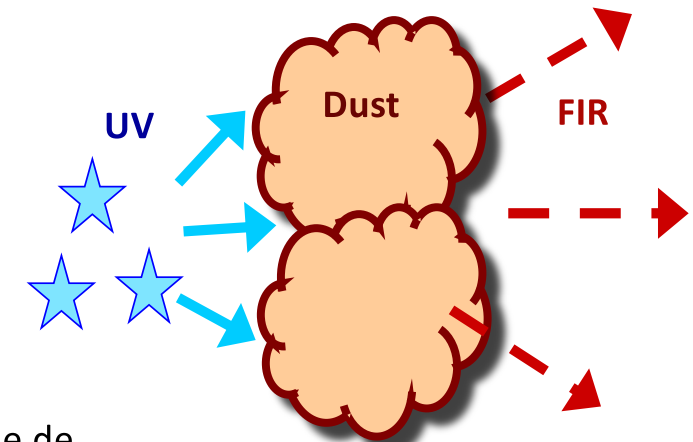
Dust and stars: an unavoidable and complex interplay

Dust Obscuration and attenuation laws in galaxies



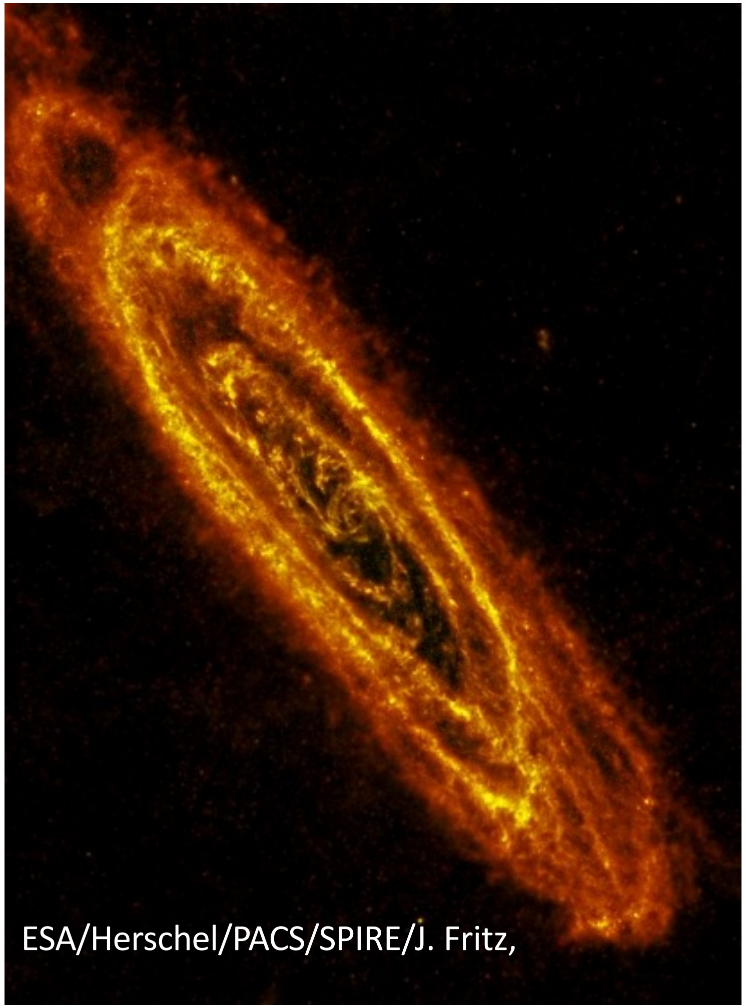
V. Buat, Laboratoire d'Astrophysique de Marseille (LAM) & Aix Marseille Université

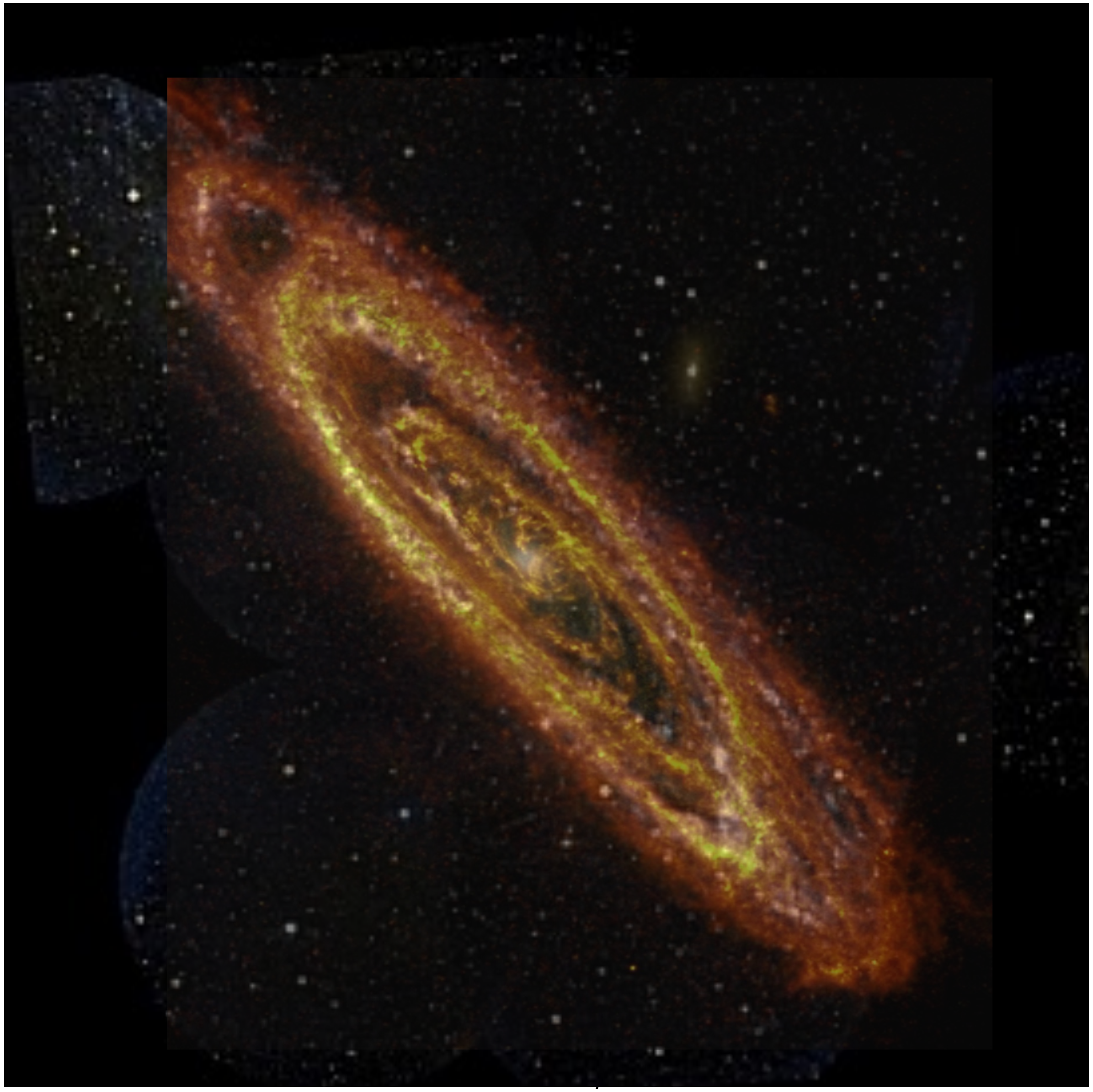
Dust is present in(almost) every galaxy, from low to high z with various distributions

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

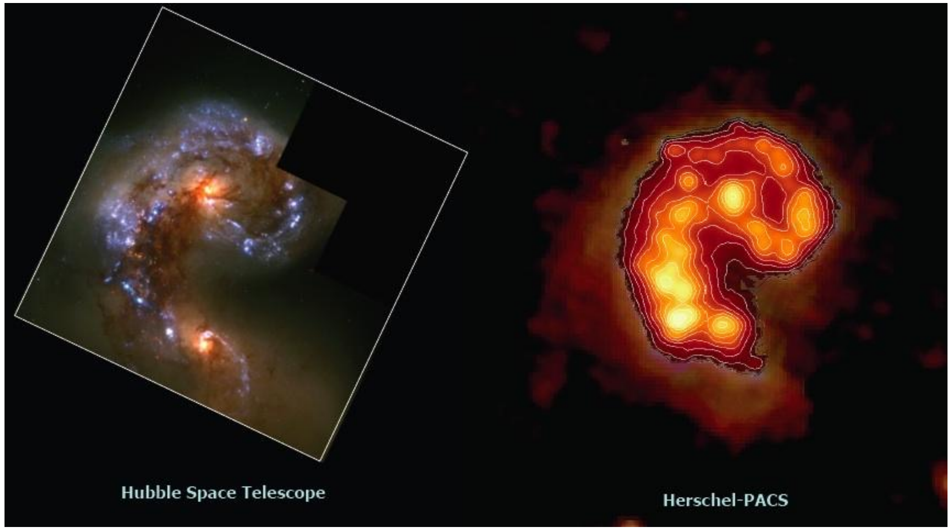
Messier 31 in UV (GALEX)

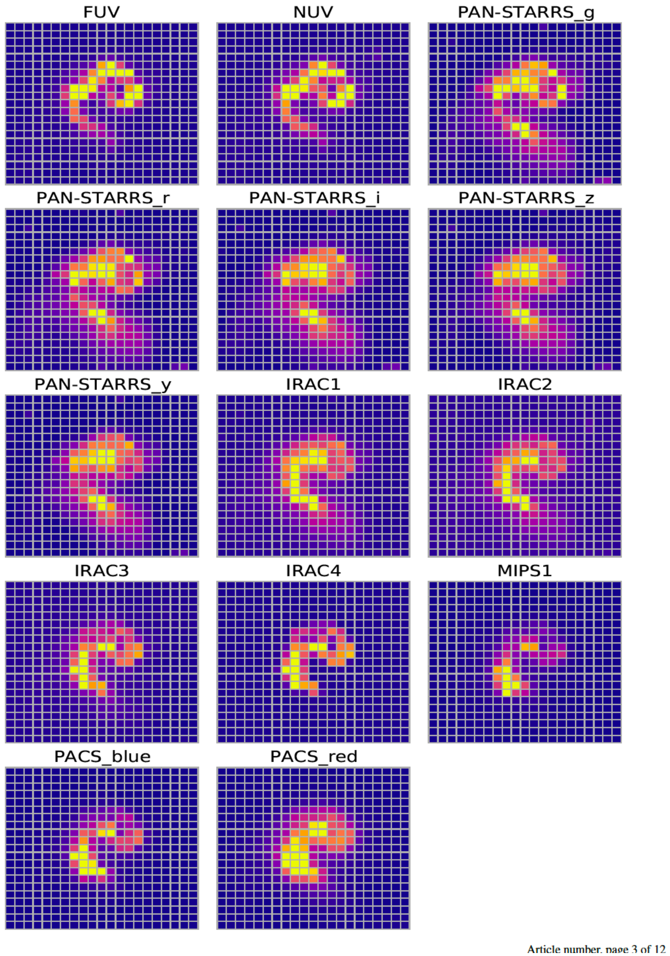
Messier 31 in IR (SPIRE)



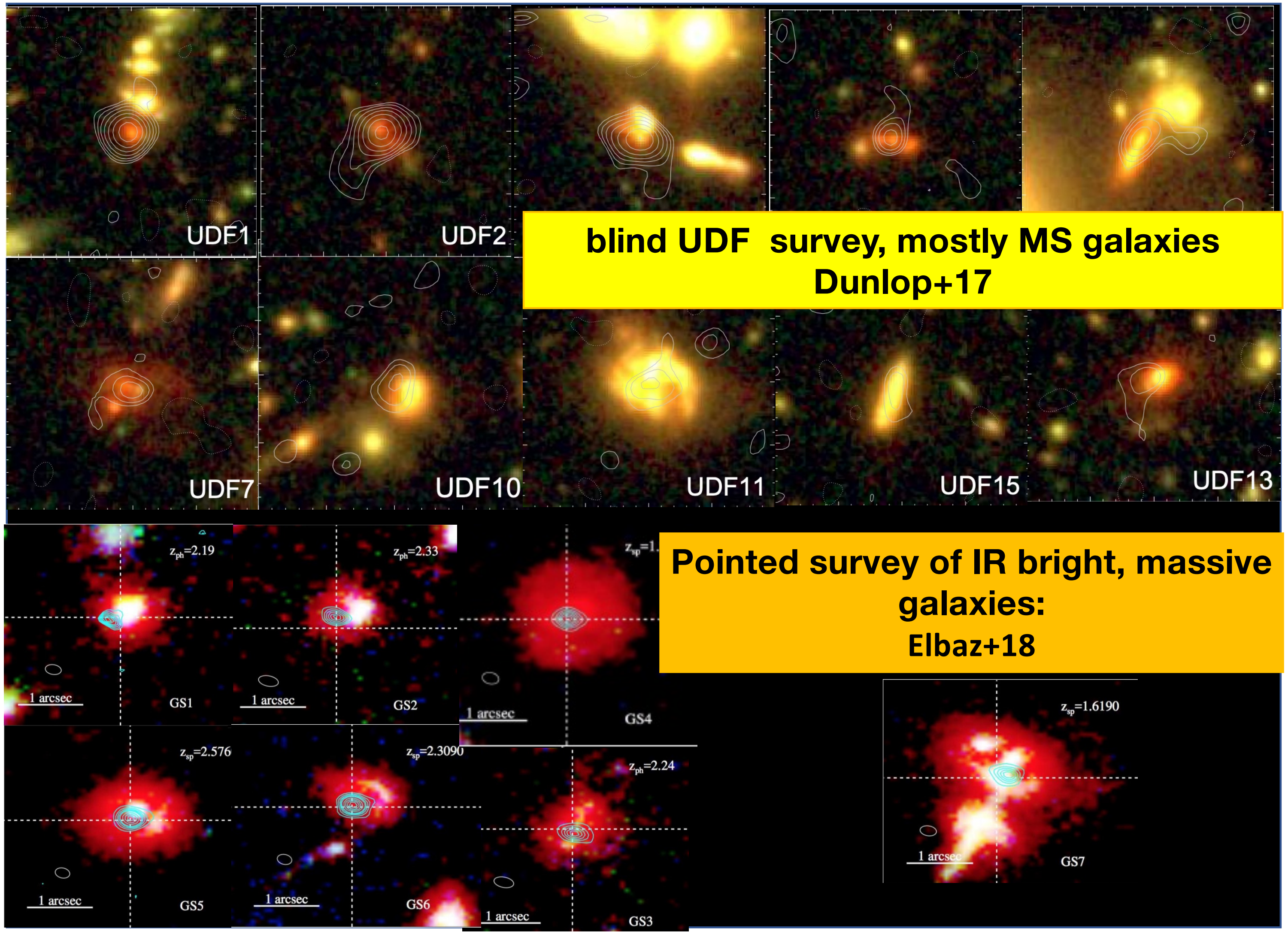


Arp244: very different structure in UV, optical, NIR far-IR (*Seille, Buat et al. subm.*)





z~2 dusty sources as seen by ALMA



Submm and optical emissions are not always , but sometimes, coincident

Sub-mm and UV-optical emissions do not match UV and dust emission are not matching Stellar emission more extended

Why studying dust obscuration is important?

