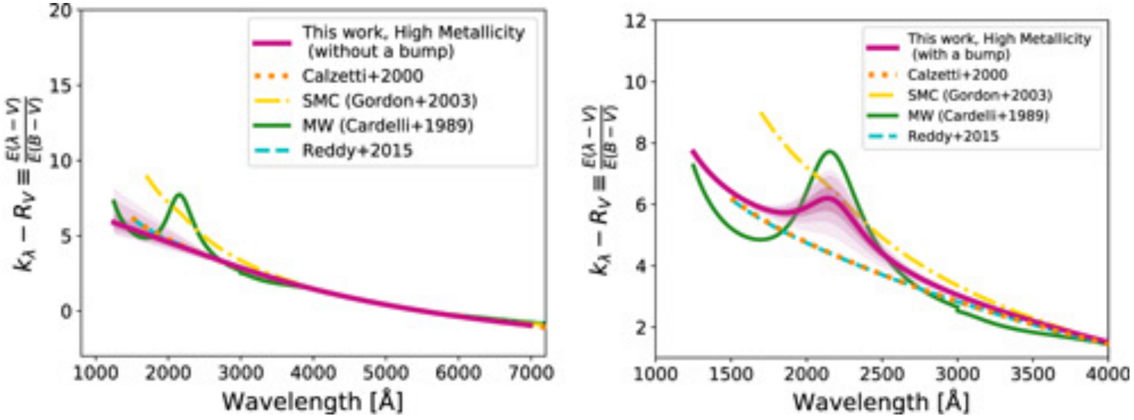
e.g. *Battisti+16, Reddy 2015, 2016:* ***mostly consistent with Calzetti curve***

*Shivaie+20* MOSDEF survey 1.4<z<2.6: variation of attenuation curve with metallity

12+log(O/H)<8.5
Steeper than Calzetti



12+log(O/H)>8.5
Consistent with Calsetti & UV bump 0.5*MW bump



# Outline

❖Dust and stellar interplay in galaxies: the framework

❖**Dust attenuation laws**

- The ‘Calzetti’ law and direct measurements
- Formalisms and shape of the attenuation law
- Attenuations laws from numerical simulations
- Attenuations laws from observations
- The case of dusty IR luminous galaxies

❖Amount of Attenuation, empirical relations

# The most usual formalisms for the attenuation laws

## Charlot & Fall 2000 (CF00)
## A model

$A_V$

$$A_\lambda^{\rm BC} = A_V^{\rm BC}(\lambda/0.55)^{n^{\rm BC}}$$
$$A_\lambda^{\rm ISM} = A_V^{\rm ISM}(\lambda/0.55)^{n^{\rm ISM}}$$

**age dependent attenuation for stars**

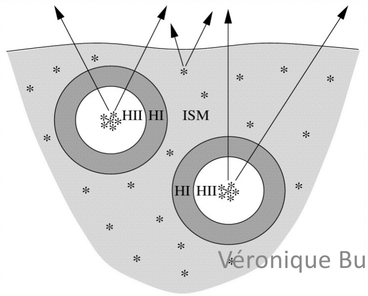
t<~$10^7$ yrs (BC+ISM) and t> ~$10^7$ yrs (BC),

**no single attenuation law**

$$\boxed{\mu = A_V^{\rm ISM}/(A_V^{\rm ISM} + A_V^{\rm BC}).}$$

**CF00: $n^{BC}=n^{ISM}=-0.7$, $\mu = 0.3$**

*(da Cunha+08, ,*
*Wild+11,Chevallard+13,*
*Lo Faro+17, Malek+18*)



## Calzetti+2000 (C00)
## A measure

E(B-V)

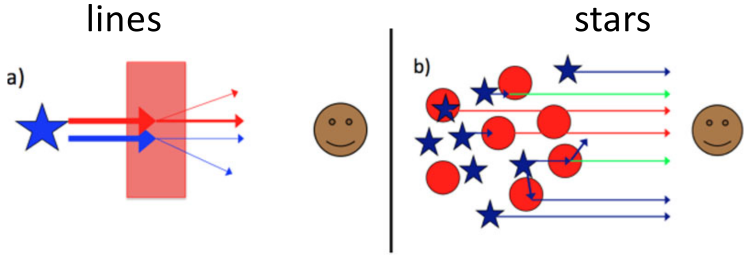
$$k(\lambda) = \left(\frac{A(\lambda)}{E(B-V)}\right)$$

**A single attenuation law for all the stellar continuum**

MW extinction+screen for nebular lines

$$\boxed{f = E(B-V)_{star}/E(B-V)_{lines}}$$

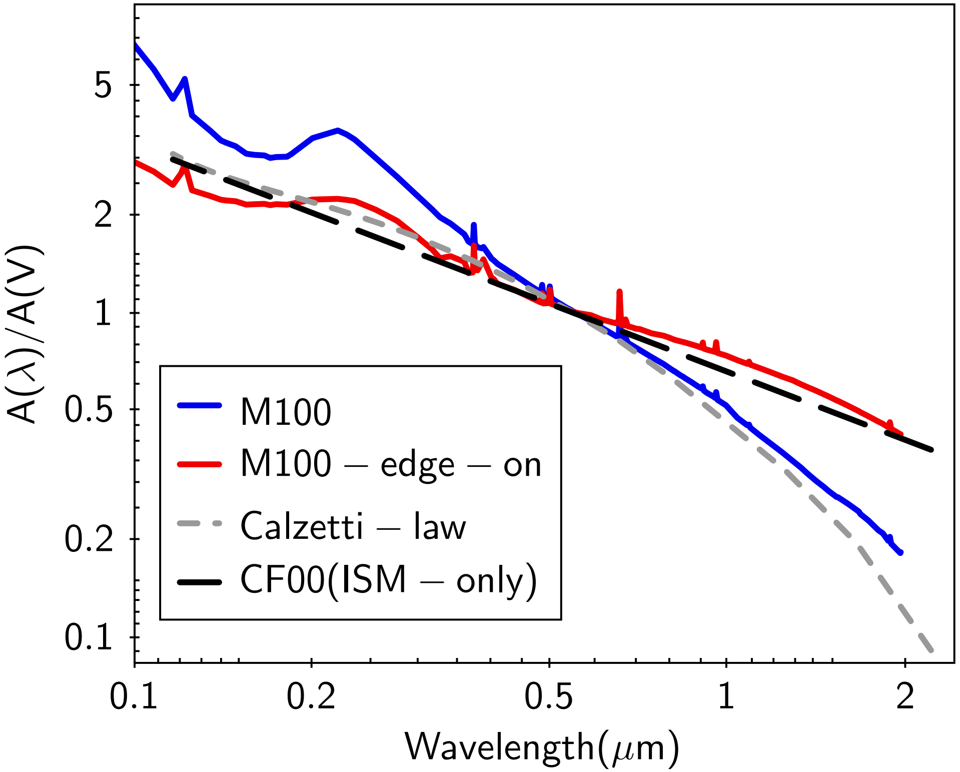
**C00- $f$ = 0.44**



# The Calzetti law is steeper than the Charlot & Fall recipe at $\lambda > \lambda_V$

**M100: Radiation Transfer modeling: SKIRT/dustpedia**

*(courtesy of A. Nersenian, S. Verstocken & M. Baes)*



- Original CF00 recipe for the ISM:
  $\lambda^{-0.7}$ , **$R_V$ ~5.8**
- Calzetti law
  **$R_V$= 4.05**

# No universal attenuation law: flexible recipes are introduced from the original recipes

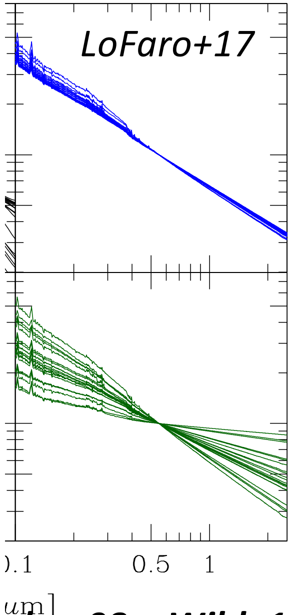
## Charlot & Fall 2000 (CF00)

→ **DouBle-Power-Law-free, free slope**

$$A_\lambda^{\mathrm{BC}} = A_{\mathrm{V}}^{\mathrm{BC}}(\lambda/0.55)^{n^{\mathrm{BC}}}$$

$$A_\lambda^{\mathrm{ISM}} = A_{\mathrm{V}}^{\mathrm{ISM}}(\lambda/0.55)^{\boxed{n^{\mathrm{ISM}}}}$$

$$\boxed{\mu = \frac{A_V^{ISM}}{A_V^{ISM} + A_V^{BC}}}$$



Magphys
μ free

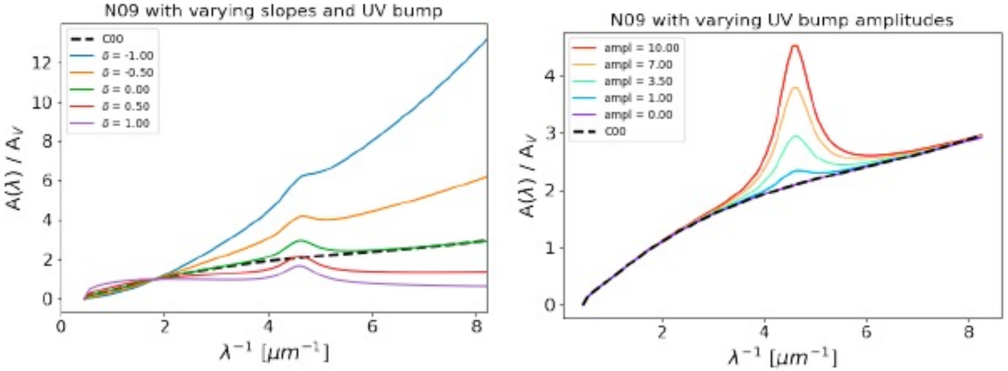
Cigale
μ & $n^{\mathrm{ISM}}$ free

*(da Cunha+08, , Wild+11,Chevallard+13,*
*Lo Faro+17, Malek+18,* **Battisti+20: adds a UV bump**

## Calzetti+2000 (C00)

→ **Calzetti-like, free slope**

$$k(\lambda) = \left(\frac{A(\lambda)}{E(B-V)} + \boxed{D(\lambda)}\right) \times \left(\frac{\lambda}{\lambda_V}\right)^{\boxed{\delta}}$$



*Narayanan+18*

*(Buat+11,12, Kriek&Conroy 13, Salmon+15,*
*Zeimann+15, Seon & Draine 2016, Corre+18)*

# Outline

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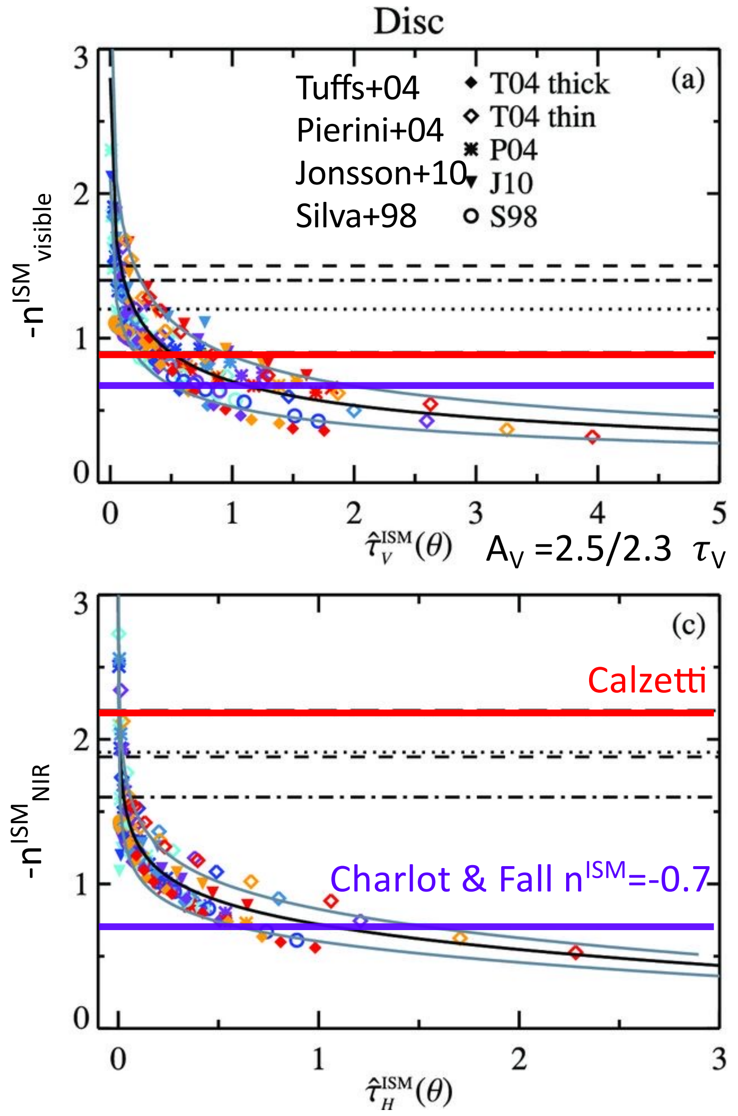
❖Amount of Attenuation, empirical relations

# Chevallard et al. 2013:

**Compilation of Radiative Transfer modeling results for disk+bulge geometries+ application of the Charlot and Fall formalism**

$$A_\lambda^{\rm BC} = A_{\rm V}^{\rm BC}(\lambda/0.55)^{n^{\rm BC}}$$
$$A_\lambda^{\rm ISM} = A_{\rm V}^{\rm ISM}(\lambda/0.55)^{n^{\rm ISM}}$$