- **To study dust properties, out of the local group, and their evolution with redshift, star formation etc…**
- **To understand the dust distribution in galaxies**
- **If your aim is not to study dust for itself, do you need to account for it →YES, most of the time**

When you are analysing UV, optical and even NIR emission of galaxies, from imaging or spectroscopy, intrinsic, emitted emission is obtained after correction for dust obscuration

- **Is it easy to perform? NO!**

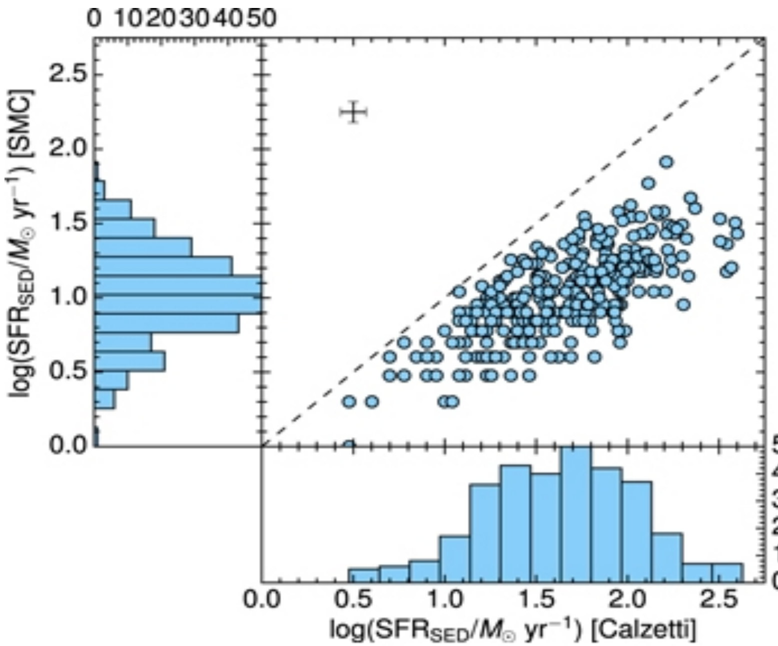
We should be able to reproduce the diversity of the situations: geometry, dust and stars content

- **What are the best conditions to derive robust estimates?**

❖With mid and far-IR measurements → **dust emission**

❖When the wavelength coverage and sampling are good enough to **characterize the stellar (old and young) populations**

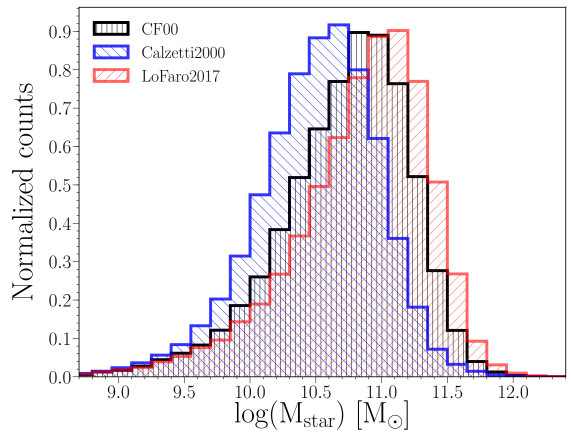
The derived quantities SFR & M_{star} are modified



Theios + 19

SMC (UV steep) and Calzetti (UV flat) curves

(no dust emission)



Malek et al. 2018

Stellar mass estimates differing by a factor 1.3

, with different recipes for dust attenuation

Outline

❖**Dust and stellar interplay in galaxies**

- Definition of extinction and attenuation curves

  Extinction & attenuation in GRB hosts

- Radiation Transfer modelling

  Short description and few results

❖**The dust attenuation law from the local to the distant universe:**

- Formalisms and shapes of the attenuation law
- Attenuations laws from numerical simulations
- Measured attenuations laws

  From spectroscopy & from photometry and SED fitting

❖**Impact of attenuation on SFR and M_{star} measurements**

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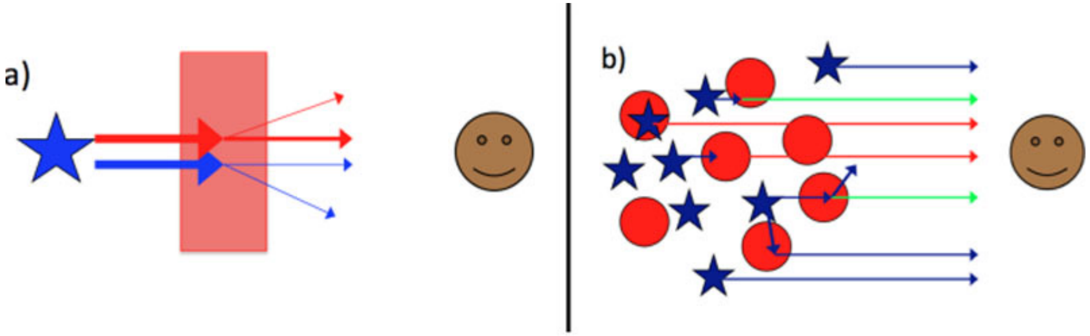
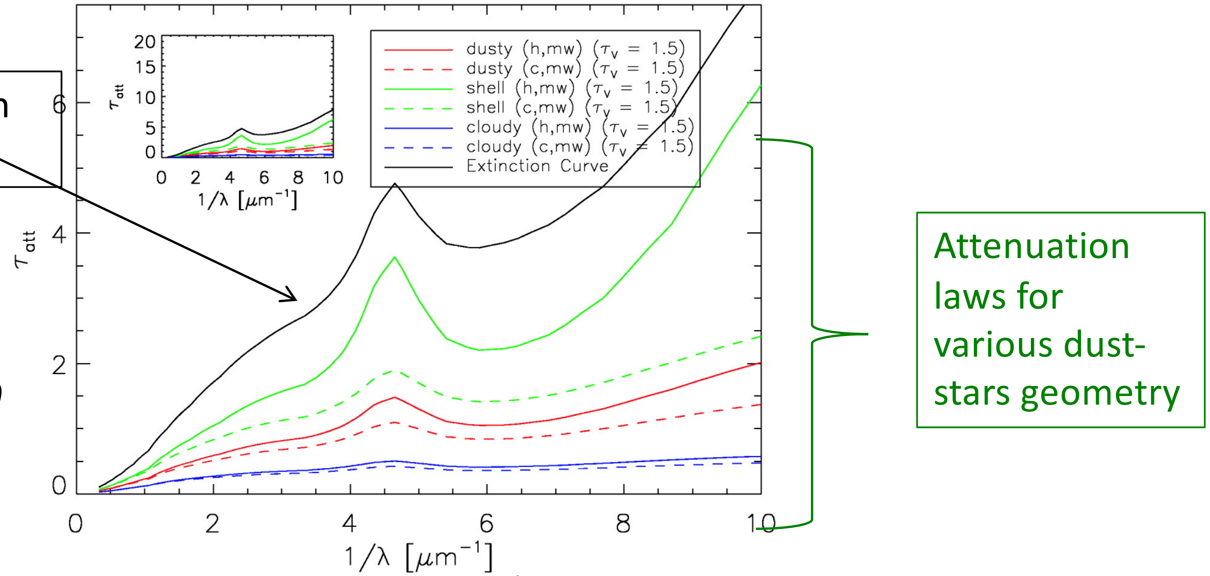
Attenuation & extinction: two different processes

Line of sight of a star
→ Extinction law

→ Dust properties



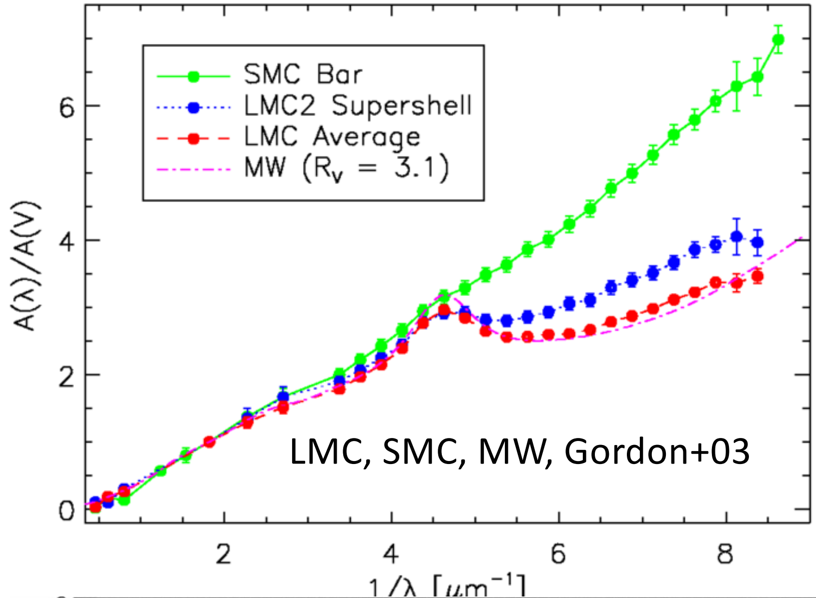
Stars and dust are mixed in different ways
→ Attenuation law
→ Dust/stars geometry



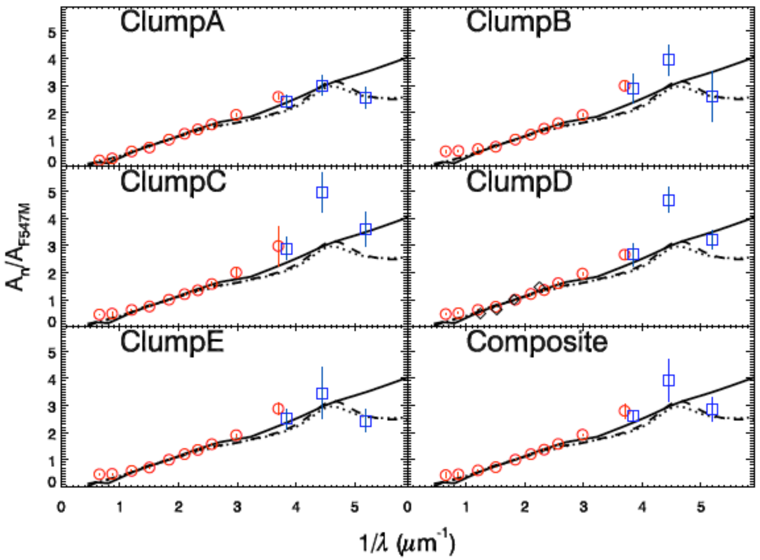
Witt & Gordon 2000

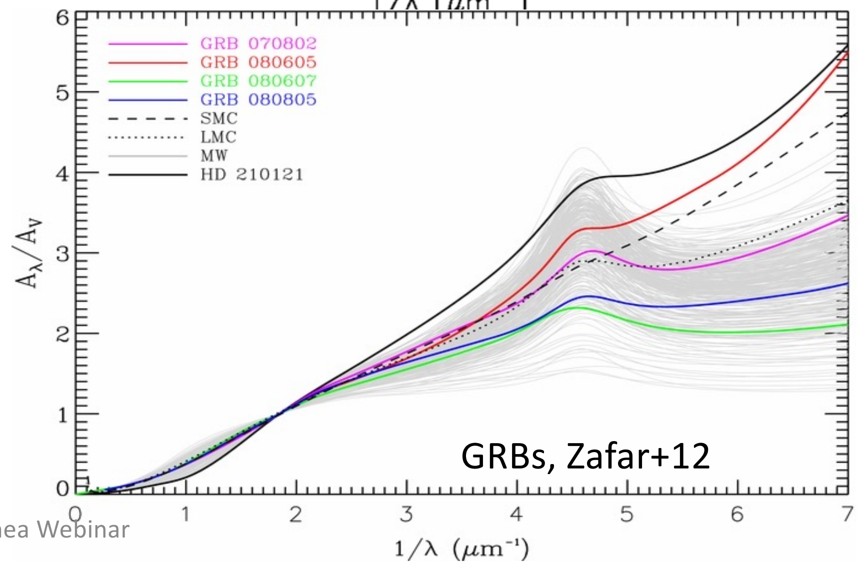
Extinction curves

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



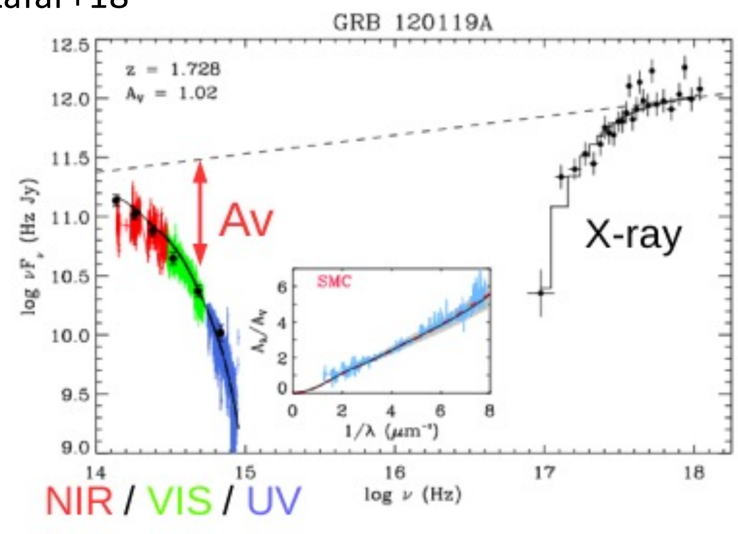
Clumps in the central part of M31, Dong+14