→ All models predict a grayer attenuation for an increasing attenuation



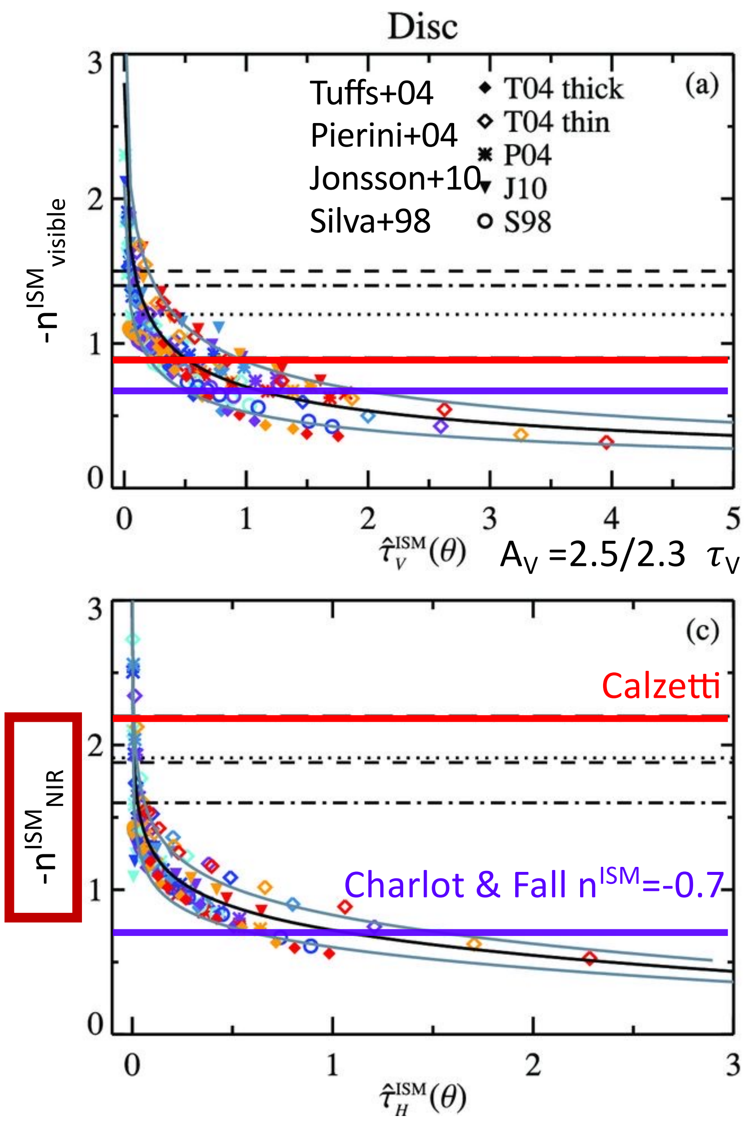
# Chevallard et al. 2013:

**Compilation of Radiative Transfer modeling results for disk+bulge geometries and Charlot and Fall flexible formalism**

$$A_\lambda^{\mathrm{BC}} = A_\mathrm{V}^{\mathrm{BC}}(\lambda/0.55)^{n^{\mathrm{BC}}}$$
$$A_\lambda^{\mathrm{ISM}} = A_\mathrm{V}^{\mathrm{ISM}}(\lambda/0.55)^{n^{\mathrm{ISM}}}$$

→ All models predict a grayer attenuation for an increasing attenuation

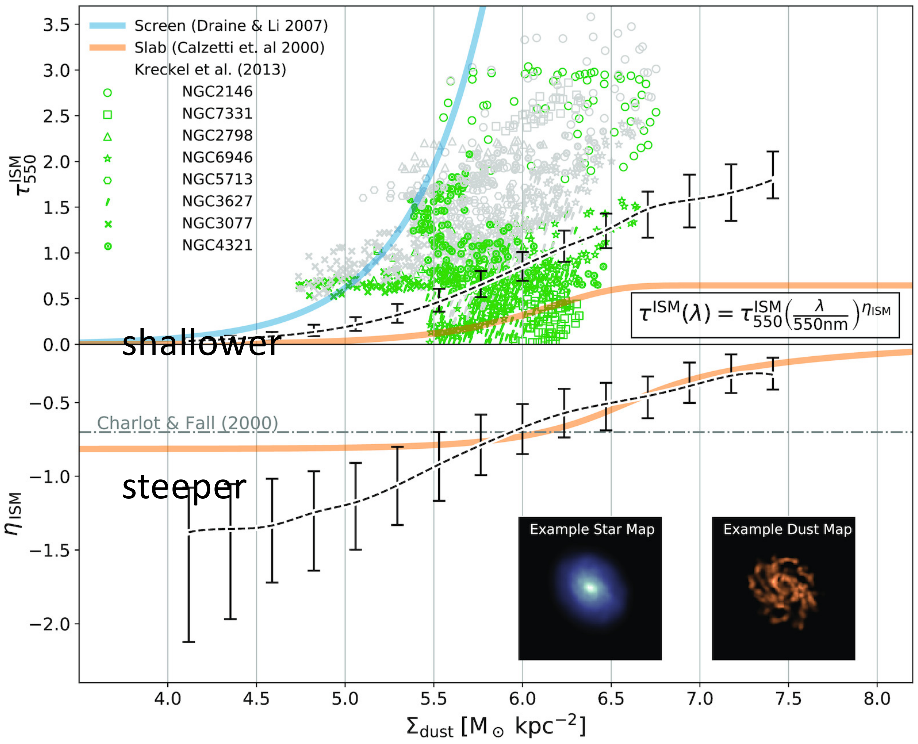
→ **Grayer attenuation curve in the NIR than any extinction curve and Calzetti law**

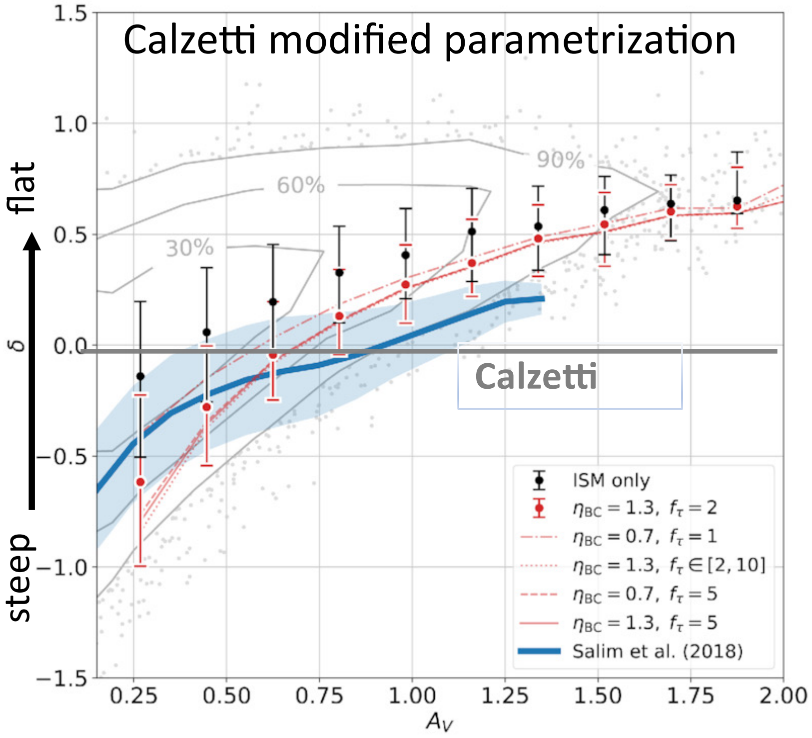


# Cosmological(Eagle) simulations +SKIRT RT & Charlot & Fall and Calzetti flexible formalisms

# → the attenuation curve flattens when $A_V$ increases

# (*Trayford+20*)





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*SED fitting methods, variation of attenuation laws*

- The case of dusty IR luminous galaxies

❖Amount of Attenuation, empirical relations

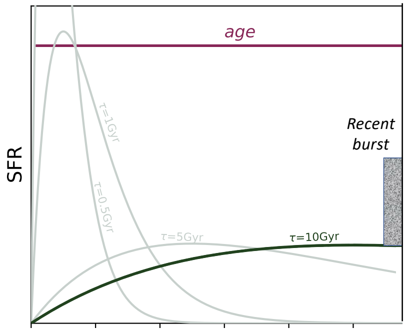
# Attenuation laws derived from observations

- **Fitting the Spectral Energy Distributions (SEDs)**

*e.g. Salim18 (z=0), Buat+09, 11, 12,18,19, Kriek & Conroy 13, Salmon +16,, Lo Faro +17, Cullen+18, Battisti+20*

# Fitting the SED (e.g. with CIGALE): the UV-optical (stellar) emission

## Star formation history



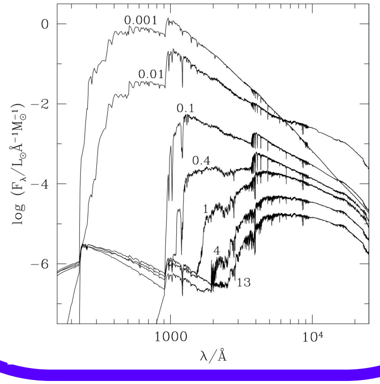
⊗

## Simple Stellar Populations

**Bruzual & Charlot 2003**

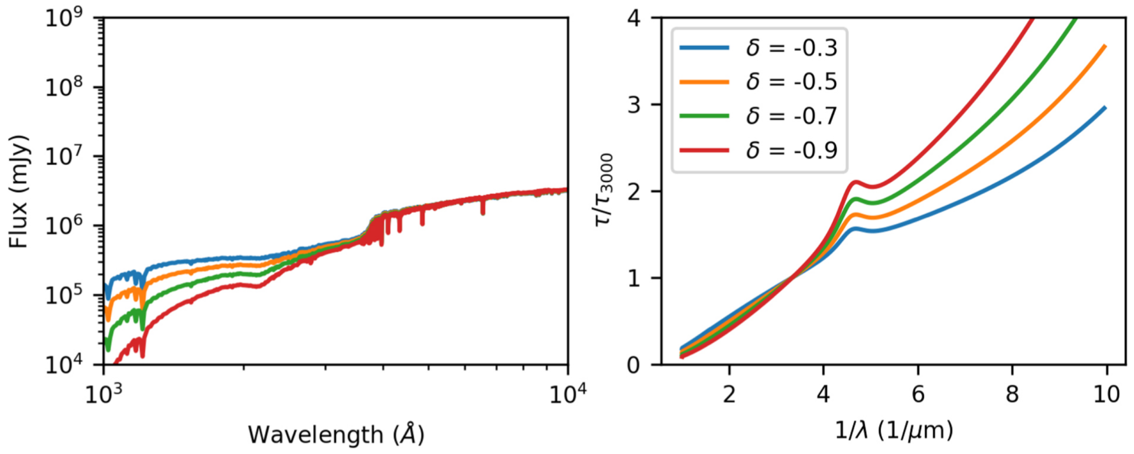
(BPASS, Maraston+05, Pegase)

**+IMF**

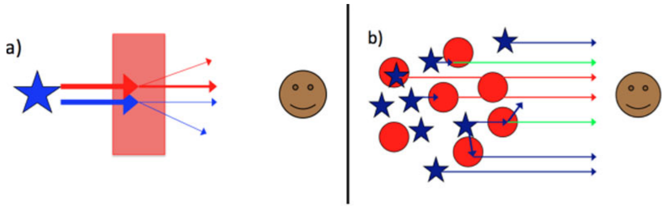


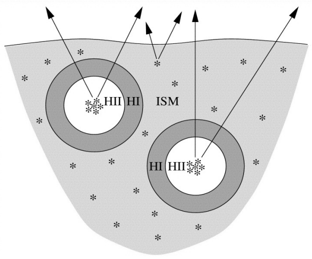
+

## Dust attenuation of the stellar continuum



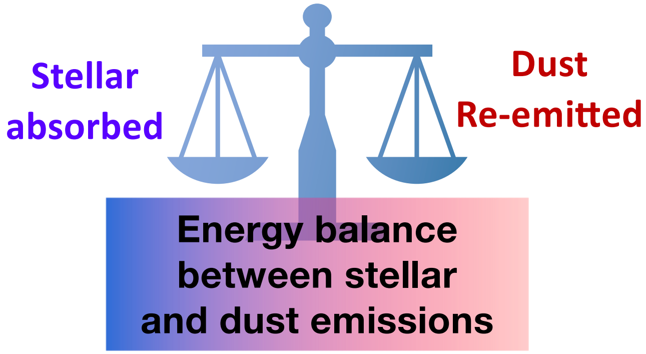
## Charlot & Fall and Calzetti flexible recipes





*Adapted from Narayanan+18, Calzetti12, Charlot&Fall00,*

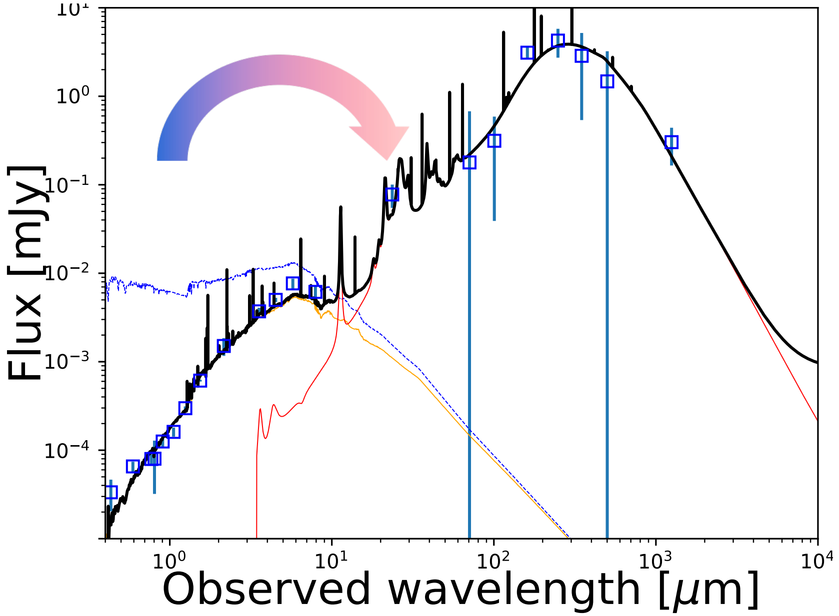
# Fitting the SED : re-emitted dust emission

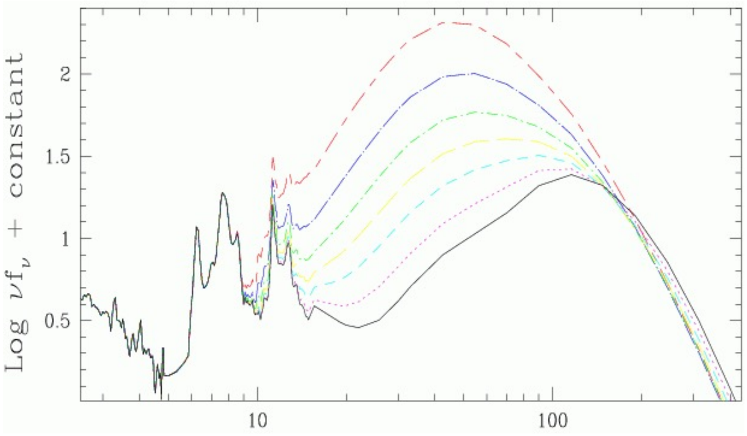


**Stellar absorbed**

**Dust Re-emitted**

**Energy balance between stellar and dust emissions**





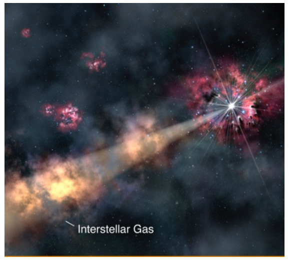
Libraries of dust emission templates as:

1. **The Dale & Helou 02 library**
2. **Draine & Li 07** (more physical, more parameters)
3. **THEMIS** models
4. (combination of **Modified**) **Black Bodies** (essentially for temperature estimations)

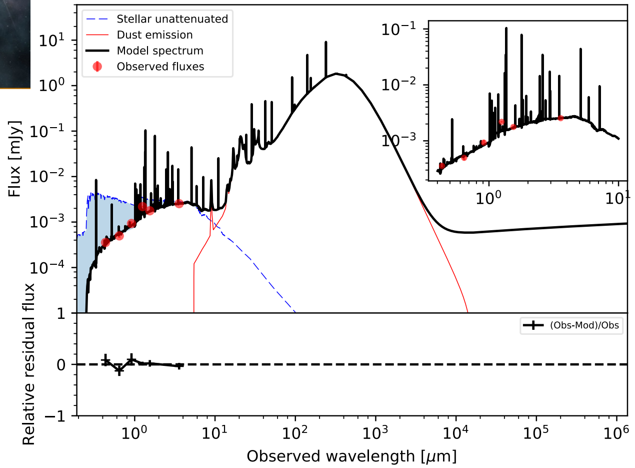
……..

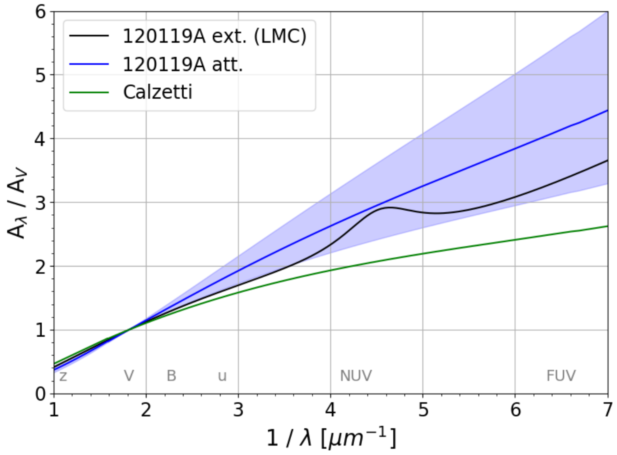
# The attenuation curve shapes the UV-to-NIR SED (with the star formation history)

*Corre+18*

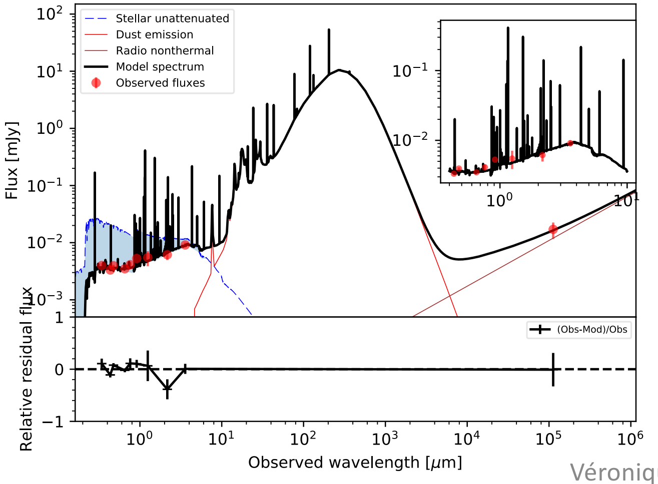


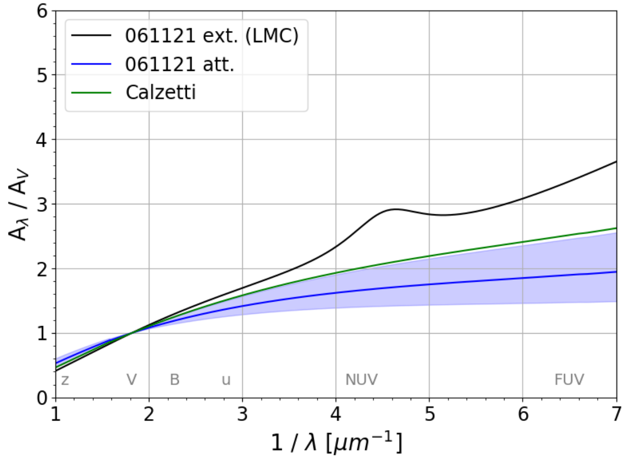
**GRB hosts**





Steep attenuation Curve
Steeper than Calzetti law

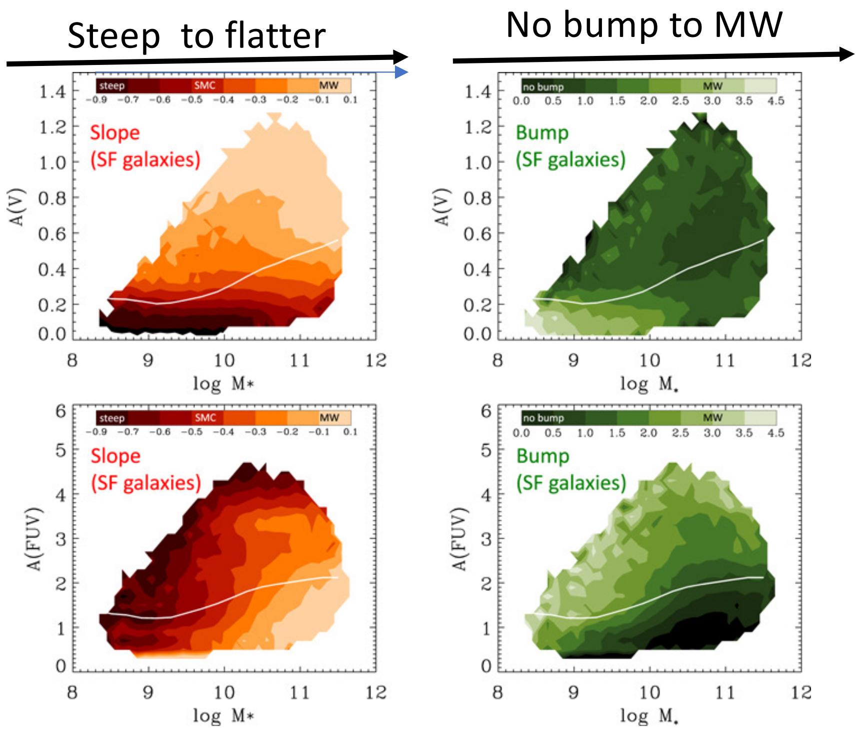




Flat Attenuation Curve
Flatter than Calzetti law

# SDSS +GALEX+WISE z~0

## fits with Calzetti flexible att. Laws (*Salim+18)*

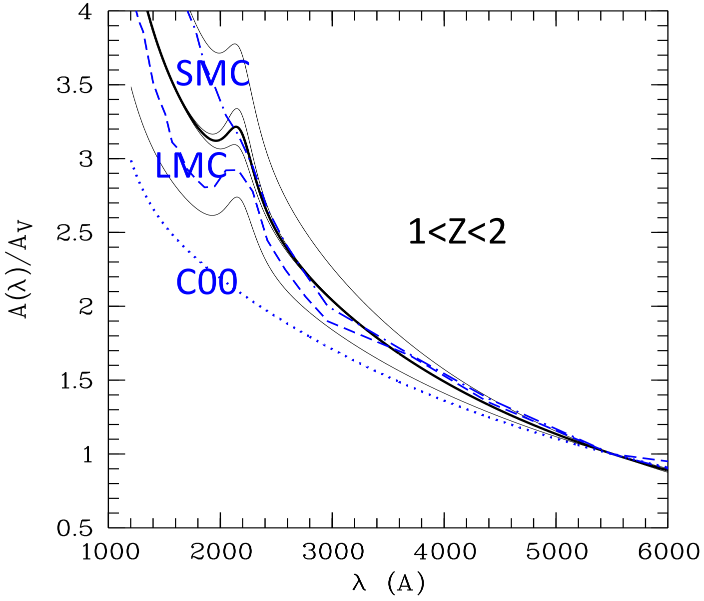


Steep to flatter

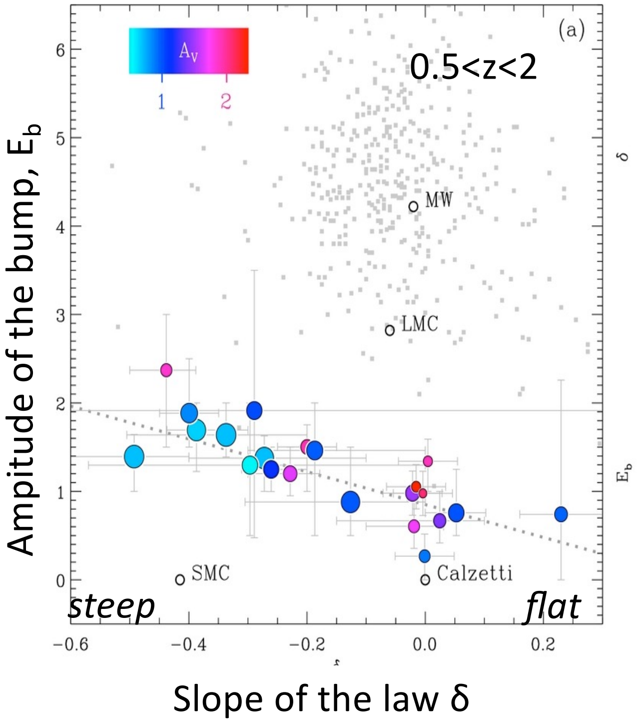
No bump to MW

- A(UV), A(V) increases with $M_{star}$
- Att. Law flattens & bump amplitude decreases when A(V), A(UV) increases (consistent with RT predictions), when $M_{star}$ increases

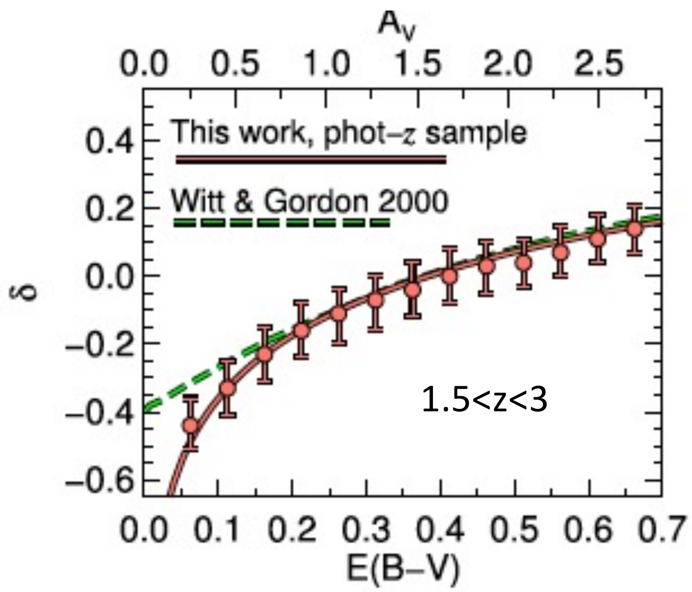
# The variation of the attenuation curve also at z>0 for optically selected, star-forming galaxies, also confirming RT results



*Buat+11,12, GOODS-H*
*Bump~LMC, steeper than C00*



*Kriek & Conroy 2013,*
*NMBS survey*



*Salmon+16, CANDELS*

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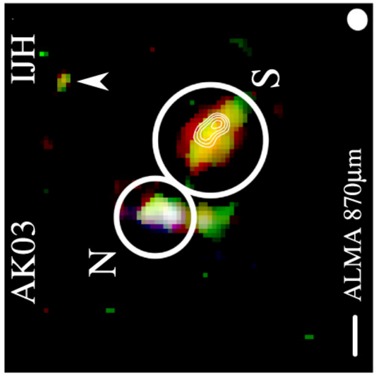
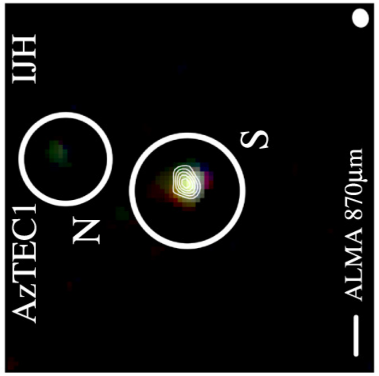
❖Amount of Attenuation, empirical relations

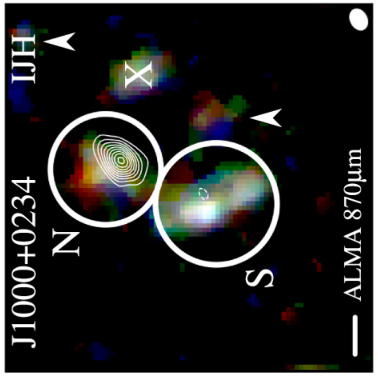
# Submillimeter galaxies (SMG) at z~4.5: HST/ALMA observations: multiple components and minor mergers, stellar and dust disconnection



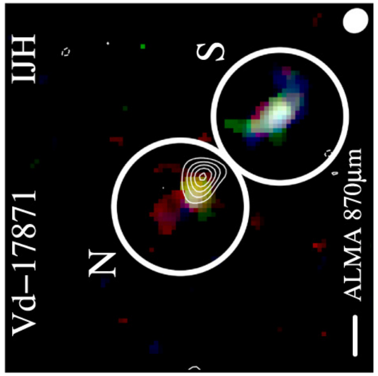
S: $SFR_{IR}$= 120 $M_{sun}yr^{-1}$
$SFR_{UV}$=25 $M_{sun}yr^{-1}$
N: $SFR_{UV}$=53 $M_{sun}yr^{-1}$



S: $SFR_{IR}$= 2400 $M_{sun}yr^{-1}$
$SFR_{UV}$=45 $M_{sun}yr^{-1}$
N: $SFR_{UV}$=8.5 $M_{sun}yr^{-1}$



S: $SFR_{UV}$=148 $M_{sun}yr^{-1}$
N: $SFR_{IR}$= 440 $M_{sun}yr^{-1}$
$SFR_{UV}$=53 $M_{sun}yr^{-1}$



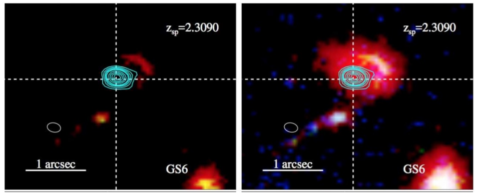
S: $SFR_{UV}$= 59 $M_{sun}yr^{-1}$
N: $SFR_{IR}$= 1120 $M_{sun}yr^{-1}$
$SFR_{UV}$=22 $M_{sun}yr^{-1}$

$SFR_{IR}$ >> $SFR_{UV}$, dust emission in the reddest (stellar) components
stellar masses also difficult to estimate