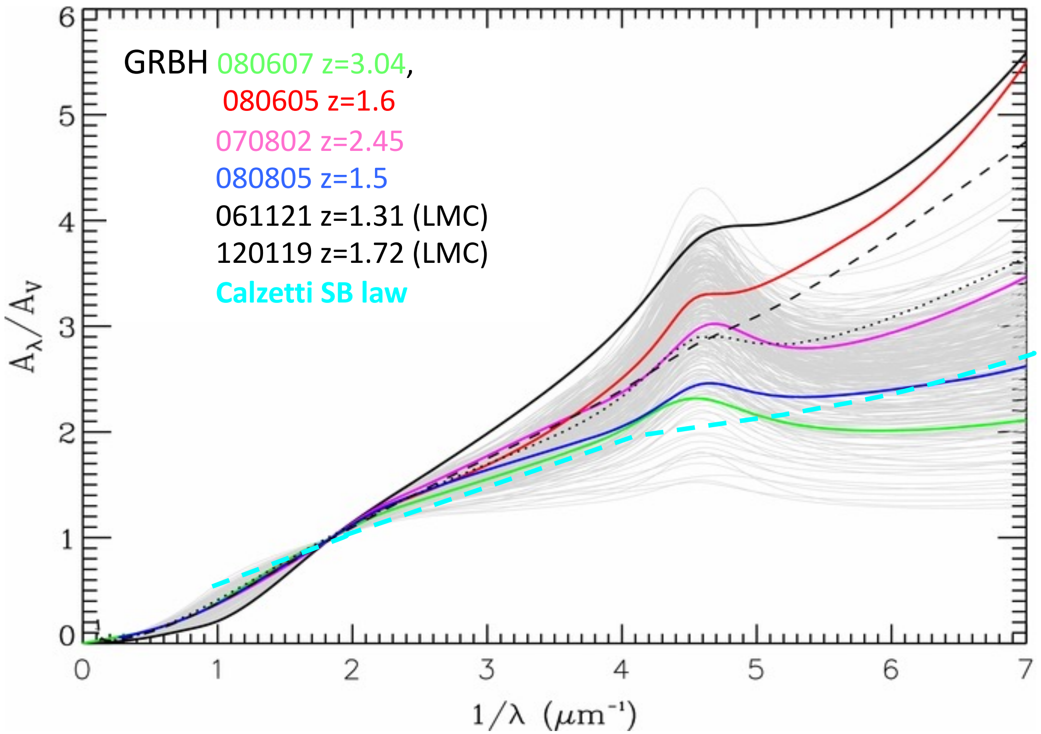


Extinction curves measured in galaxies hosting γ-rays bursts

Zafar+18



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



D. Corre, PhD thesis

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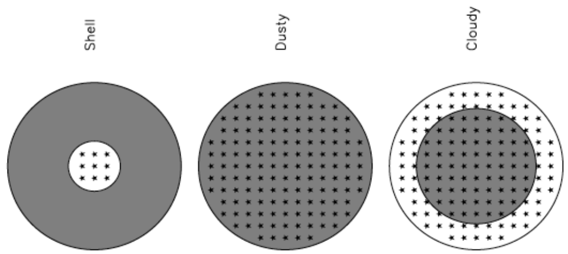
Radiation transfer modelling: a framework to understand the main features of dust obscuration in galaxies

- **Dust models**: **optical properties, chemical composition, grain size distribution**
- **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**: **large scale distribution** (kpc) and **star forming clouds** (pc) (Silva+98, Popescu+00: 'diffuse' medium & obscured clumps

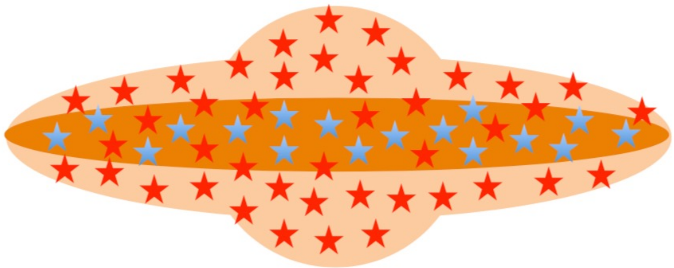
Radiation transfer modelling: different configurations

- **Simple global geometry and stellar content**:
  to test **dust properties** and local distributions
  (e.g. Witt & Gordon 00, Seon and Draine 17, Law+18)



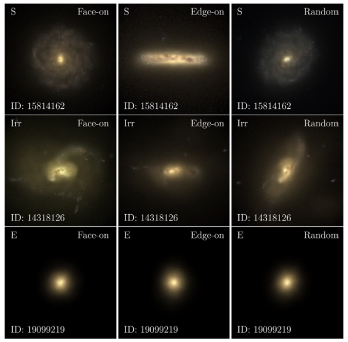
Spherical geometry, Homogeneous stellar Populations *Witt&Gordon00*

- **Galaxy-like simplified geometries**, to produce libraries or to fit nearby galaxies (e.g. M51, M31, NGC 891)
  Mostly MW dust, stellar and dust distributions are tested
  (e.g. Pierini+04, Silva+98, Tuffs+04, De Looze+14, Viaene+17, Nersenian+19)



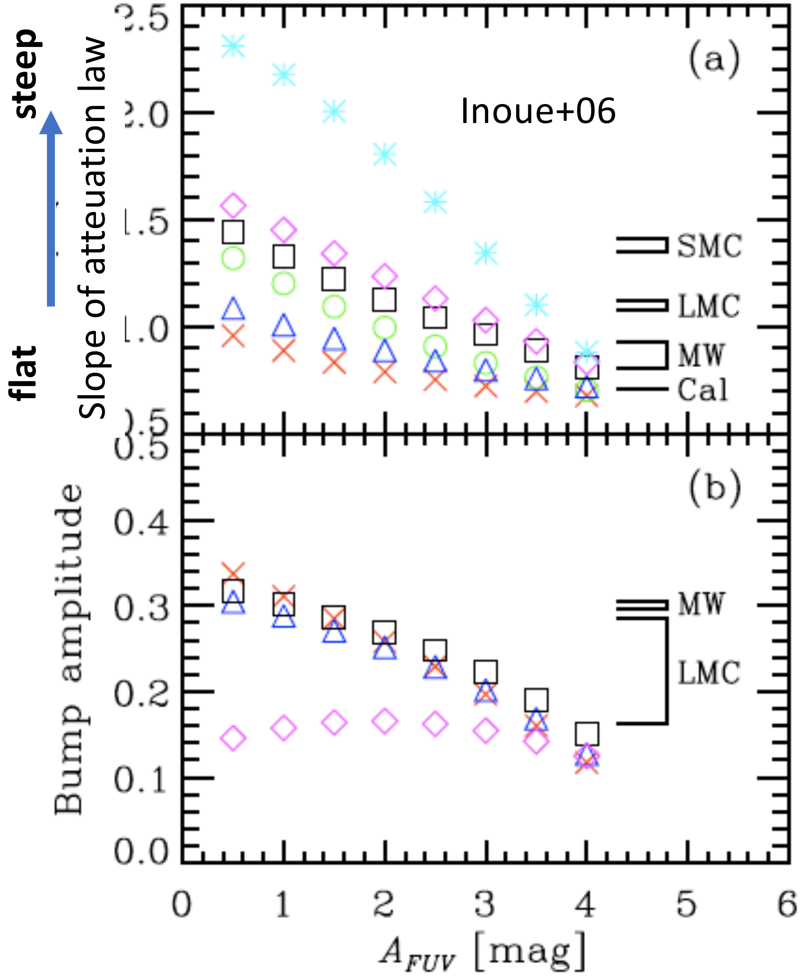
M51, M31, dustpedia sample *deLooze+14*

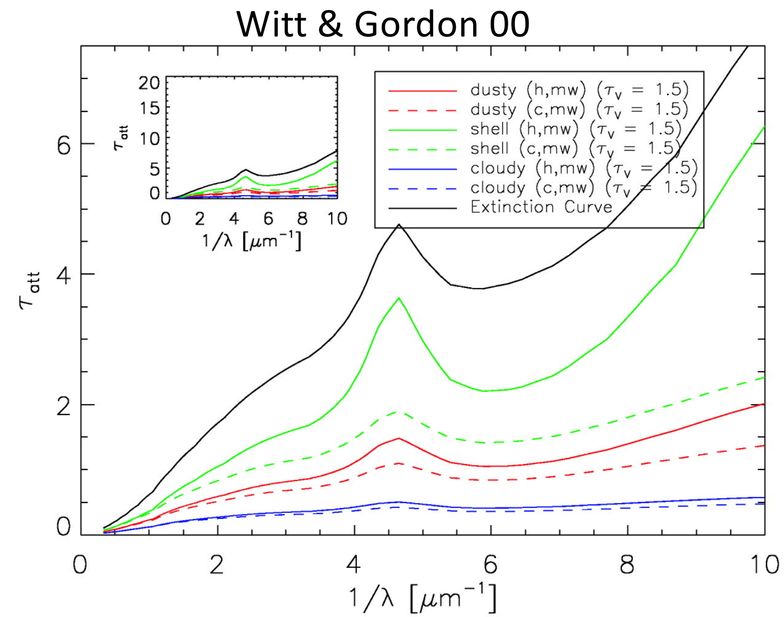
- **Application to simulated galaxies**: **post-processing of hydrodynamical simulations**
  to explore different galaxy types (isolated, mergers, ULIRGs) and provide statistical analyses
  (e.g. Trayford+17, 20, Roebuck+19, Baes+19)



Eagle simulations+ SKIRT modelling *Trayford+17*

1. RT modelling: Flattening of the attenuation curve & decrease of the UV bump amplitude when attenuation increases, shallower than the extinction curve with simple stellar populations

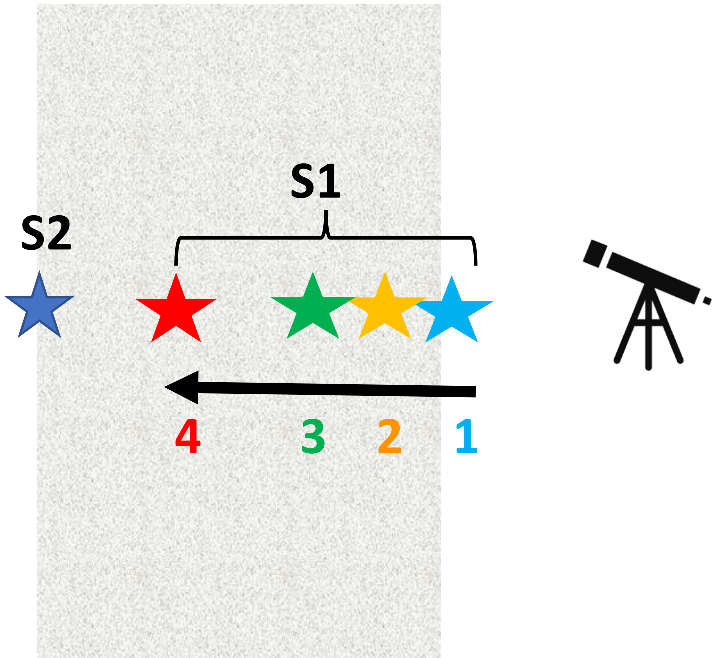




Bluer light come from less onscured line of sight than redder light

See also Seon & Draine 2016

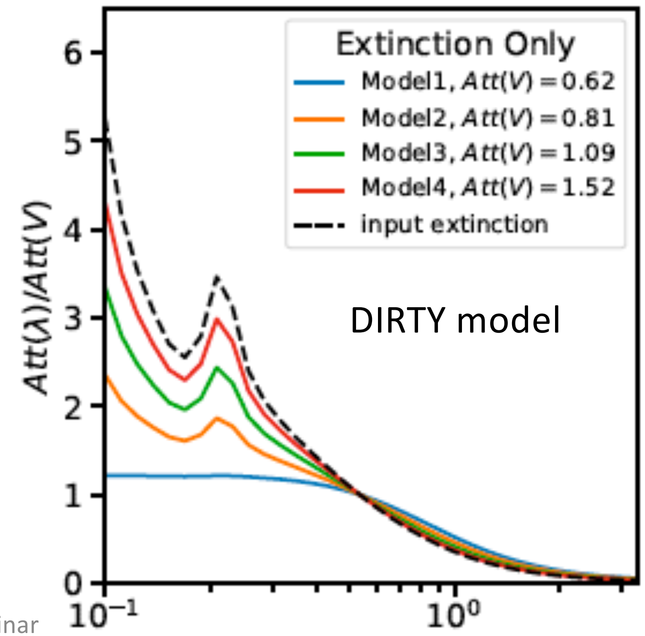
- **Uniform dust slab: A(V)= 2 mag**
- **Star 2-S2 behind the slab**
- **Star 1-S1 before the slab → inside the slab**



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

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

Attenuation curve always flatter than the extinction curve



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

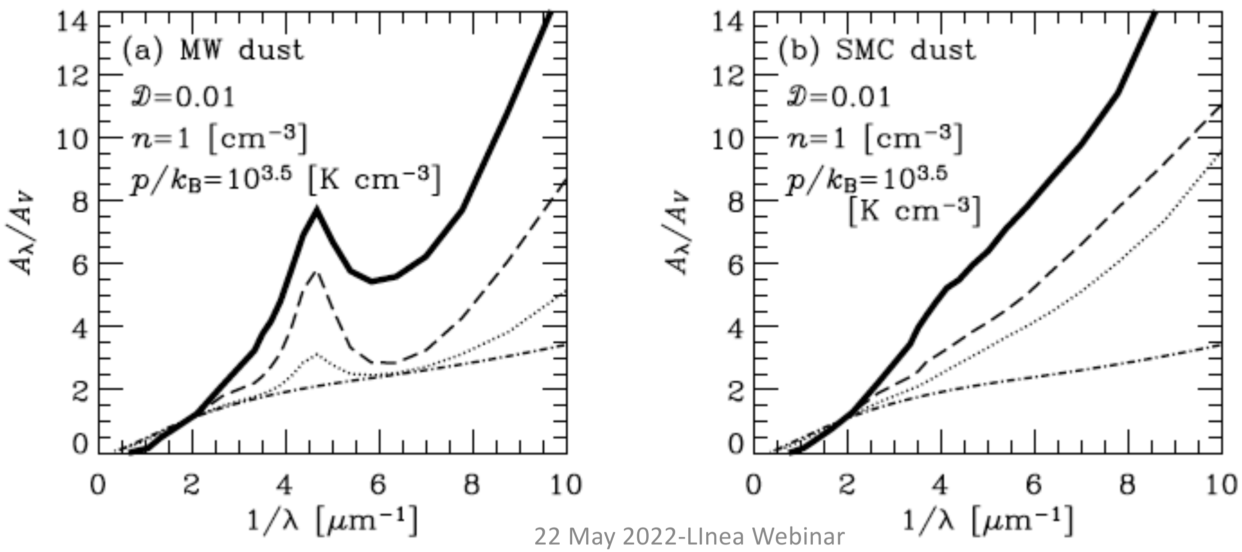
Youngest stars in dusty clumps & older stars in a smooth dust distribution

Age selective attenuation → steeper attenuation laws

Emission at short wavelengths comes from young stars

Standard age limit for birth clouds : 10 Myr

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

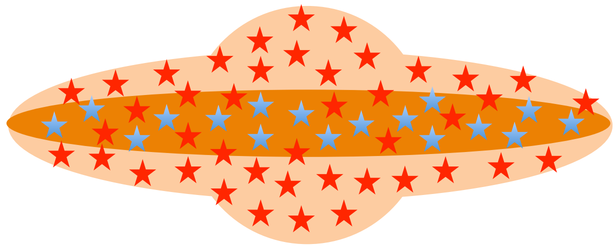


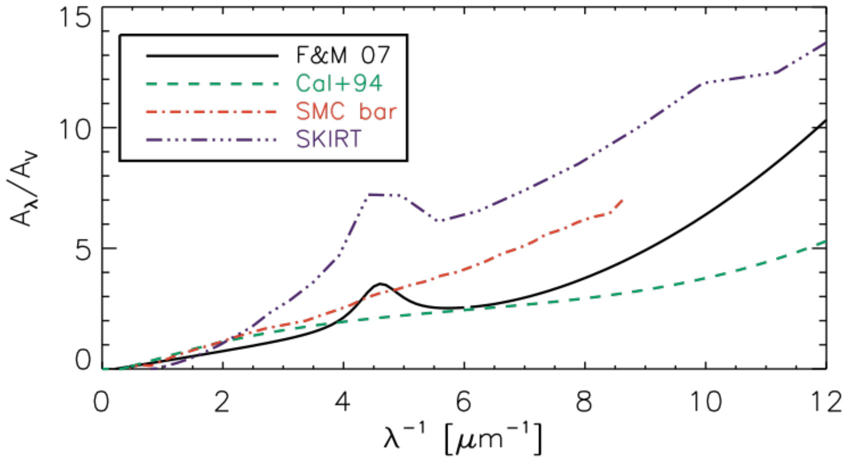
Inoue 2005

M51 De Looze+14, SKIRT code

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 [$L_{\odot,V}$]	3.2×10^9
Thick disk[b]	2D geometry	IRAC 3.6 μm[c]
	h_z [pc]	450
	L_V [$L_{\odot,V}$]	2.0×10^{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	Hα + 0.031 × MIPS 24 μm[g]
	h_z [pc]	100
	SFR [$M_\odot$ yr^{-1}]	3
	M_d [$M_\odot$]	4.5×10^6
Dust		
Thin disk[h]	2D geometry	A_{FUV}[i]
	h_z [pc]	225
	M_d [$M_\odot$]	7.3×10^7



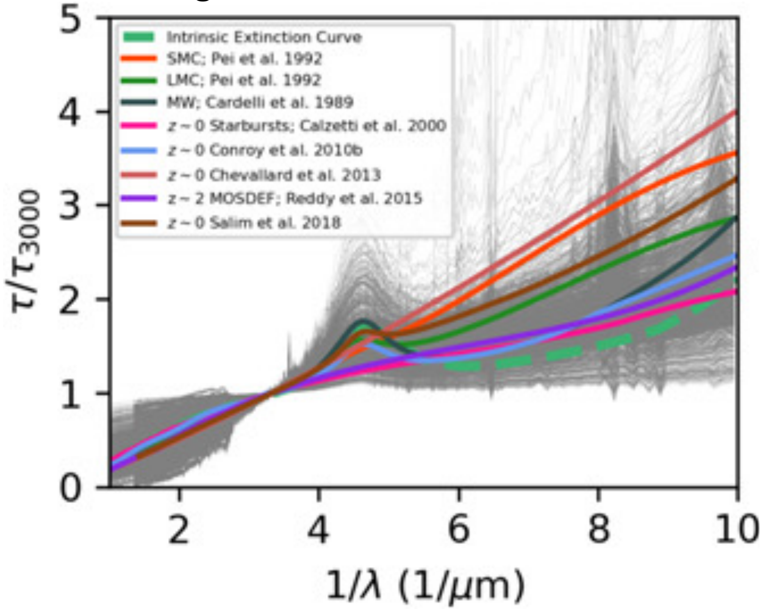


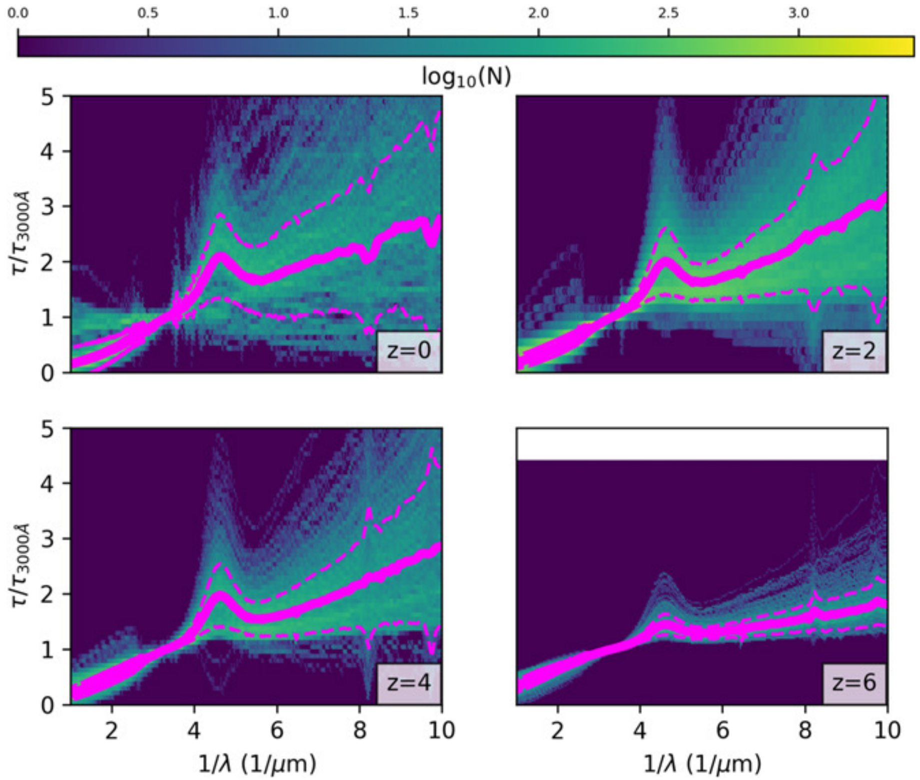
Radiation transfer modeling on simulated galaxies: more complex geometry, coupled with galaxy evolution

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

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

A single MW-like extinction curve





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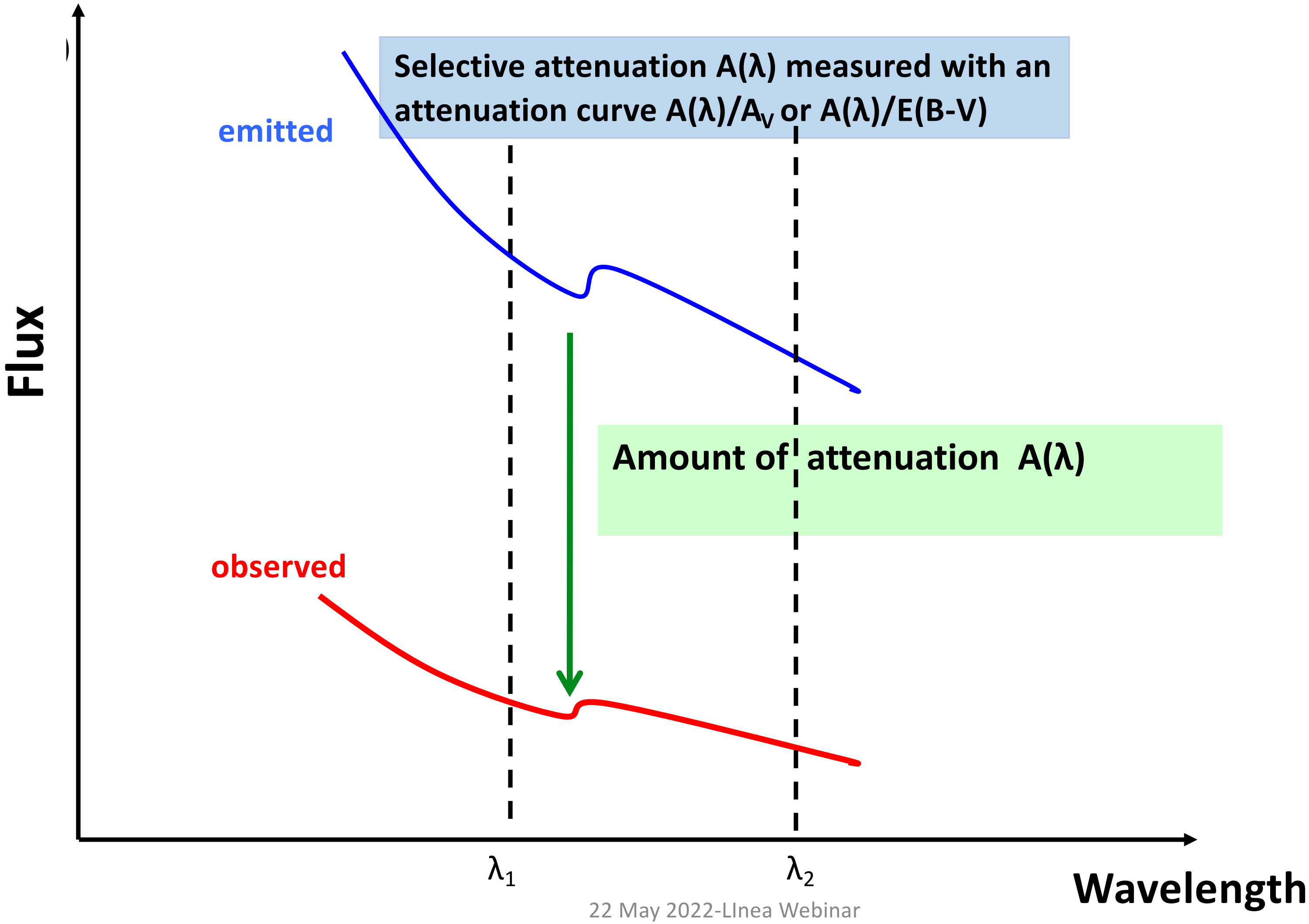
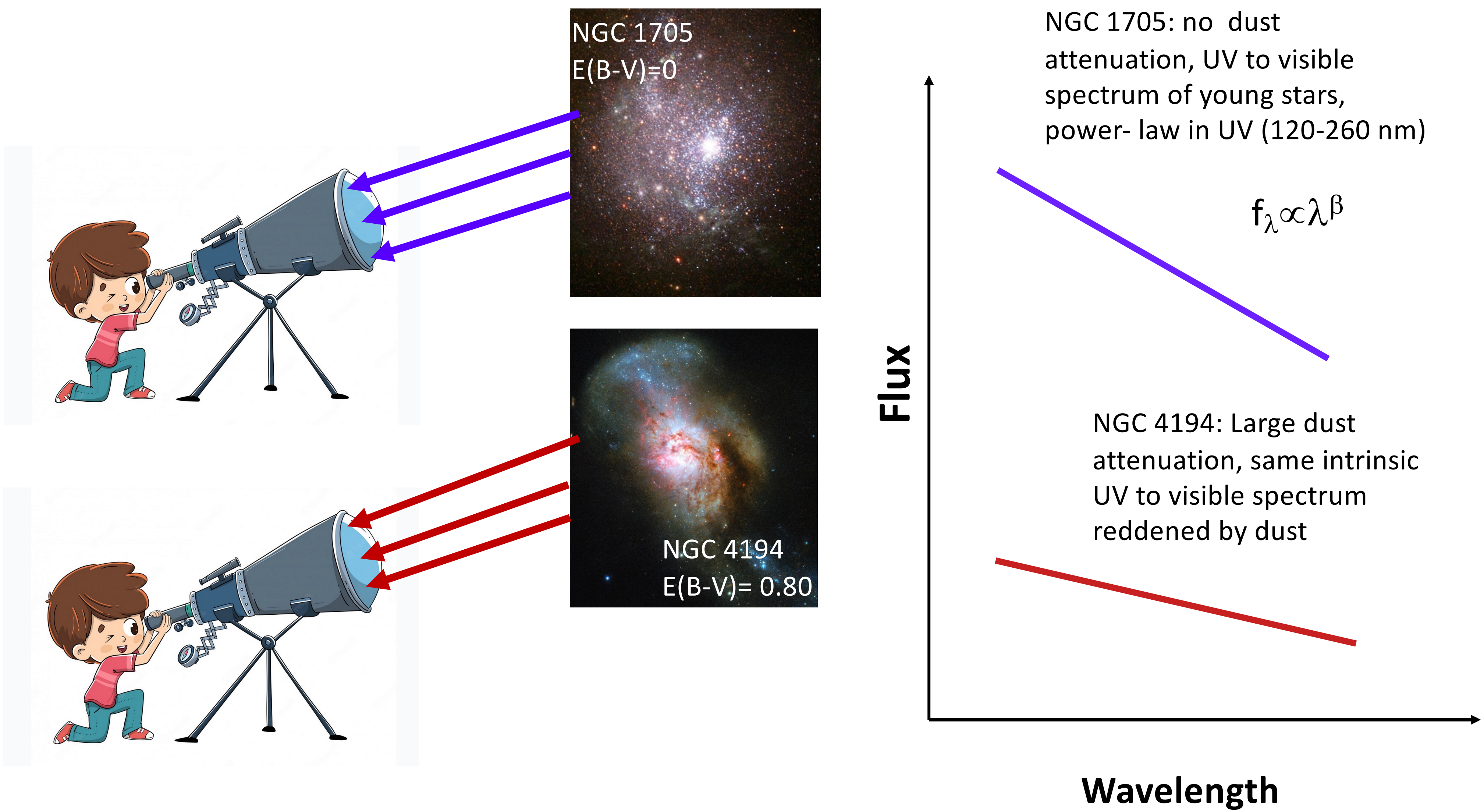
Dust attenuation: a dramatic effect on the SED