*Gomez-Guijarro+18*

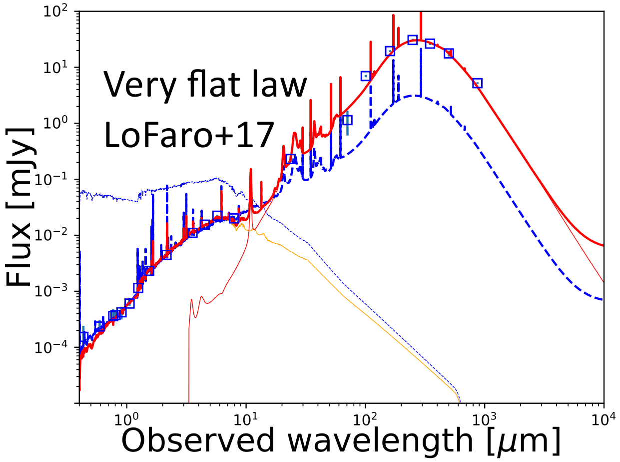
# Fitting the SED of IR bright galaxies observed with ALMA at z~2

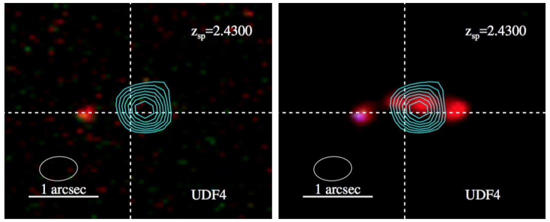
- **UV-NIR rest frame data**: stellar continuum → recovers at most half of the IR dust luminosty
- **Fit of the full UV-submm**: stellar and dust emission→ various ‘flat’ attenuation laws, from Calzetti to much flatter



$L_{dust}^{UV\text{-}NIR} = 0.11\ L_{dust}^{IR}$

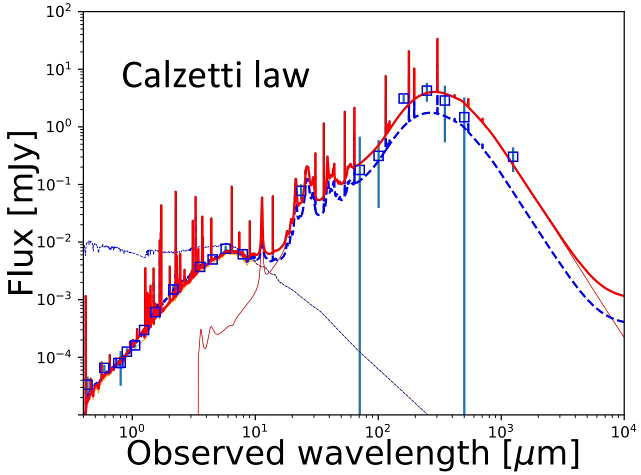
Best fit for GS6





$\mathbf{L_{dust}^{UV\text{-}NIR} = 0.47\ L_{dust}^{IR}}$

Best fit for UDF4

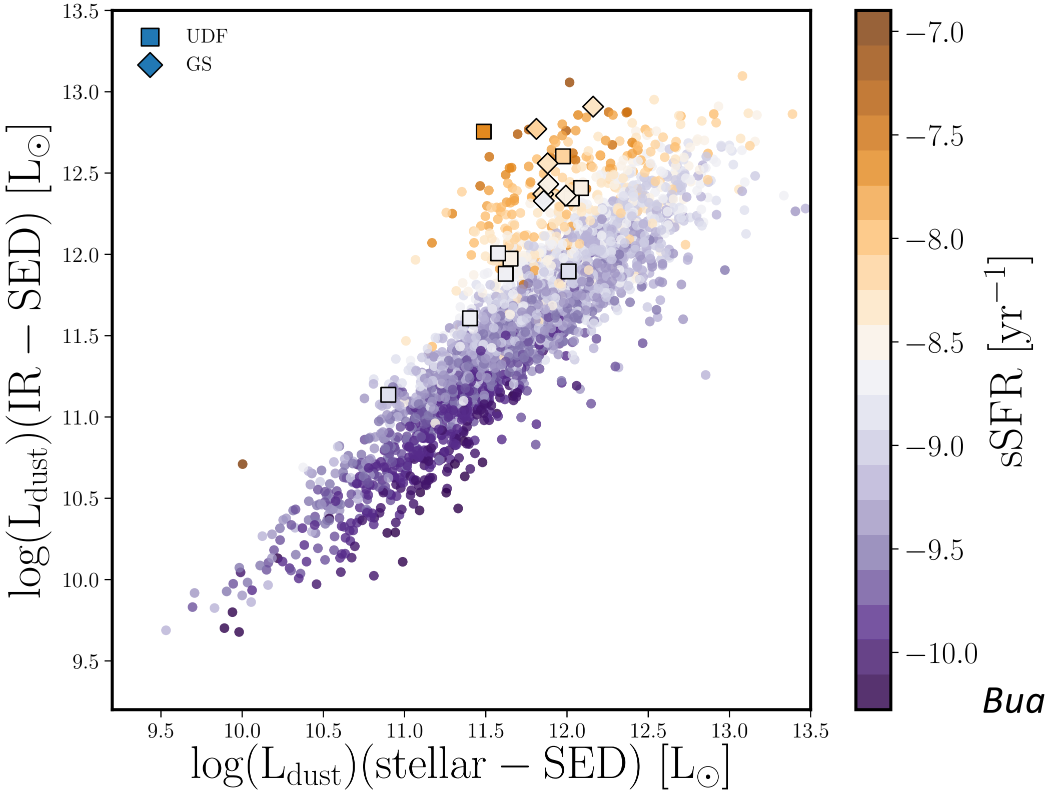


*Buat+19*

# Dusty galaxies with a large amount of hidden SFR are rare objects:

Dusty galaxies detected in ALMA blind or pointed surveys depart from this general trend:
high sSFR, massive and IR bright

COSMOS galaxies
with IR/Herschel data (HELP) :
$L_{IR}$ estimated from stellar SED
consistent with $L_{IR}$ from the IR-SED
except for galaxies with high sSFR



*Buat +19*

# Outline

❖Dust and stellar interplay in galaxies

❖Dust attenuation laws

**❖Amount of Attenuation, empirical relations**

- The IRX-β, (dust attenuation) relation
- Attenuation-stellar mass relation
- Nebular and stellar attenuation

# Outline

❖Dust and stellar interplay in galaxies

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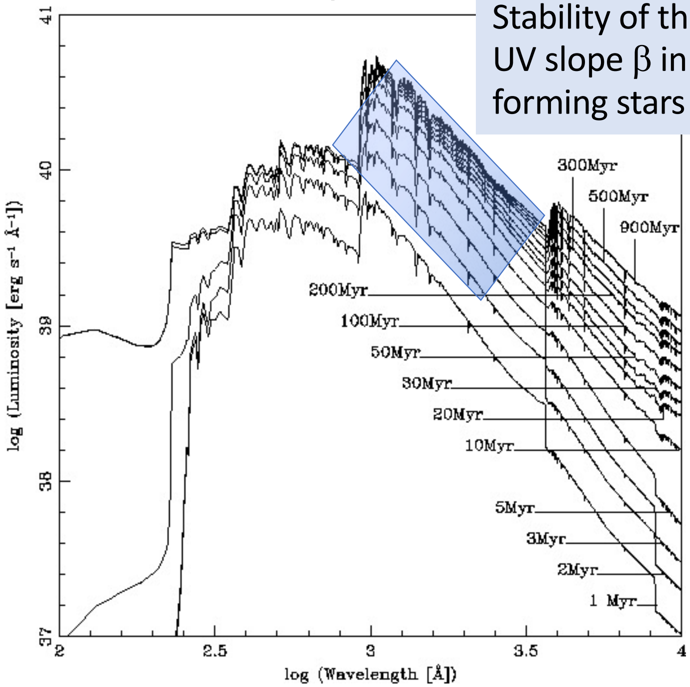
# Beginning of the story: the original IRX-β relation

*Meurer et al. 1995, 1999*

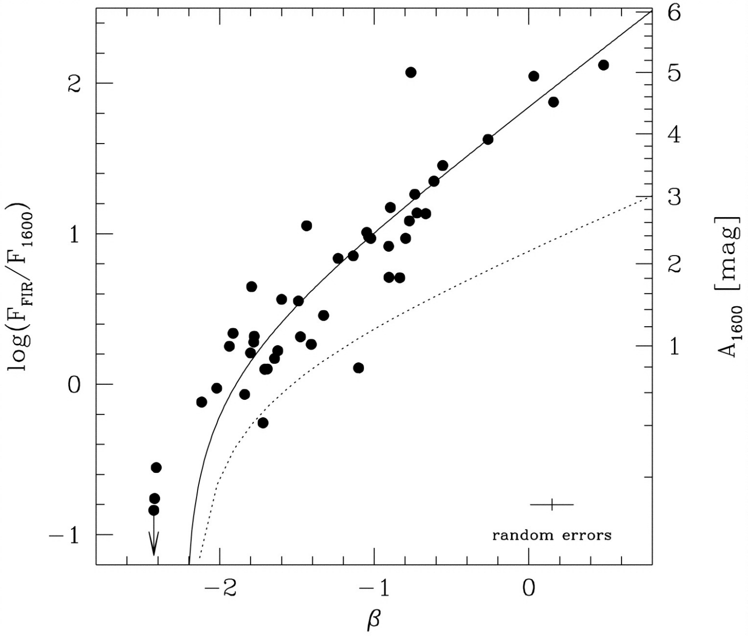
$f_\lambda \propto \lambda^\beta$(1200-2500Å),
$\beta \simeq -2.2$



Stability of the intrinsic UV slope β in galaxies forming stars actively

Starbust99: stellar populations synthesis models

β: a proxy for dust attenuation in **local starburst galaxies (Calzetti sample already used to build the 'Calzetti' law)**



The relation of Meurer+99 is found consistent with the Calzetti law, **but is not a measure of the law**

# Simple physics to understand the origin of the IRX- β relation

Dust emission = stellar light absorbed $L_{ir} \propto \int_{\lambda_{min}}^{\lambda_{max}} (1 - e^{-\tau_\lambda}) d\lambda$ With a major contribution of UV photons ( $\tau_{UV}$)

UV light observed $L_{UV} \propto e^{-\tau_{UV}}$

$$\boxed{IRX = \frac{L_{IR}}{L_{UV}} = f(\tau_\lambda) \quad \tau_\lambda \sim \tau_{UV}}$$

$f_\lambda \propto \lambda^\beta$ → Slope β

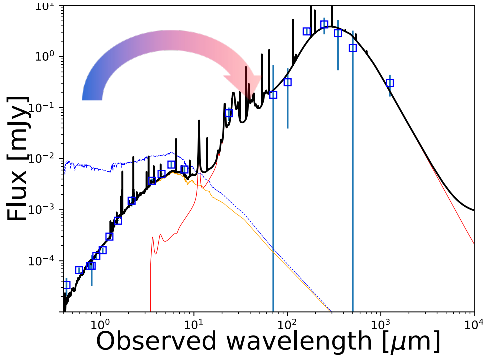
$$\beta = \frac{\log(F_{\lambda 1}/F_{\lambda 2})}{\lambda 1 - \lambda 2}$$

$F_{\lambda i} \propto e^{-\tau_{\lambda i}}$

$$\boxed{\beta \propto \tau_{\lambda 2} - \tau_{\lambda 1}}$$

→ Dependence on both the attenuation curve in UV ( β ) and on the total amount of attenuation (IRX)

→ **The IRX- β diagram is a diagnostic to study/measure dust attenuation in galaxies**



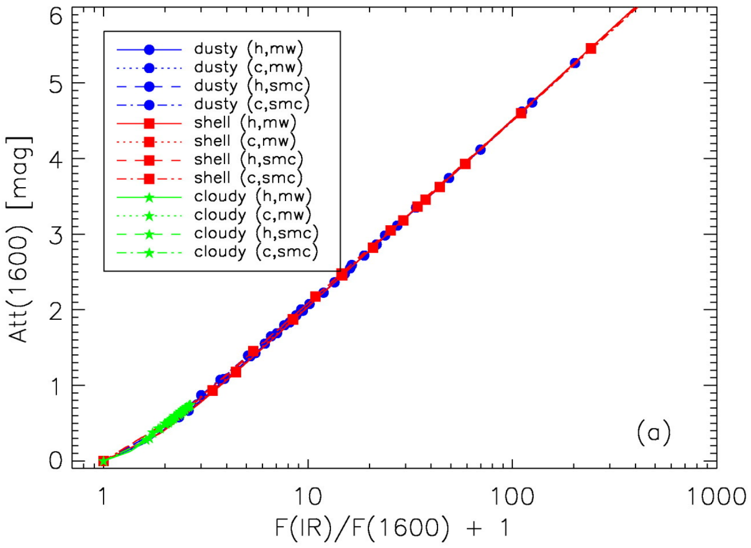
# IRX = $L_{IR}$ / $L_{FUV(obs)}$

with $L_{IR}$ : 5-1000 μm, $L_{FUV} = \nu.F\nu$ at ~150 nm

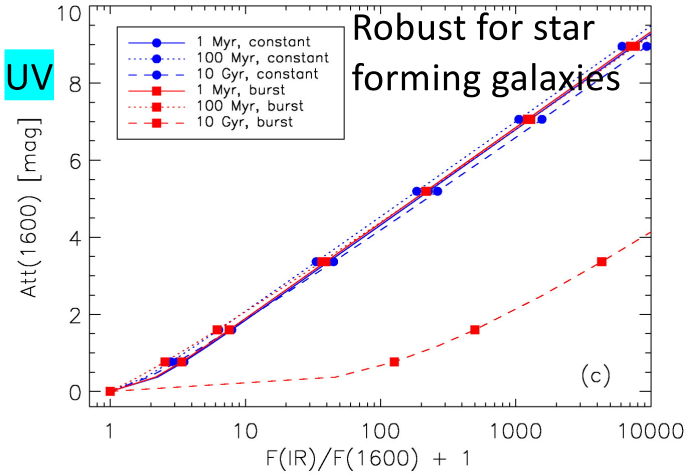
## $A_{FUV}$ = f(IRX)

a very robust proxy of dust attenuation in the UV **for star forming galaxies, both from models and observations**