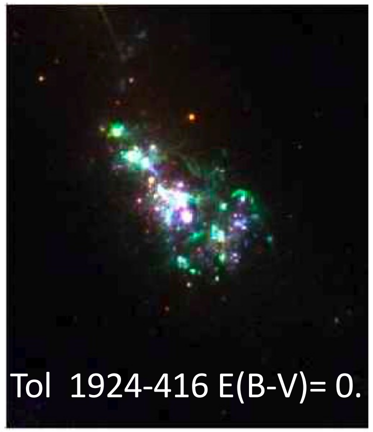


The 'famous' Calzetti law

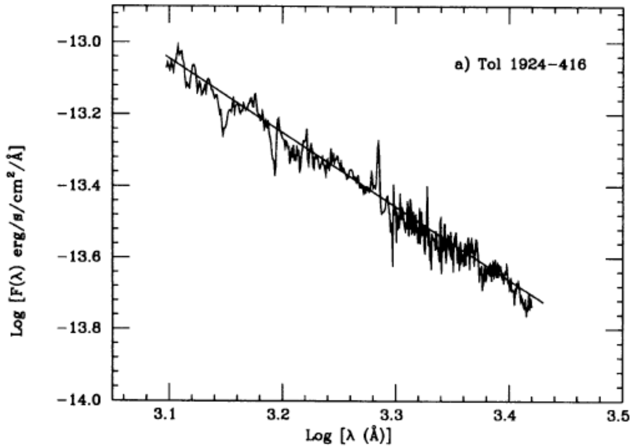
It is an empirical law, obtained by applying to galaxies the method to measure extinction curves along the line of sight of stars

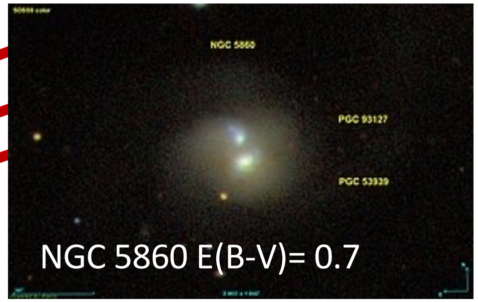
- ✓ **A sample of nearby galaxies with a central starburst**: UV spectra and Balmer decrements **Hα/Hβ**
- ✓Galaxies classified as a function of their obscuration measured with Hα/Hβ
- ✓**The UV-visible spectrum supposed to ONLY vary with the effects of dust:** a reasonable assumption for starbursts and in UV

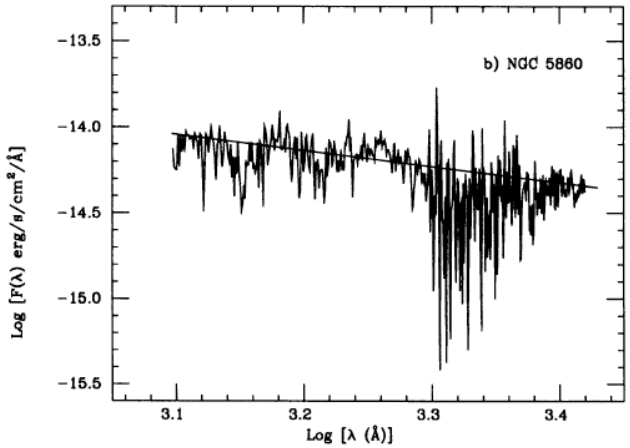

NGC 1705
E(B-V)=0
NGC 4194
E(B-V)= 0.80
NGC 1705: no dust attenuation, UV to visible spectrum of young stars, power- law in UV (120-260 nm)
$f_\lambda \propto \lambda^\beta$
NGC 4194: Large dust attenuation, same intrinsic UV to visible spectrum reddened by dust
Flux
Wavelength


Tol 1924-416 E(B-V)= 0.

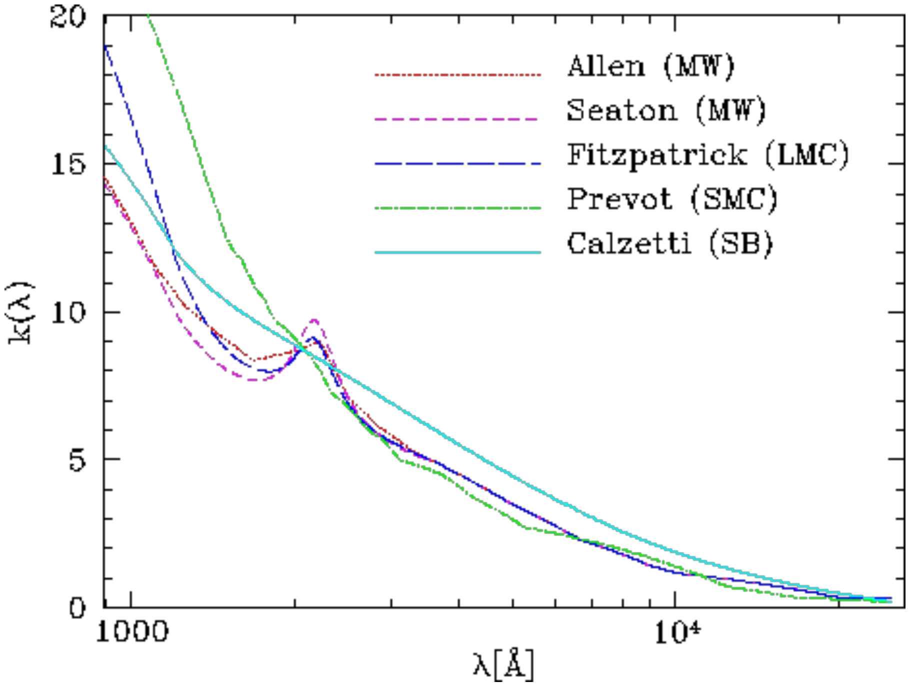
I,V,U


a) Tol 1924-416
Log [F(λ) erg/s/cm²/Å]
Log [λ (Å)]
-13.0
-13.2
-13.4
-13.6
-13.8
-14.0
3.1
3.2
3.3
3.4
3.5


NGC 5860
PGC 93127
PGC 53939
NGC 5860 E(B-V)= 0.7


b) NGC 5860
Log [F(λ) erg/s/cm²/Å]
Log [λ (Å)]
-13.5
-14.0
-14.5
-15.0
-15.5
3.1
3.2
3.3
3.4

The shape of the Calzetti-Starburst law



- The **Calzetti attenuation law** is compared to **extinction laws for the MW, LMC, SMC**
- The **attenuation law IS NOT an extinction law even if it** is expressed as $k(\lambda) = A(\lambda)/E(B-V)$
- **No UV bump**, a general shape similar to the MW extinction curve, and **grayer (flatter) than the LMC & SMC extinction curves**

The original Calzetti's recipe

- Apply) the starburst law k(λ), as a function of $E(B\text{-}V)_{stars}$ (for stars) uniformly to the whole stellar continuum (UV-to-NIR)
- If you also work with emission lines from HII regions:

  Apply the relation $E(B\text{-}V)_{gas} = E(B\text{-}V)_{stars}/0.44$

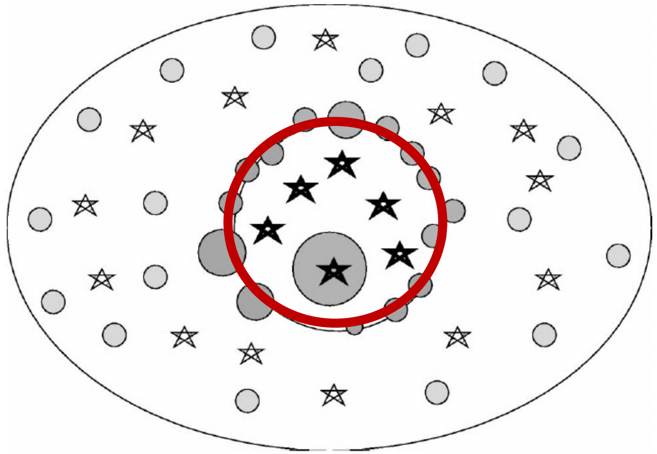
Assume a foreground screen

and a MW extinction curve

→If any of these steps is modified,

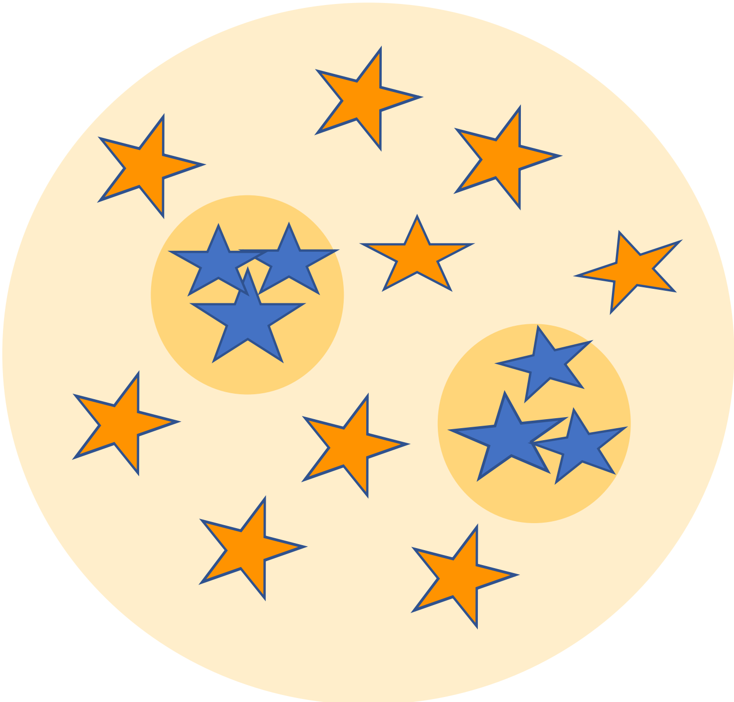
the starburst law as measured by Calzetti

is no more valid



Adapted from Calzetti 2001

The Charlot and Fall (2003) recipe: power-laws and differential attenuation



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

age dependent attenuation for stars: birth clouds and ISM

t<~10^7 yrs (BC+ISM)

and t> ~10^7 yrs (ISM only),

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

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

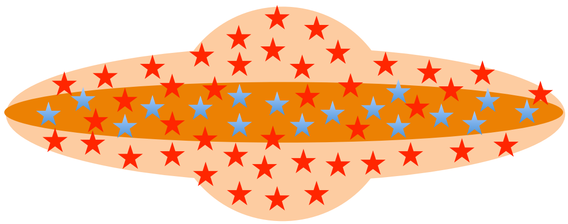
Original values

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

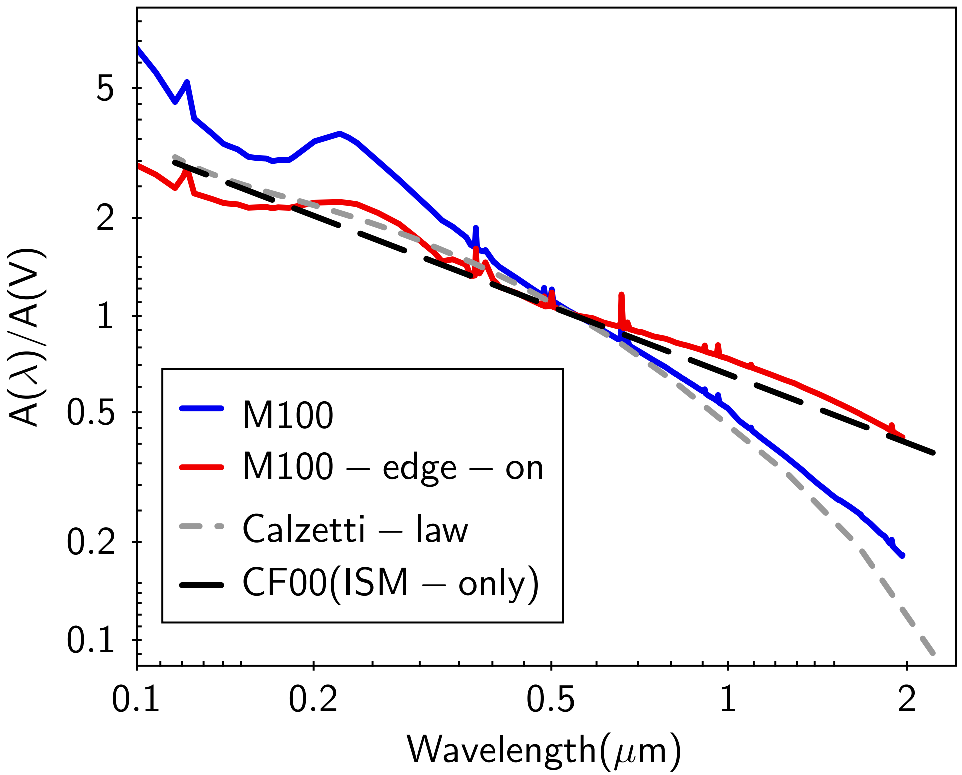
$$\mu = A_{\rm V}^{\rm ISM}/(A_{\rm V}^{\rm ISM} + A_{\rm V}^{\rm BC}).$$

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)



De Looze+14



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

No universal attenuation laws: flexible recipes are needed

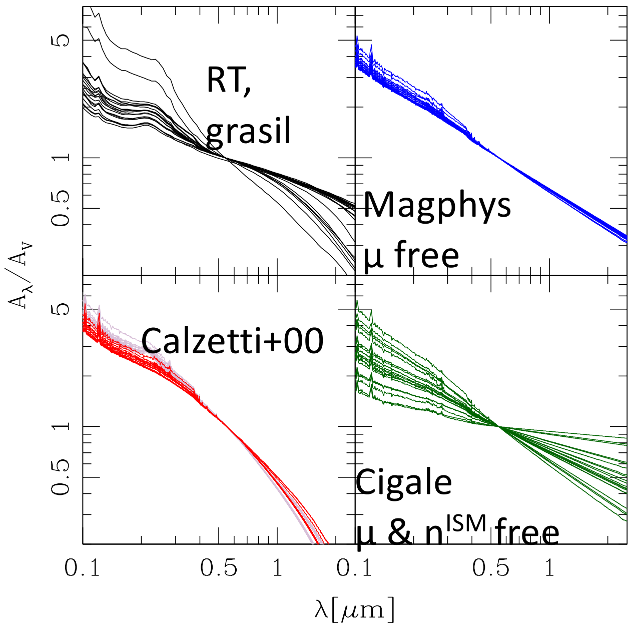
Charlot & Fall 2000 (CF00)

→ DouBle-Power-Law-free, free slope

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

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

+ μ free



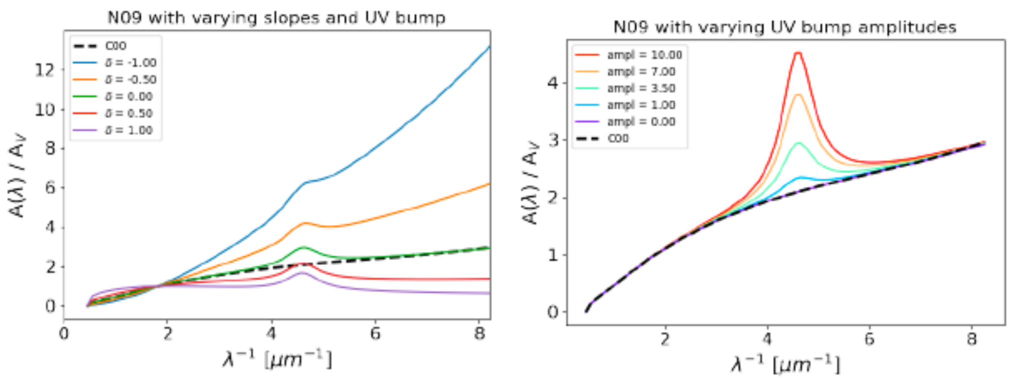
LoFaro+17

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

Calzetti+2000 (C00)

→ Calzetti-like, free slope

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



Narayanan+18

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

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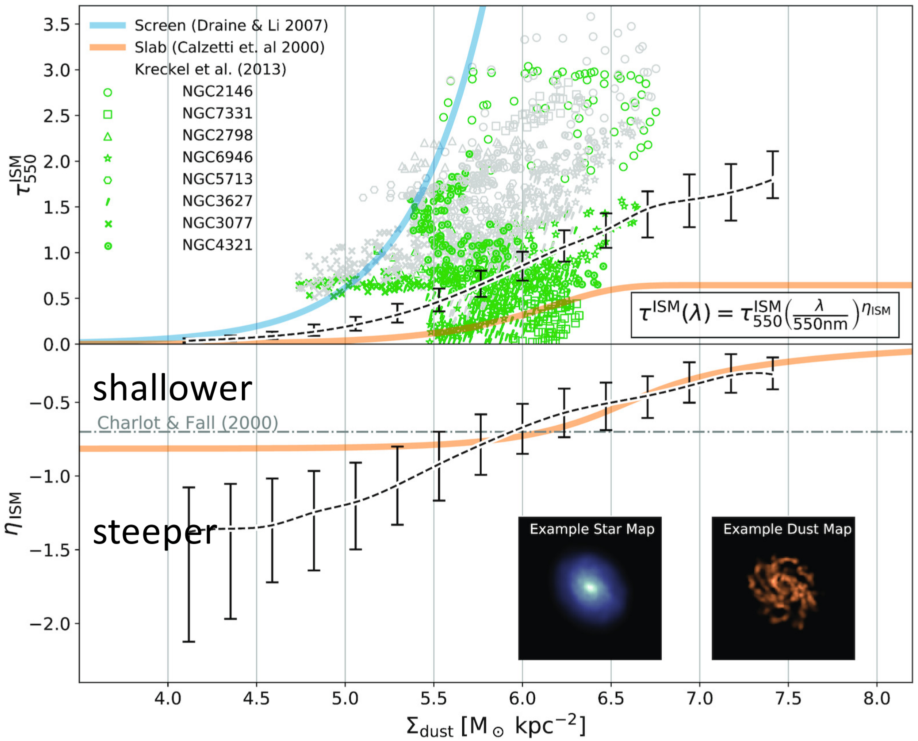
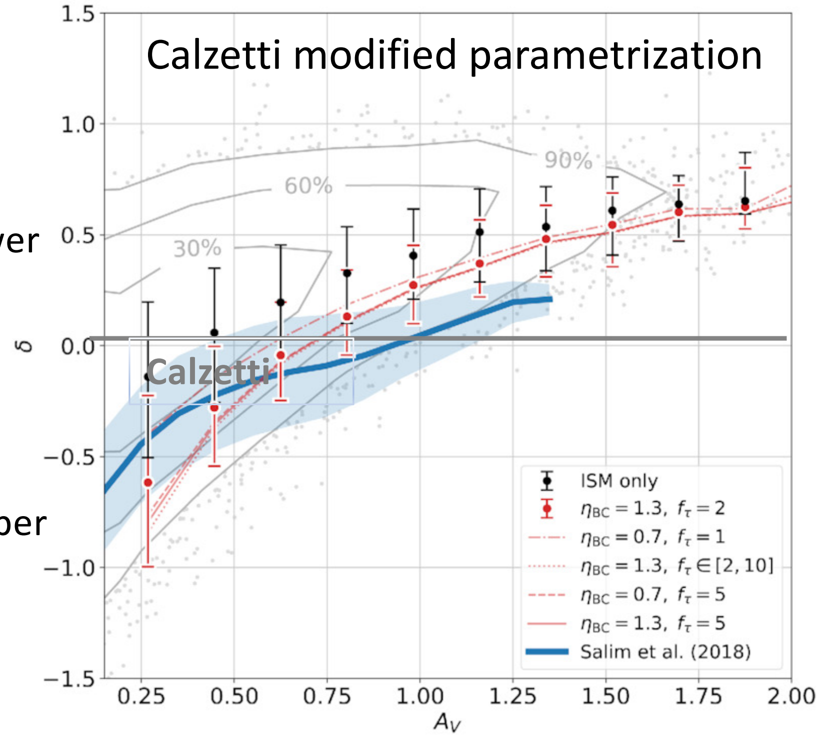
Eagle simulations +SKIRT RT + Charlot & Fall & Calzetti formalisms
→ the attenuation curve flattens when A_V increases

Trayford+20



shallower

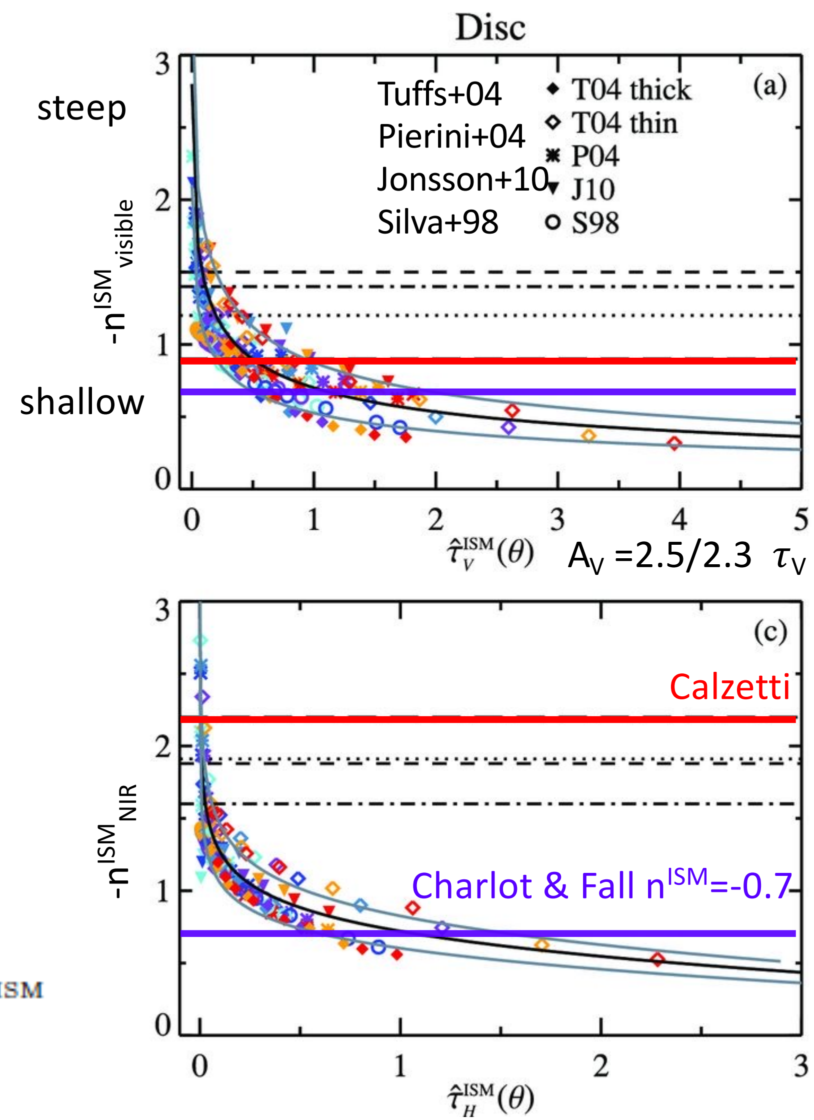
steeper



Chevallard et al. 2013:

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

→ All models predict a grayer attenuation for an increasing attenuation



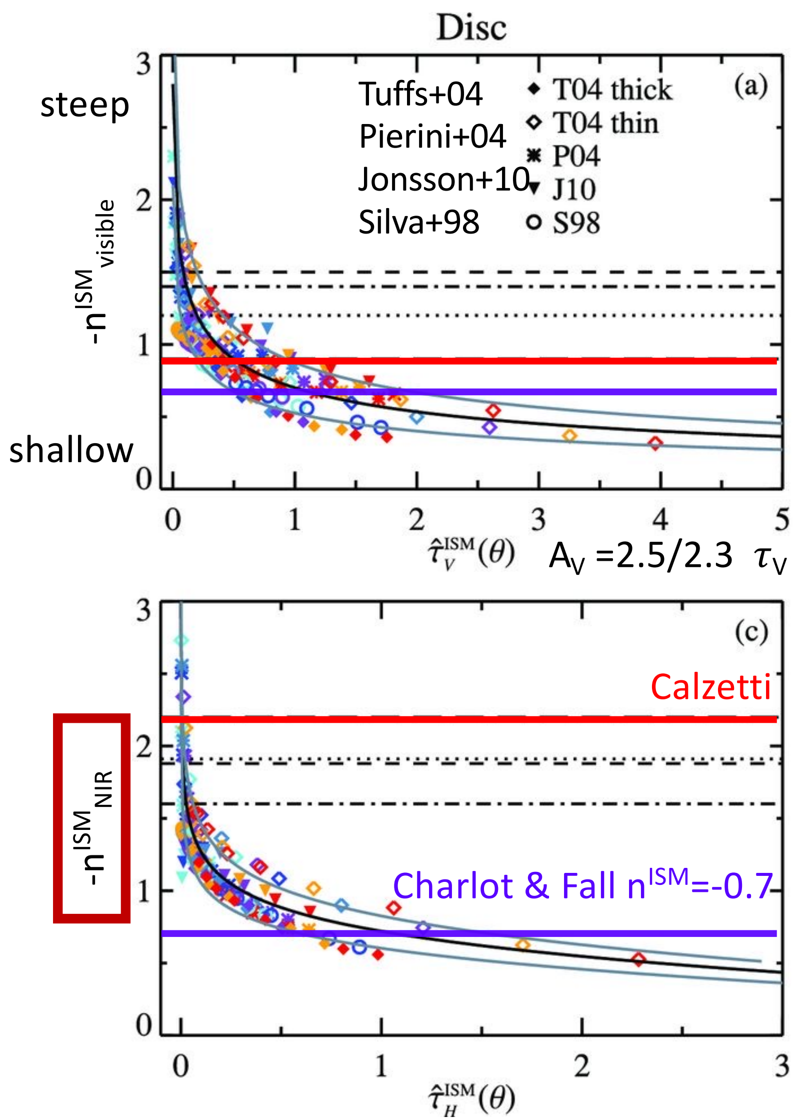
$$A_\lambda^{\rm ISM} = A_V^{\rm ISM}(\lambda/0.55)^{n^{\rm ISM}}$$

Chevallard et al. 2013:

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

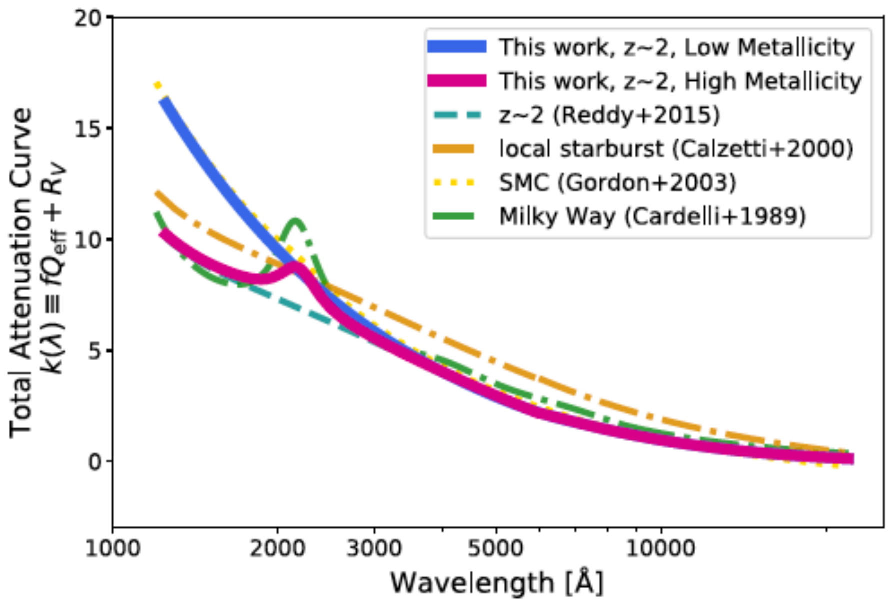
→ All models predict a grayer attenuation for an increasing attenuation

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



Attenuation laws derived from spectroscopy

Calzetti+94 method: Balmer optical depth to quantify attenuation, comparison of UV spectra or multi-wavelength photometry



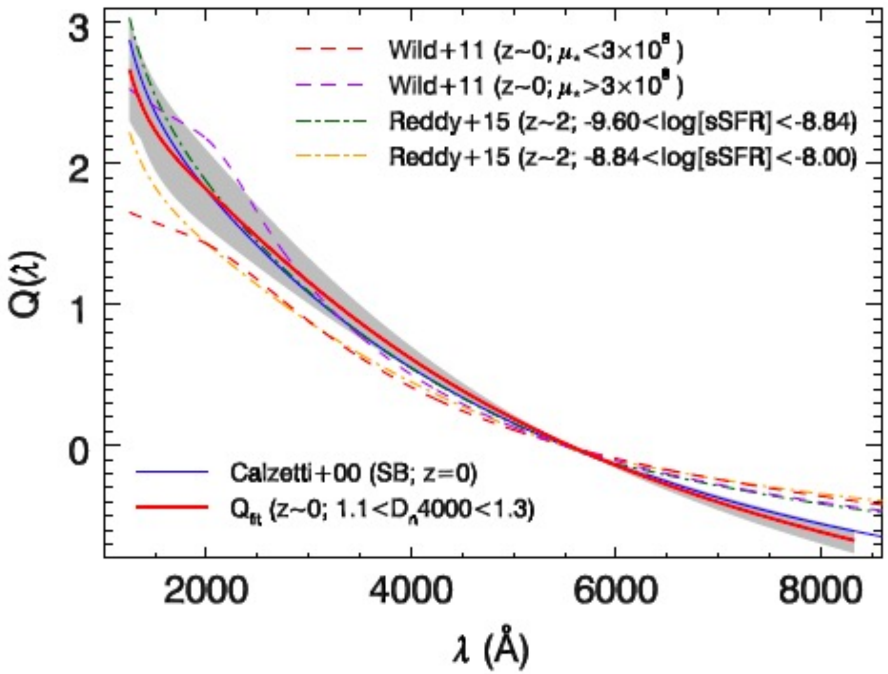
MOSDEF survey (Keck/MOSFIRE), z=2
Shivaie+20

- 2 metallicity bins, 48 galaxies/bin → stack

- High metallicity (12+log(O/H) >8.5) , UV bump, shallow slope
- Low metallicity (12+log(O/H) <8.5), similar to SMC extinction curves

Attenuation laws derived from spectroscopy (2)

Calzetti+94 method: Balmer optical depth to quantify attenuation, comparison of UV spectra or multi-wavelength photometry



Battisti+16
SDSS spectroscopy (BD)
multiwavelength photometry:
GALEX (UV), SDSS photometry
10000 galaxies at z<0.1

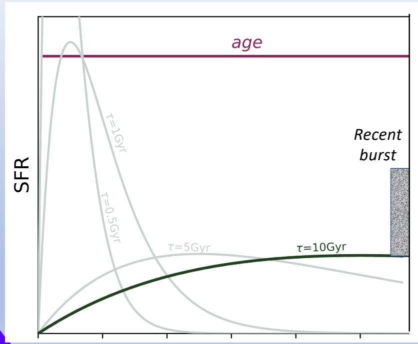
Close to the Calzetti law, no bump

Attenuation laws derived from photometric observations and SED fitting

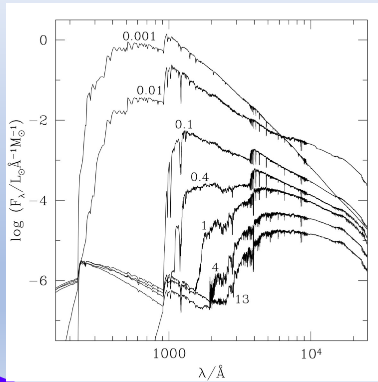
e.g. Salim18 (z=0), Buat+09, 11, 12,18,19, Kriek & Conroy 13, Salmon +16,, Lo Faro +17, Cullen+18, Battisti+20

Fitting the SED (with CIGALE): the UV-optical (stellar) emission

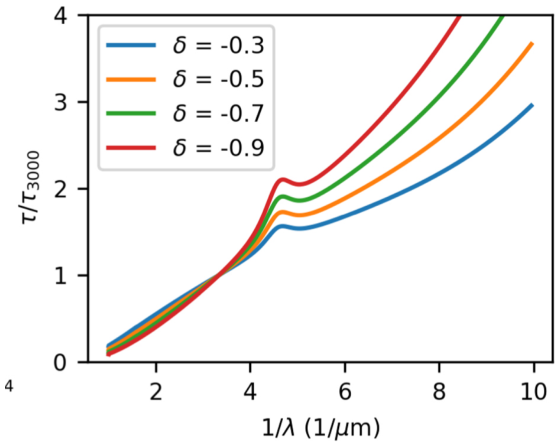
Star formation history



Simple Stellar Populations



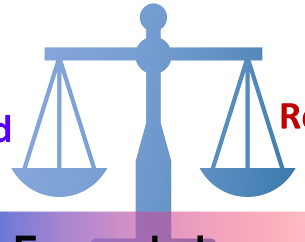
Dust attenuation of the stellar continuum



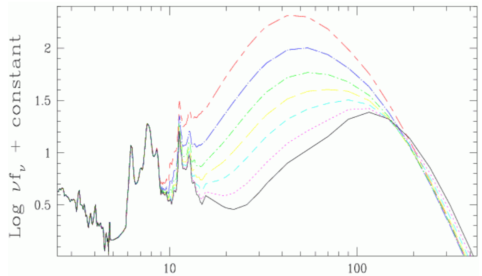
(Boquien et al. 2019)

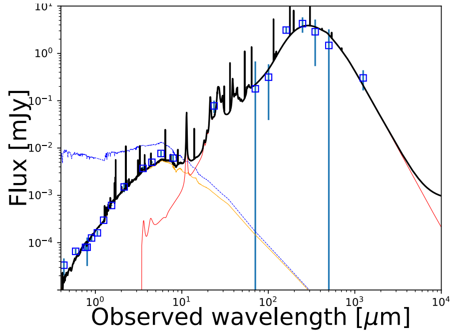
Stellar absorbed

Dust Re-emitted



Energy balance between stellar and dust emissions

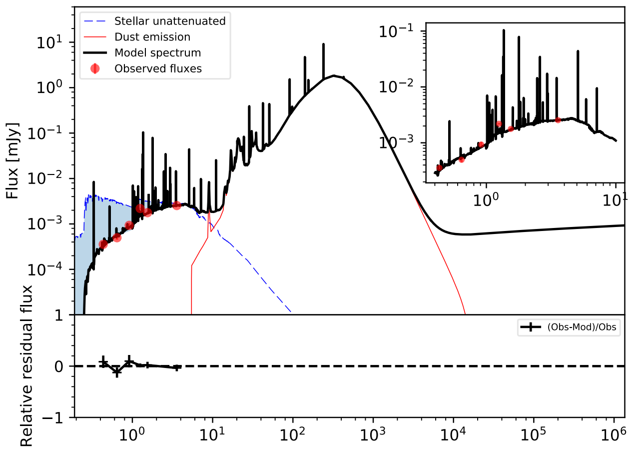


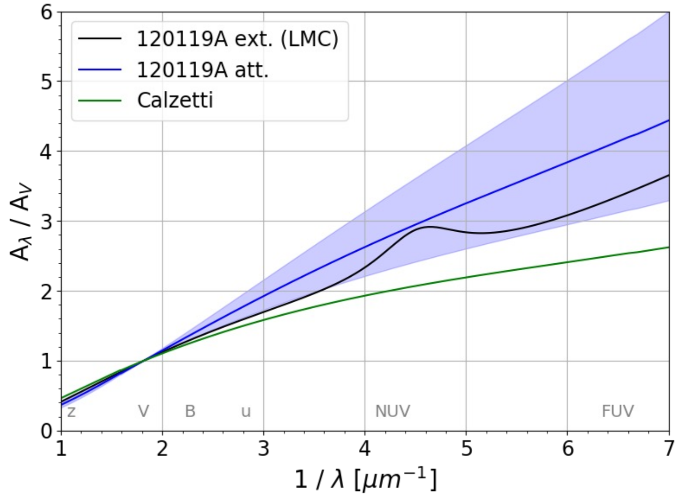


Credits: Narayanan+18, Bruzual & Charlot 03, Dale& Helou 02,

Fit of photometric data from galaxies hosting GRBs → shape of the attenuation law (Corre, Buat+18)

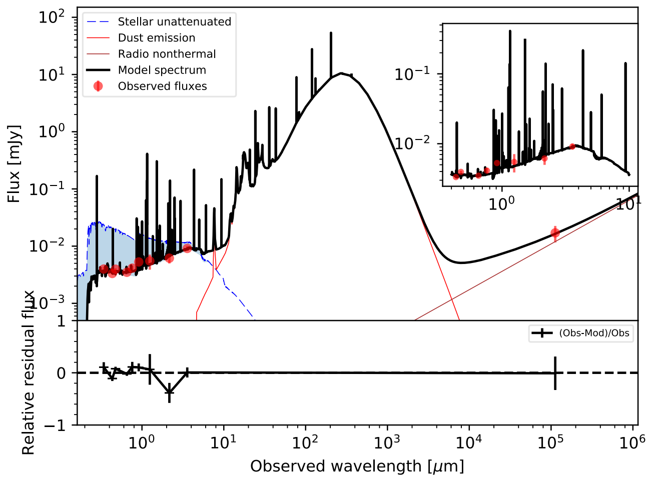
Best model for 120119A at z = 1.72. Reduced χ^2=0.32