*e.g. Meurer et al. 99, Buat+05,+11, Hao et al. 11,*

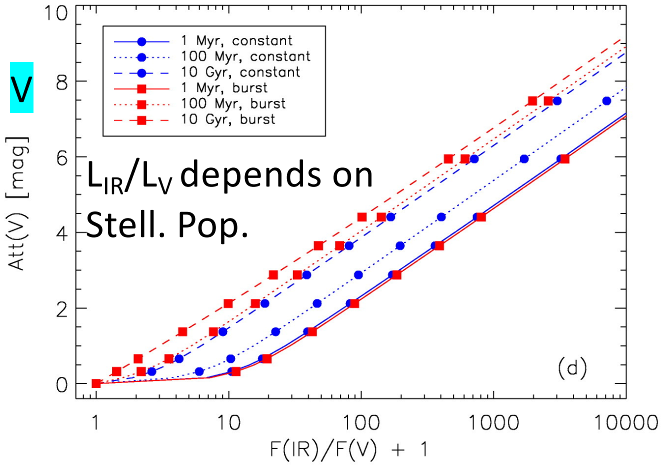


*Models of Witt & Gordon, 00, Gordon+00*



UV

Robust for star forming galaxies



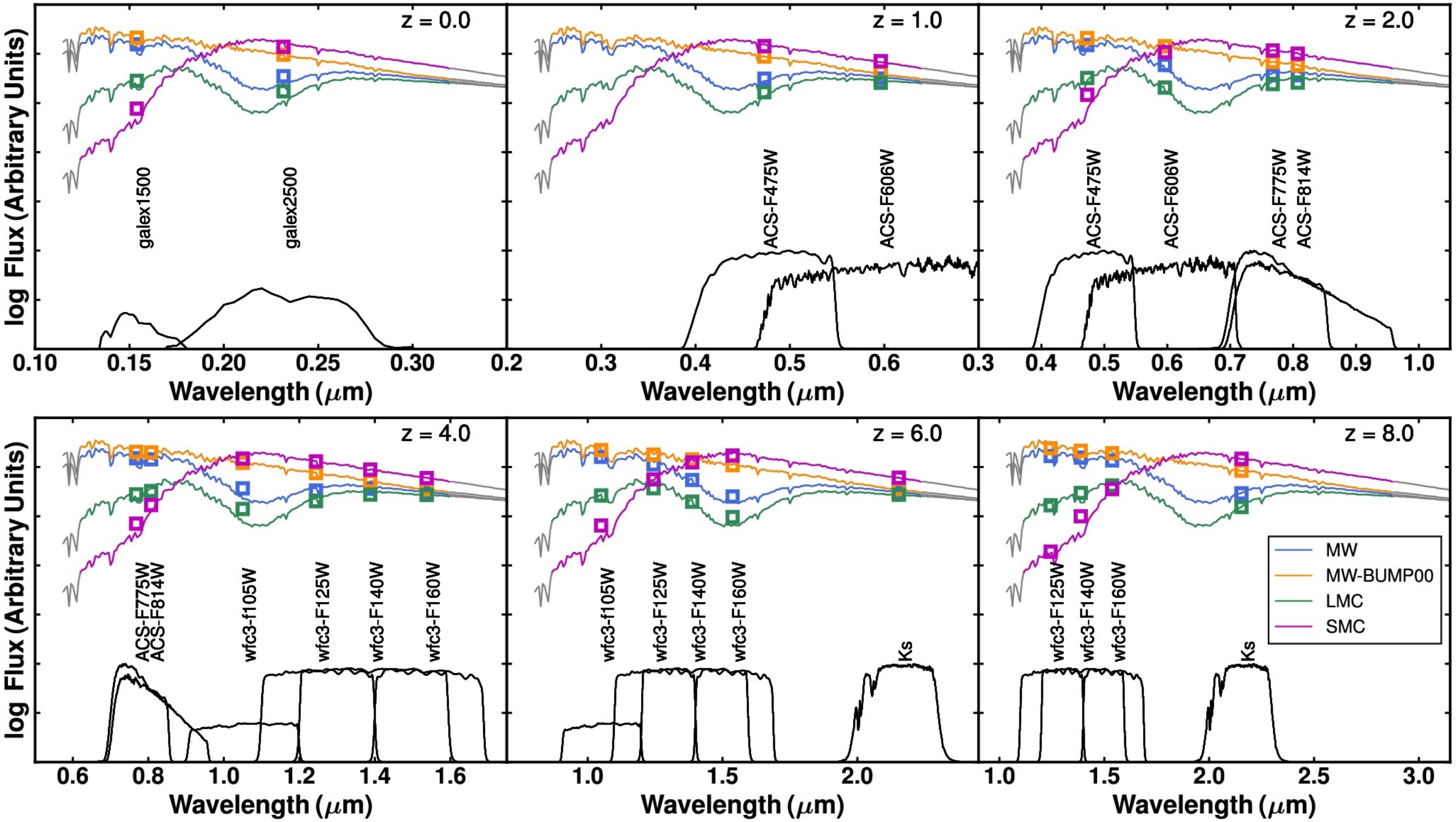
V

$L_{IR}/L_V$ depends on Stell. Pop.

# **How to measure β?** most of the time with broad band filters:

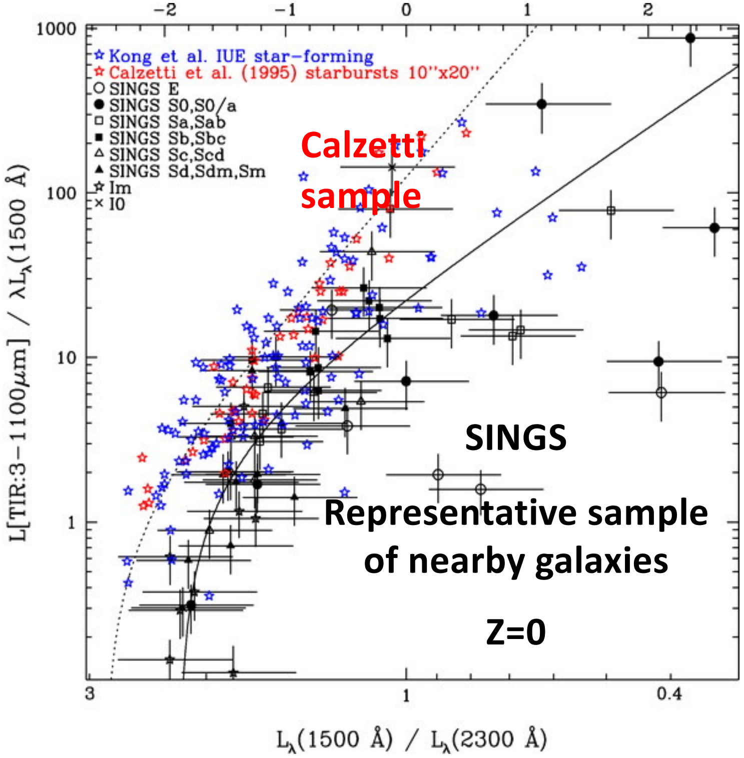
does not always give a good representation of the UV spectrum

easier at z>0



*Popping+17*

# IRX-β: a complex situation from observations at z=0



**Calzetti sample**

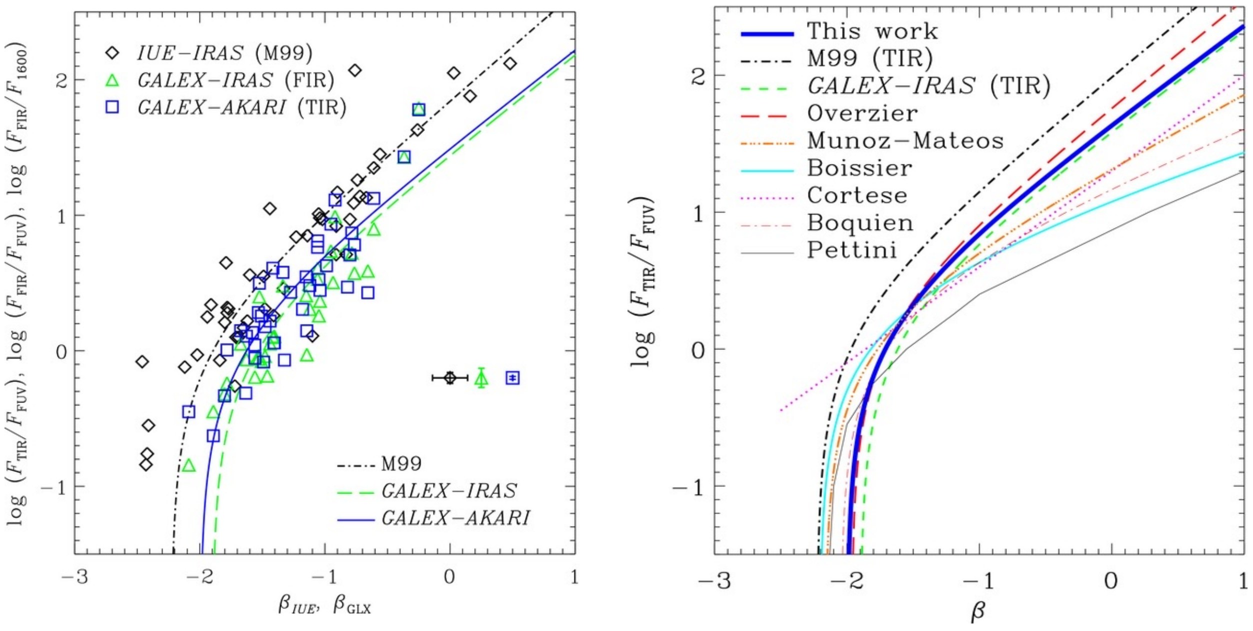
**SINGS**

**Representative sample of nearby galaxies**

**Z=0**

*Dale et al. 07: Spitzer and GALEX data*

*Takeuchi+12*



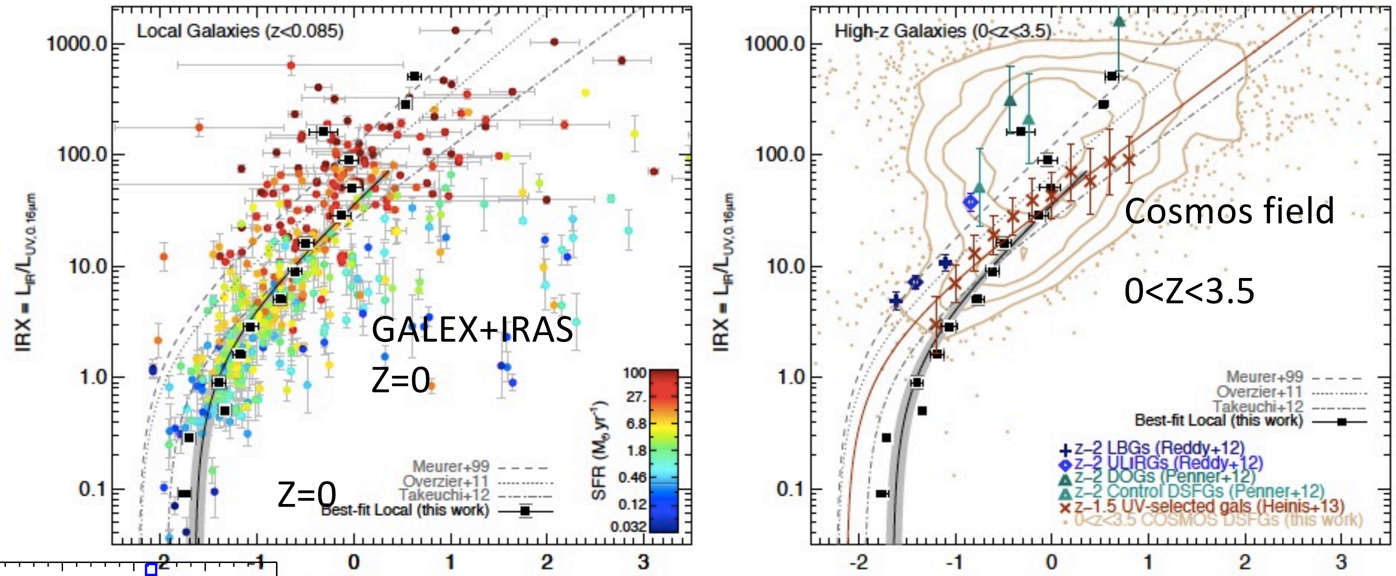
Calibration: IR and UV measured with different spatial resolution from IRAS & IUE (original work) to GALEX and Spitzer or Akari

IUE: 10''*20'' aperture

IRAS: integrated fluxes

# IRX-β: other samples, other redshifts….

*Casey+14*



GALEX+IRAS

Z=0

Z=0

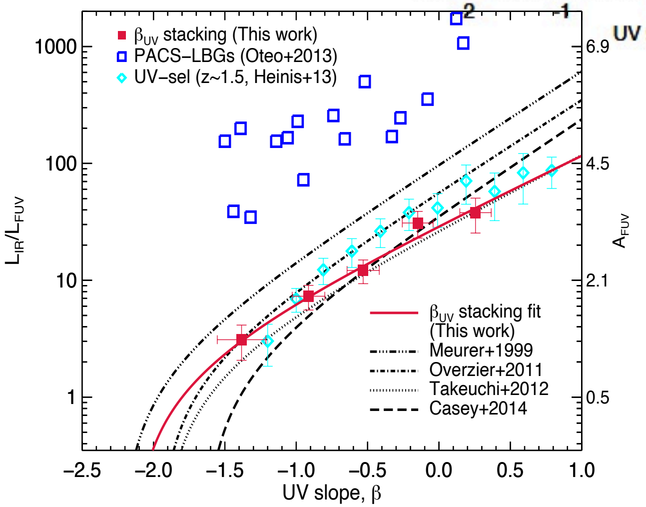
Cosmos field

0<Z<3.5

*Alvarez-Marquez+16*

Herschel stacked data on LBG

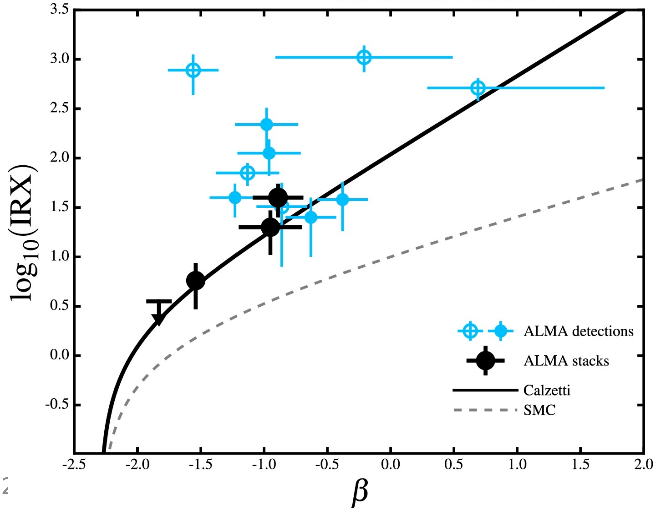
Z~3



Mc Lure+ 17

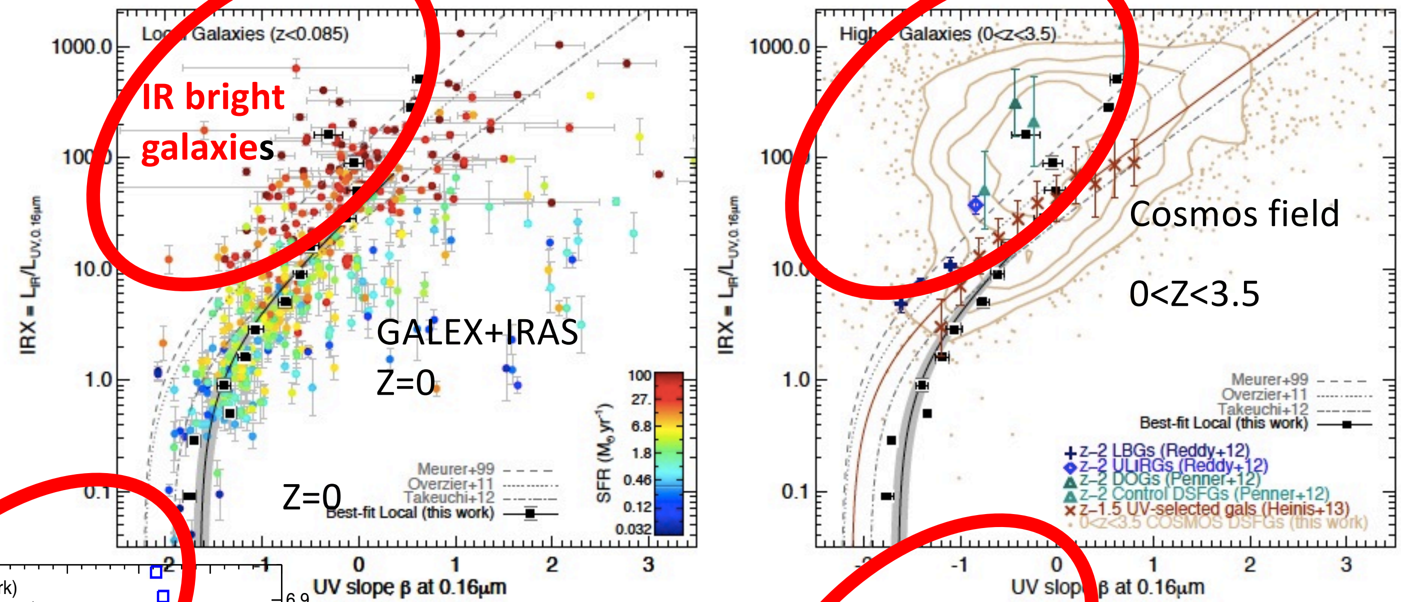
ALMA measurements

2<z<3



# IRX-β: other samples, other redshifts….

*Casey+14*



**IR bright galaxies**

GALEX+IRAS

Z=0

Z=0

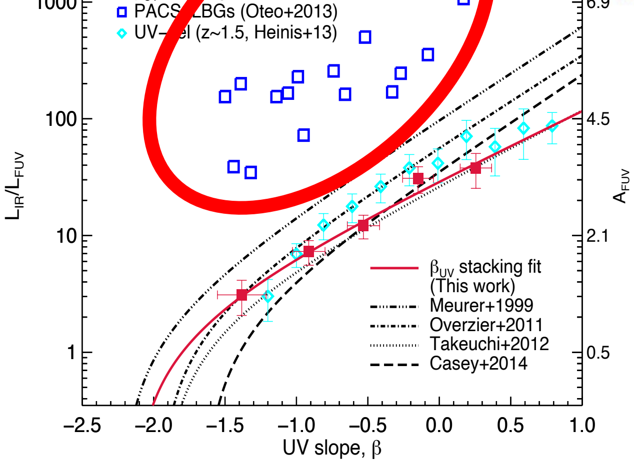
Cosmos field

0<Z<3.5

Alvarez-Marquez+16

Herschel stacked data on LBG

Z~3

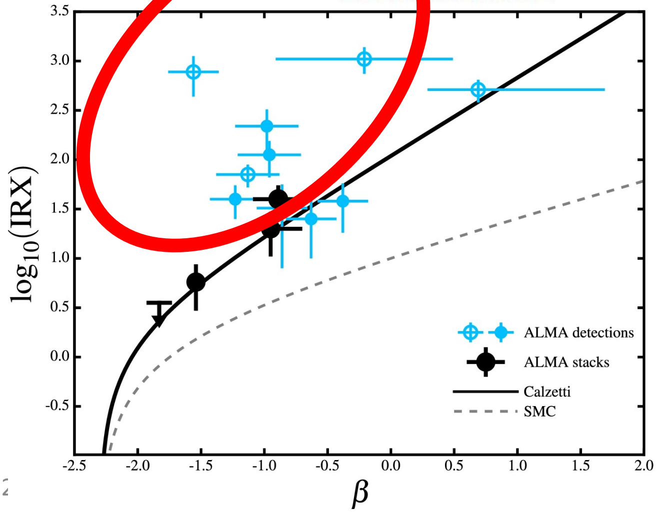


Fudamoto et al. 2020

ALMA data

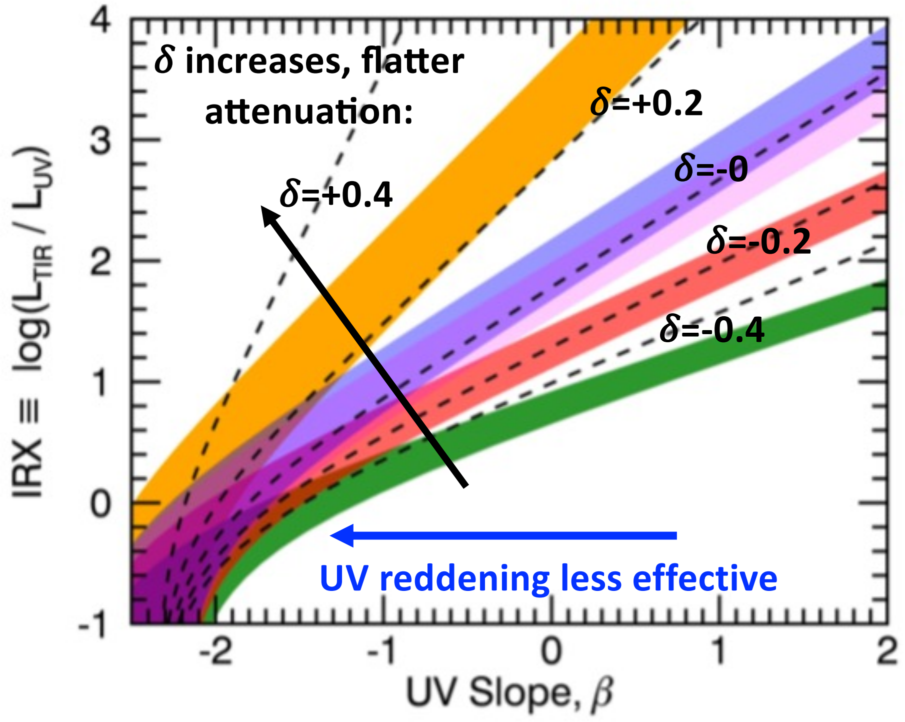
ALPINE project

Z=4.5 & 5.5



# Modeling the IRX-β diagram (1)
# Variations with the shape of the attenuation curve in the UV

*Salmon+16*



δ increases, flatter attenuation:

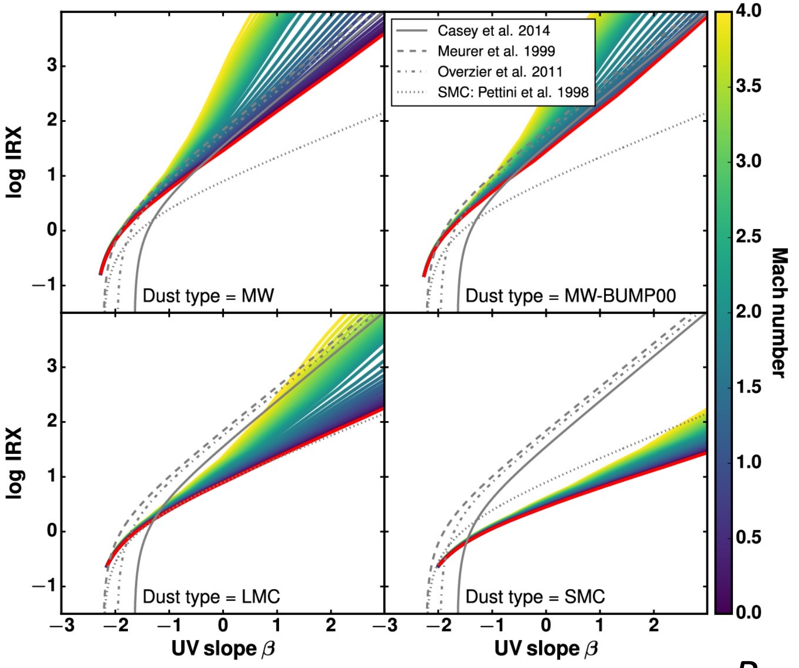
UV reddening less effective

*See also: Lo Faro +17 , Safarzadeh+16*

# Modeling the IRX-β plot (2)

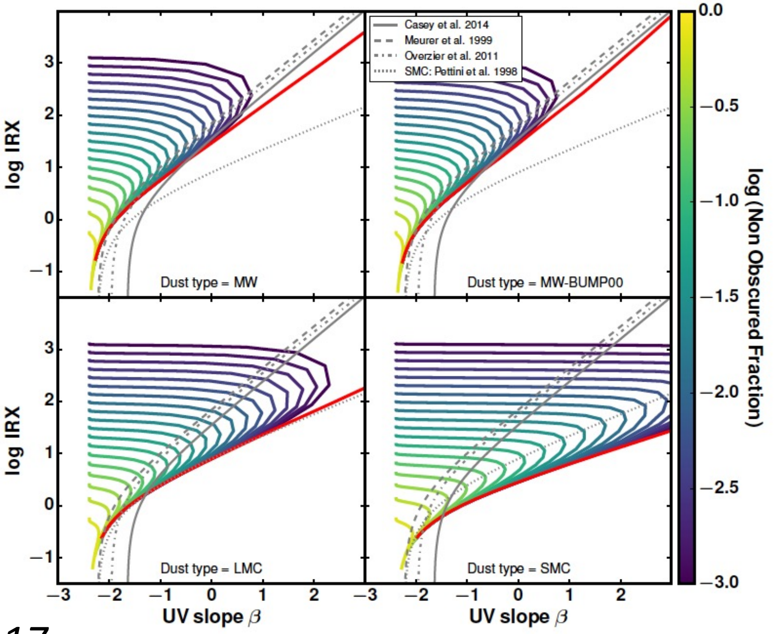
## Impact of stars/dust geometry

Turbulence and clumpiness:
grayer attenuation, lower reddening of $\beta$

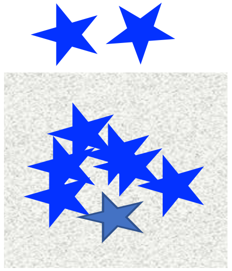


Popping+17

A fraction of the stellar light is unobscured:
Screen+holes structure
populate the upper part of the plot (locus of IR bright galaxies)

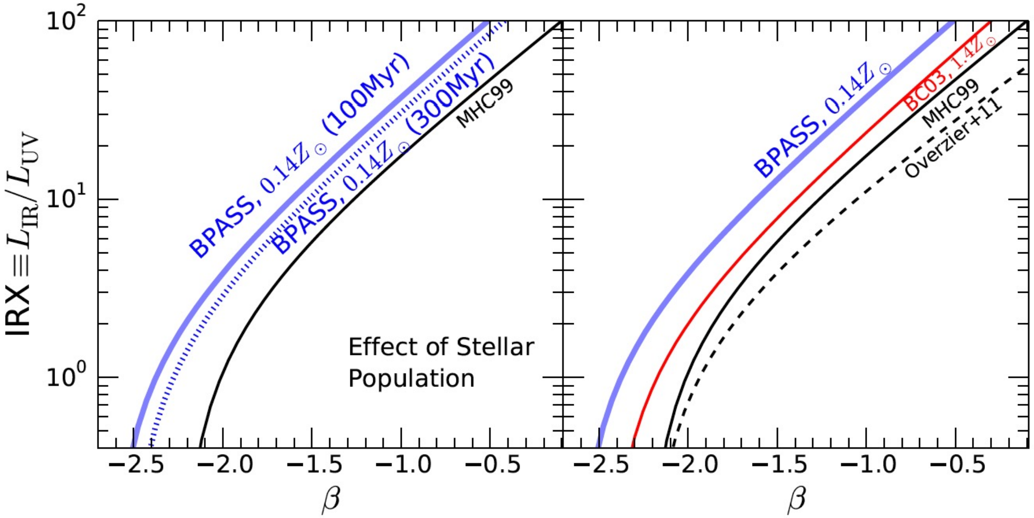


The UV light from the non-obscured stars dominate→ $\beta$ decreases



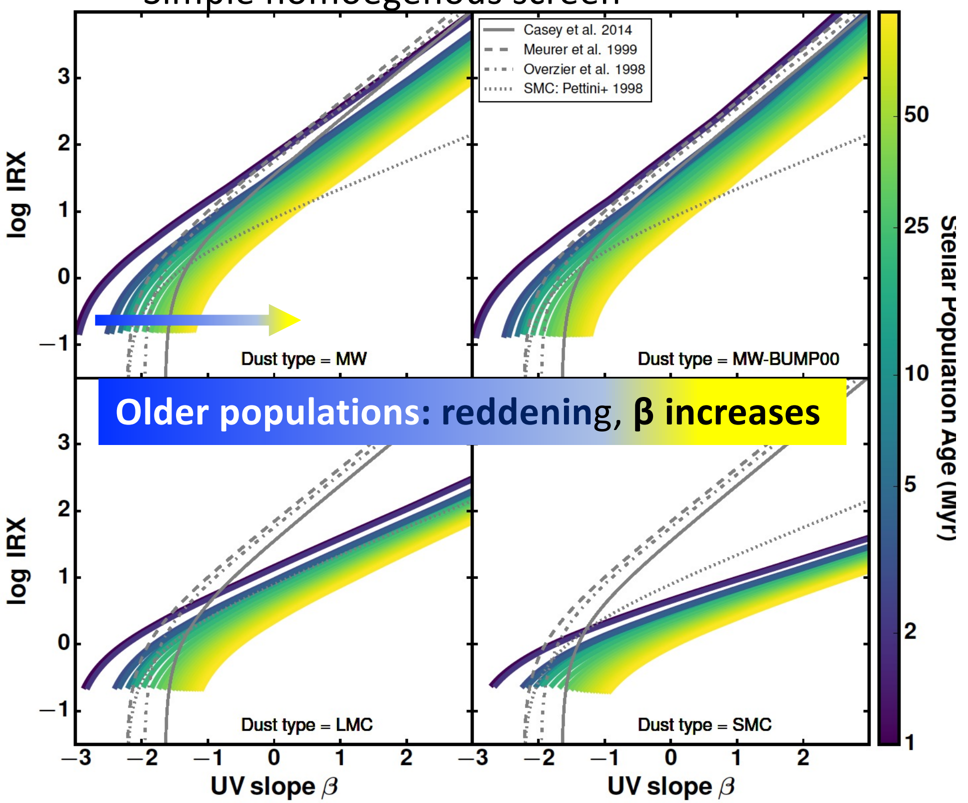
# Modeling the IRX-β plot (3)

## Impact of stellar populations



*Reddy et al. 2017*, modifying stellar models (BPASS including binaries) change the intrinsic $\beta$ value

Simple homoegenous screen

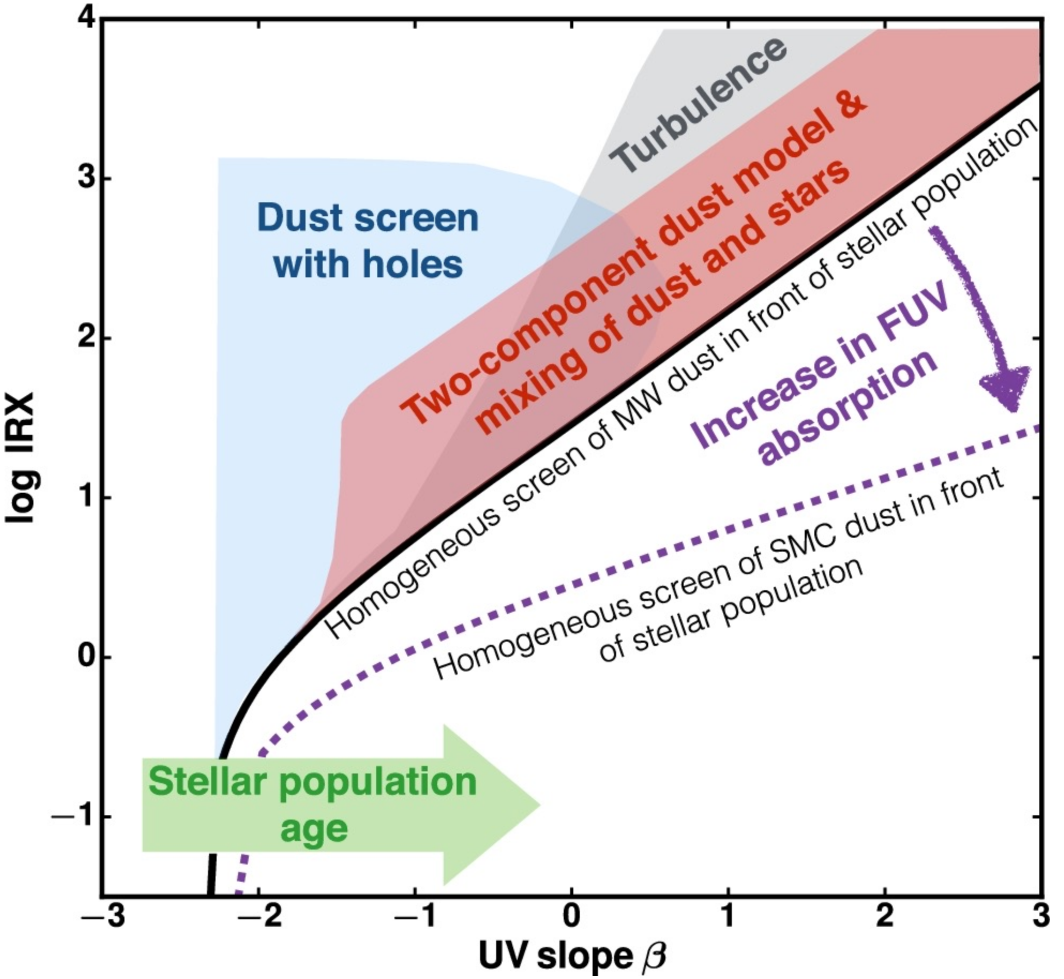


**Older populations: reddening, β increases**

*Popping et al 2017*: broadening with the age of the young stellar populations

**IRX (attenuation in UV) increases with β, but the exact position in the IRX- β diagram depends on dust and stellar properties**

*Popping+17*



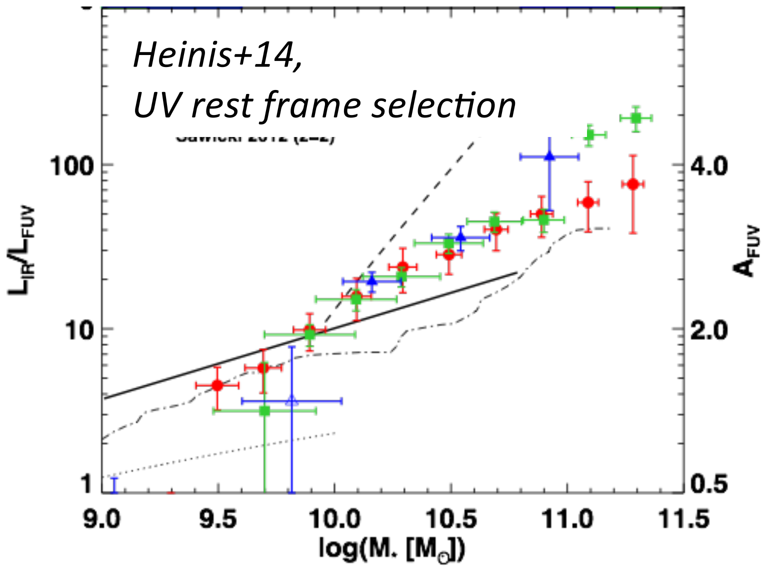
# Outline

- ❖Dust and stellar interplay in galaxies
- ❖Dust attenuation laws
- ❖**Amount of Attenuation, empirical relations**
  - The IRX-β, dust attenuation relation
  - Attenuation-stellar mass relation
  - Nebular and stellar attenuation

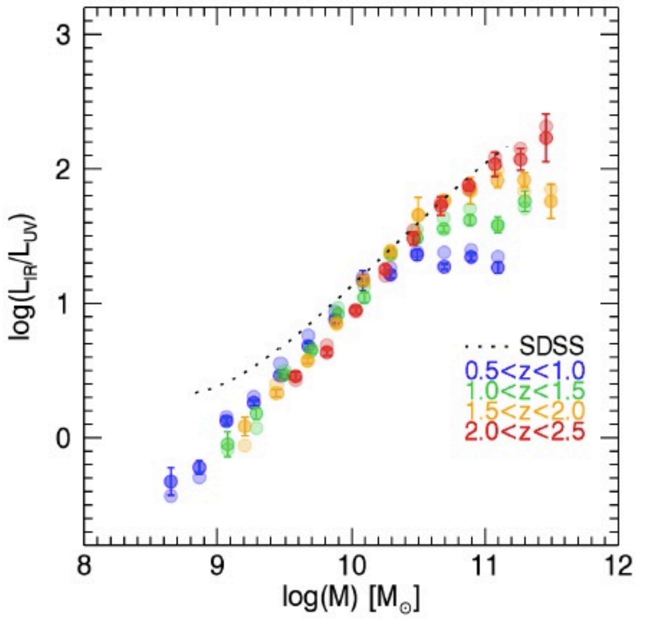
# Attenuation-stellar mass relation

Star forming galaxies (Stacking of Spitzer/Herschel data):
relatively well established for ~1<z<~3 (cosmic noon)

Z=1.5, 3, 4



*Heinis+14,*
*UV rest frame selection*

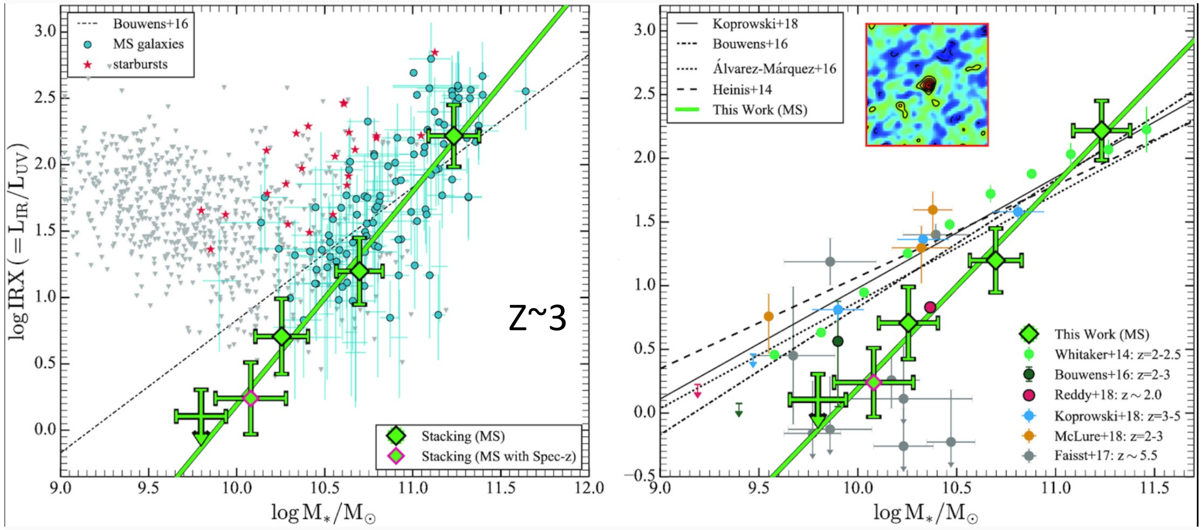


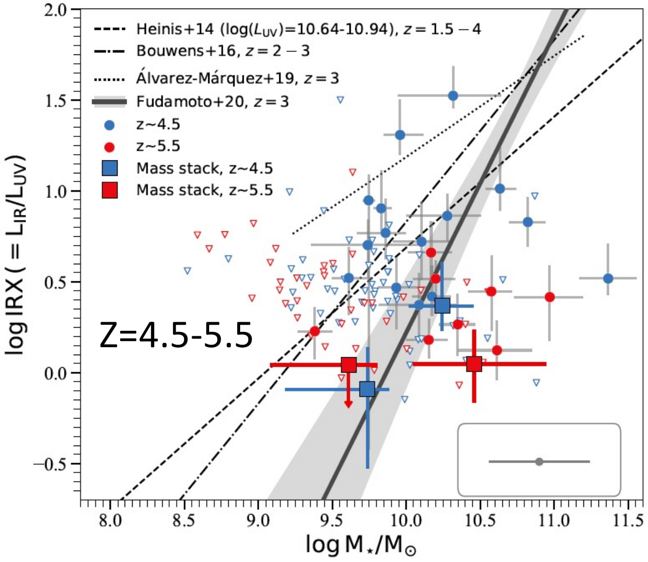
*See also Oteo+14, Panella+15, Dunlop+16….*

*Whitaker+14, CANDELS , UVJ selection, MIPS stacking*

# Relations $L_{IR}/L_{UV}$ (IRX) with $M_{star}$ still uncertain at z>3, possible decrease of IRX at a given mass

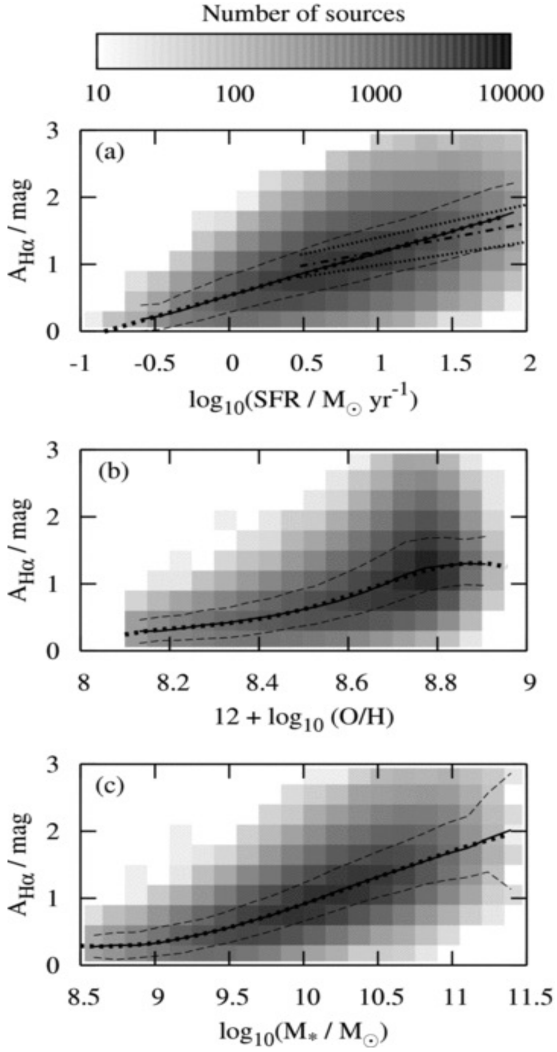
*Fudamoto 2020a,b*



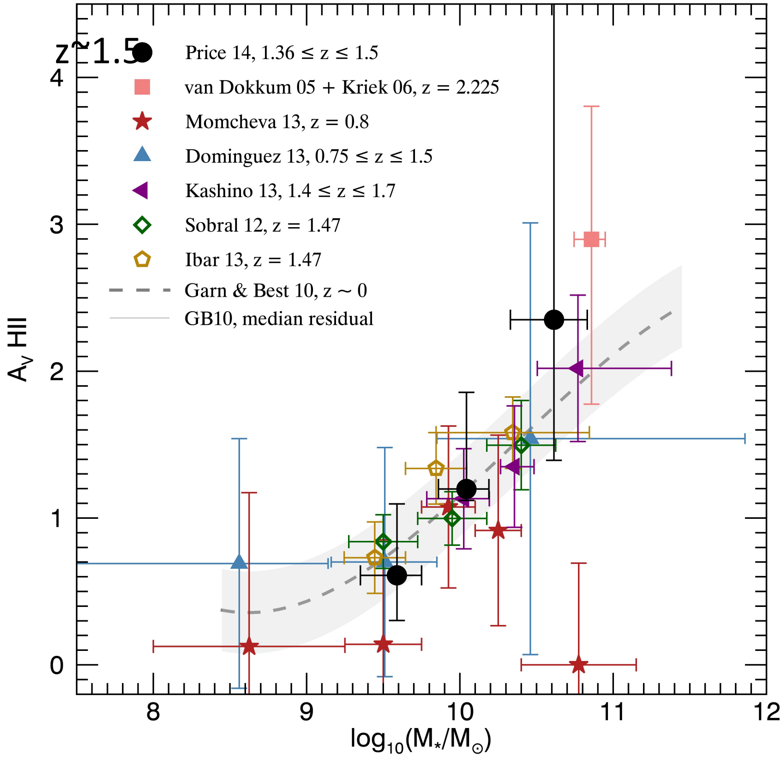


# Attenuation-Stellar mass relation also found for nebular lines

*Garn & Best, 2010, SDSS*



Stacking analysis



*Price+14*

# Outline

❖Dust and stellar interplay in galaxies

❖Dust attenuation laws

**❖Amount of Attenuation, empirical relations**

- The IRX-β, dust attenuation relation
- Attenuation-stellar mass relation
- Nebular and stellar attenuation

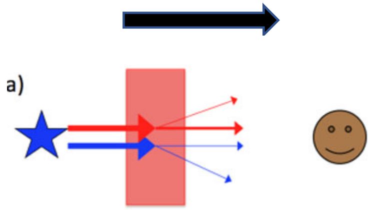
# Measurement of extinction in the lines based on the Balmer decrement

$BD = \frac{F_{H\alpha}}{F_{H\beta}}$

case B recombination, T~$10^4$ K

$BD_0 = 2.86$

Screen model



E(B-V)$_{lines}$ calculated by comparing BD observed to BD$_0$ and assuming an extinction law k($\lambda$)

$$E(B-V)_{line} = \frac{2.5}{k(H\beta) - k(H\alpha)} \log_{10}\left(\frac{BD}{2.86}\right), \qquad (1)$$

- k($\lambda$) Milky Way: $E(B-V)_{line} = 2.34 \log_{10} (BD/2.86)$, $A(H\alpha) = 2.54\ E(B-V)_{line}$
- k($\lambda$) SMC : $E(B-V)_{line} = 2.28 \log_{10} (BD/2.86)$, $A(H\alpha) = 2.17\ E(B-V)_{line}$
- k($\lambda$) *Calzetti:* $E(B-V)_{line} = 1.96 \log_{10} (BD/2.86)$; $A(H\alpha) = 3.33\ E(B-V)_{line}$

**→ The results depend on the choice of the extinction law (with a simple homogeneous screen)**

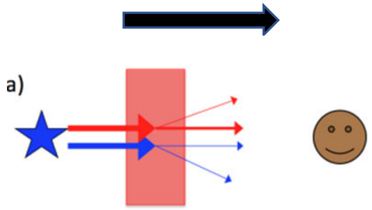
# Measurement of extinction in the lines based on the Balmer decrement

$$BD = \frac{F_{H\alpha}}{F_{H\beta}}$$

case B recombination, T~$10^4$ K

$BD_0$=2.86

Screen model



$E(B\text{-}V)_{lines}$ calculated by comparing BD observed to $BD_0$ and assuming an extinction law $k(\lambda)$

$$E(B\text{-}V)_{line} = \frac{2.5}{k(H\beta) - k(H\alpha)} \log_{10}\left(\frac{BD}{2.86}\right), \qquad (1)$$

- $k(\lambda)$ Milky Way: $E(B\text{-}V)_{line} = 2.34 \log_{10}(BD/2.86)$, $A(H\alpha) = 2.54\ E(B\text{-}V)_{line}$
- $k(\lambda)$ SMC : $E(B\text{-}V)_{line} = 2.28 \log_{10}(BD/2.86)$, $A(H\alpha) = 2.17\ E(B\text{-}V)_{line}$
- $k(\lambda)$ *Calzetti:* $E(B\text{-}V)_{line} = 1.96 \log_{10}(BD/2.86)$; $A(H\alpha) = 3.33\ E(B\text{-}V)_{line}$

→ **The results depend on the choice of the extinction law (with a simple homogeneous screen)**

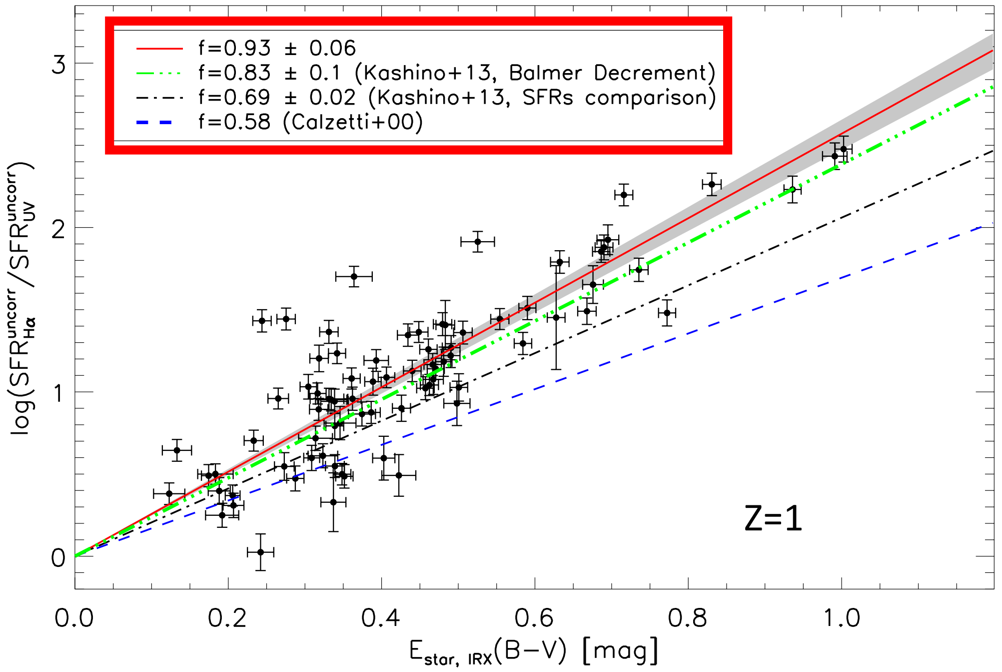
In several studies the Calzetti law is also used to measure the nebular/line attenuation which leads to a factor 2.34/1.96=1.2 in order to compare with the original relation of Calzetti

→ $E(B\text{-}V)_s = 0.44\ E(B\text{-}V)_{line}$ becomes $E(B\text{-}V)_s = 0.57\ E(B\text{-}V)_{line}$

→ $f$=0.44 becomes $f$=0.57

# Large variations of f= E(B-V)$_s$/E(B-V)$_{line}$

Comparison of SFR(UV) and SFR(H$\alpha$) to deduce attenuations in the GOODS-S field +3D-HST & Herschel data

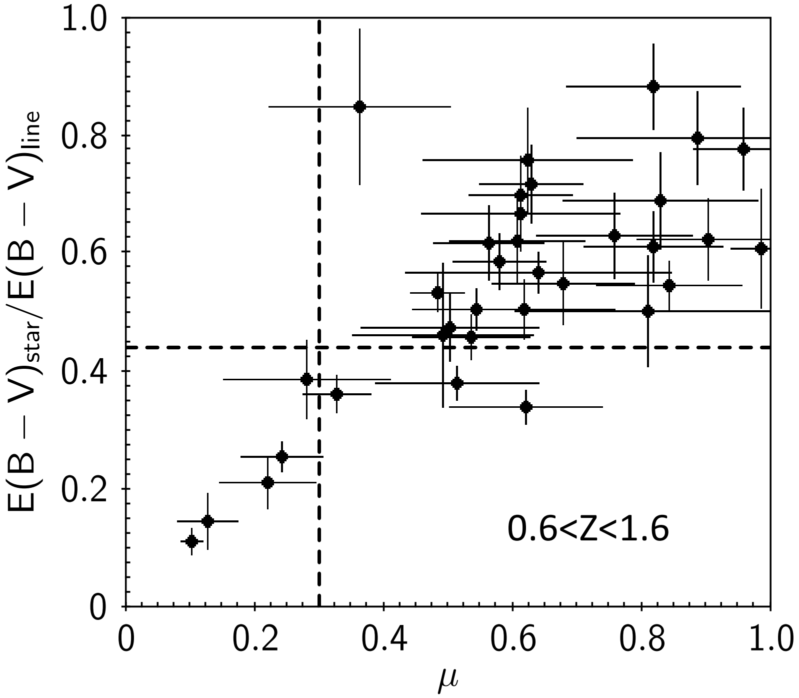


*Puglisi+16 see also Kashino+13*

μ (CF00) and f (C00) correlate

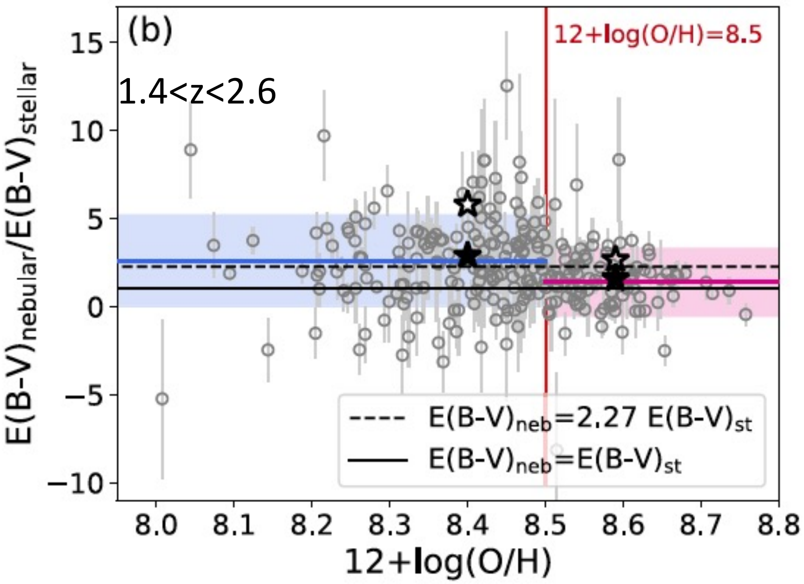
<f>= 0.54, <μ>=0.6

COSMOS -3D-HST field

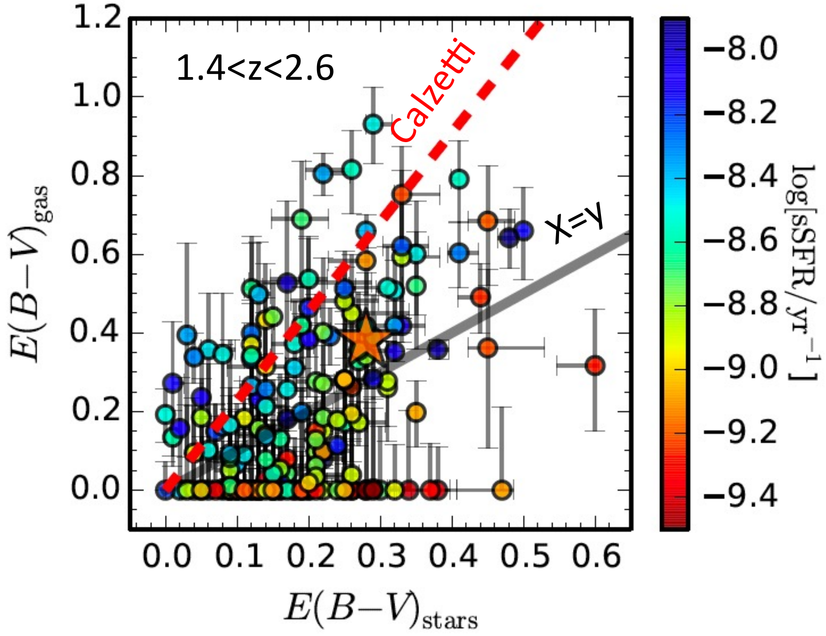


*Buat+18, see also Price+14*

# f= $E(B\text{-}V)_s/E(B\text{-}V)_{line}$ could vary with 12+log(O/H), stellar mass, intensity of SFR? still very uncertain trends



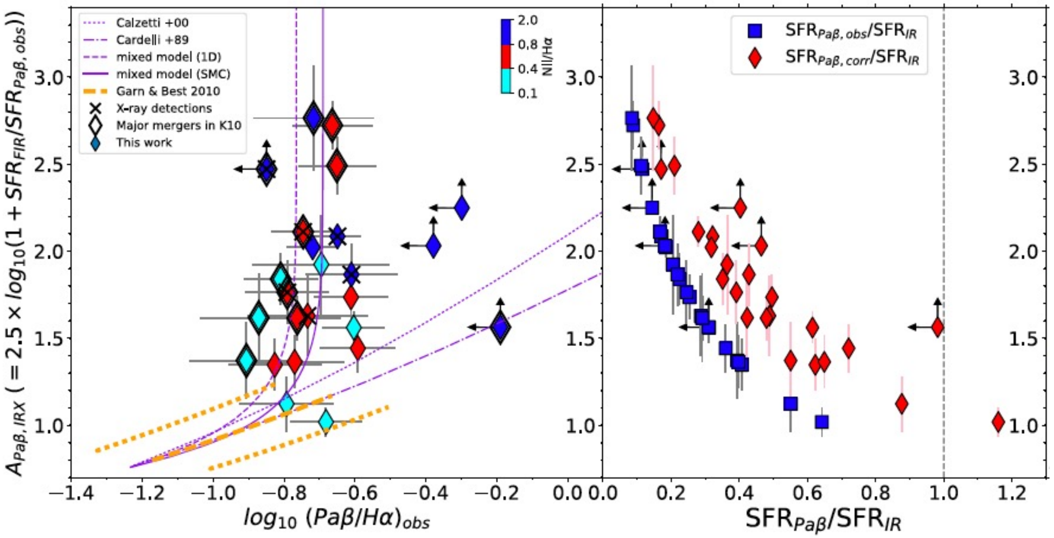
*Shivaie+20*



*Reddy+15*

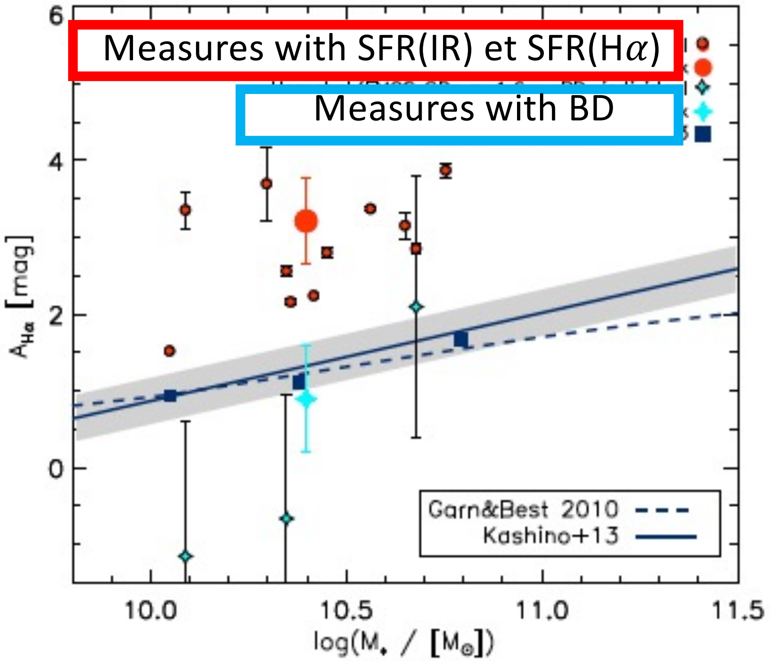
# Extreme obscuration in massive starburst galaxies:

## Hydrogen recombination line ratios are unable to recover all the obscuration



strong attenuation even in the Pa$\beta$ line

*Calabro +18*



Measures with SFR(IR) et SFR(H$\alpha$)

Measures with BD

*Puglisi+17*

# Few concluding remarks

- **Radiation Transfer modeling gives the theoretical framework** to understand the physical processes, to model resolved nearby galaxies and are introduced in numerical simulations
- **'Effective'** dust **attenuation laws are measured in galaxies and they are found not to be universal** and to flatten when the amount of attenuation increases, as expected from RT modeling
- **The different recipes** used to model the attenuation laws **are not equivalent in the visible-NIR domain** with implications on stellar mass measurements
- **The IRX-$\beta$ plot** is very sensitive to dust/stars interplay but difficult to handle
- **The obscuration of emission lines** in HII regions is not very well constrained out of the nearby universe. Data and models are still needed