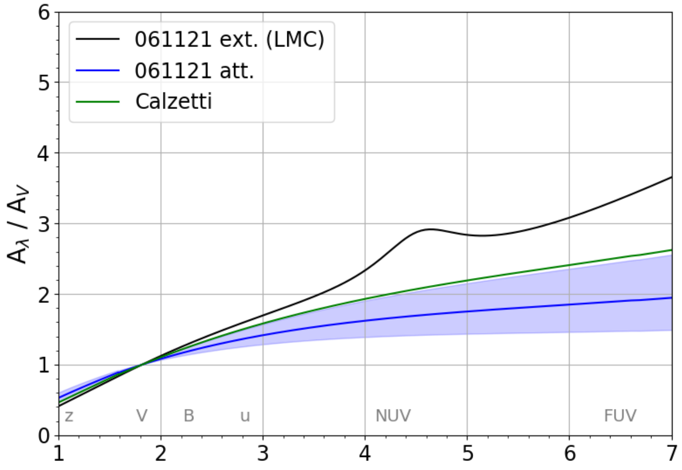




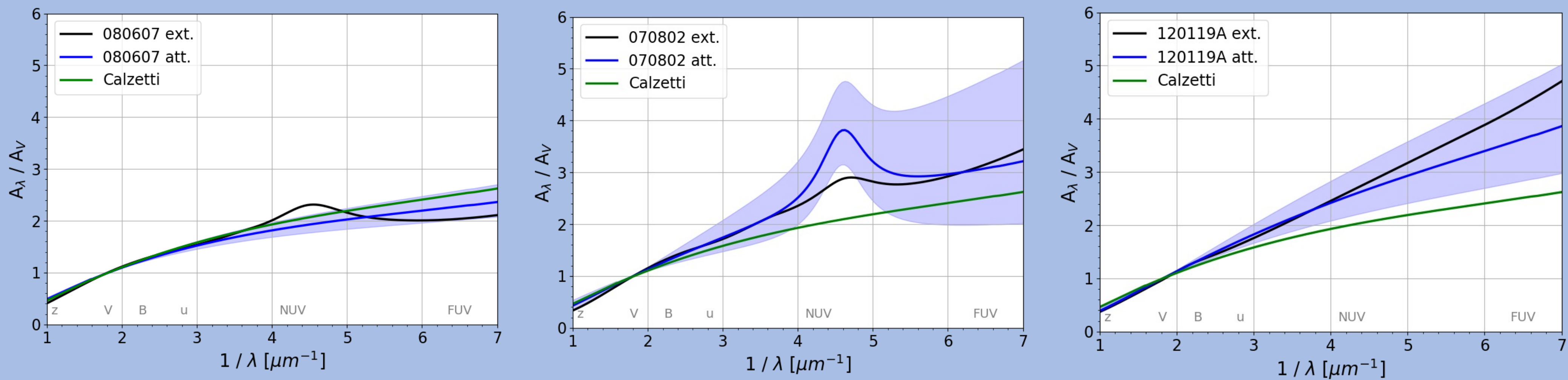
Steep attenuation Curve
Steeper than Calzetti law

Best model for 061121 at z = 1.314. Reduced χ^2=0.74



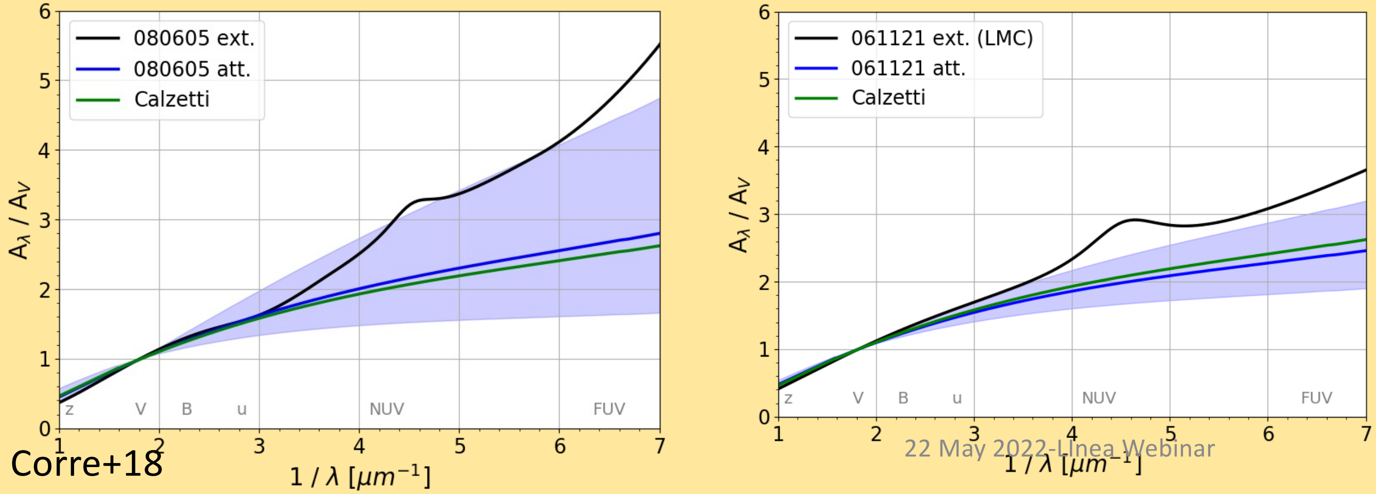


Flat attenuation Curve
Flatter than Calzetti law



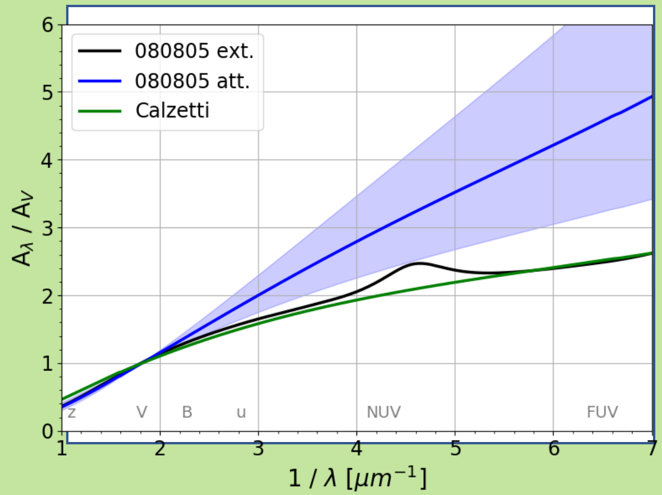
Att curve similar to Ext curve

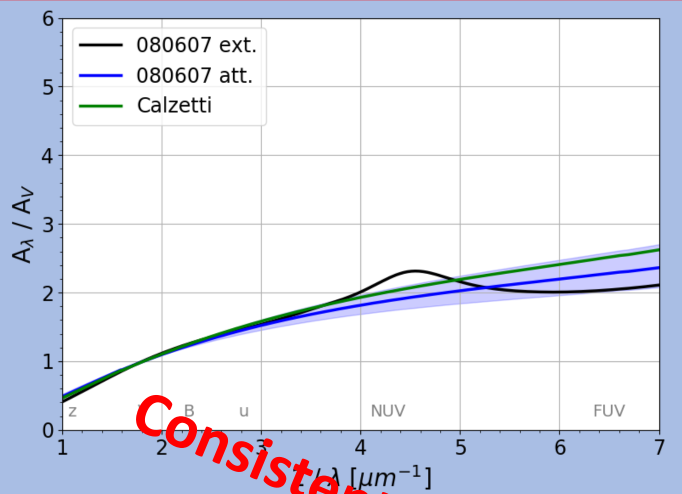
Att curve flatter than Ext curve

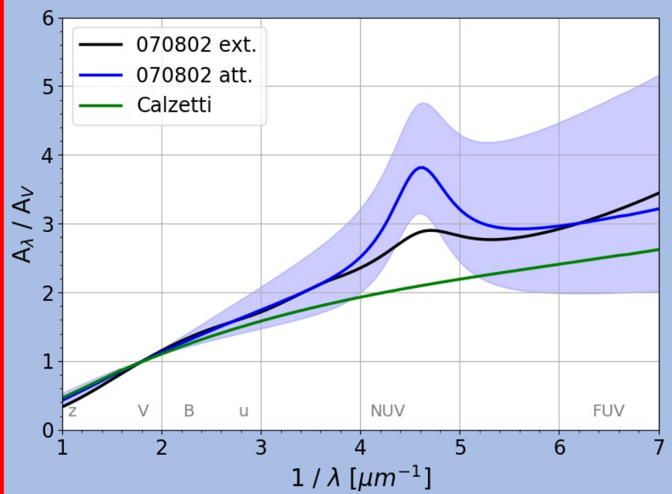


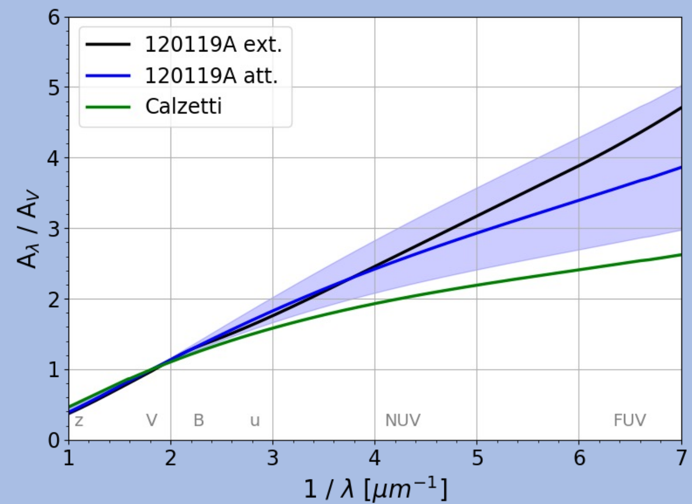
Corre+18

Att curve steeper than Ext curve





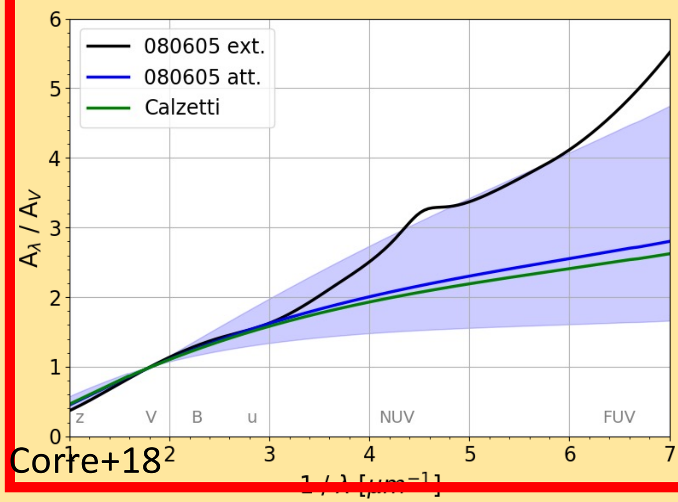


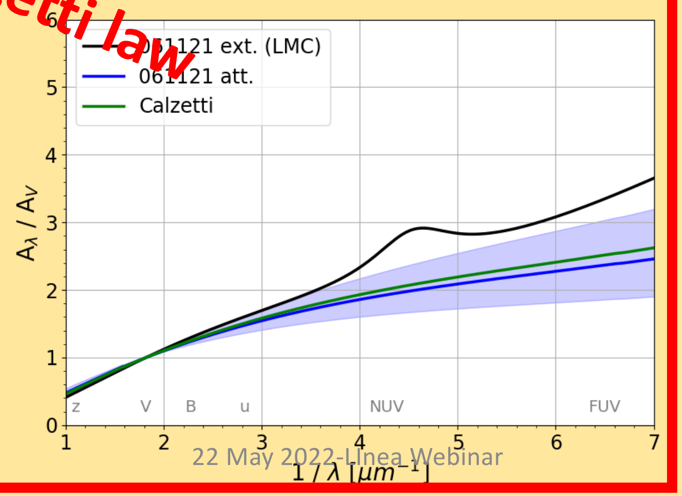


Consistent with the Calzetti law

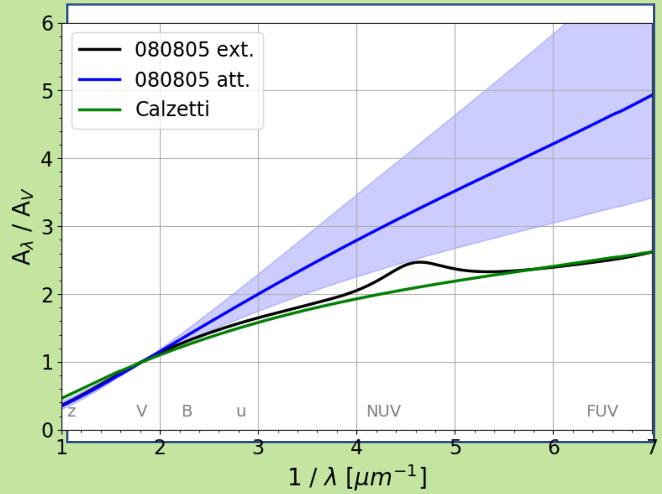
Att curve similar to Ext curve

Att curve flatter than Ext curve





Att curve steeper than Ext curve

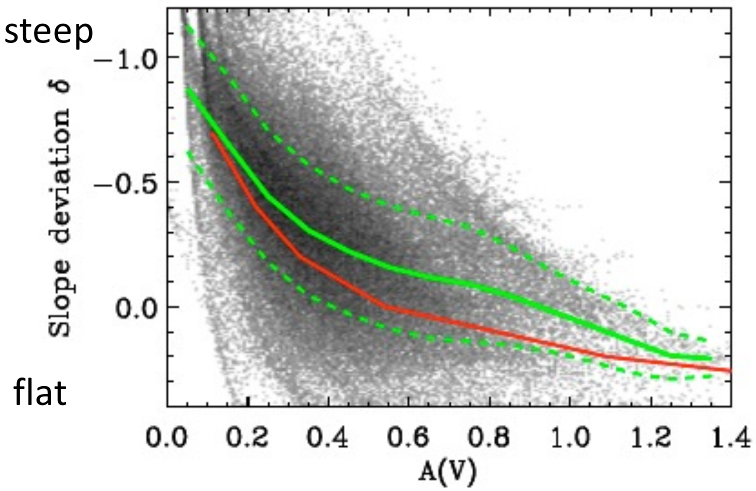


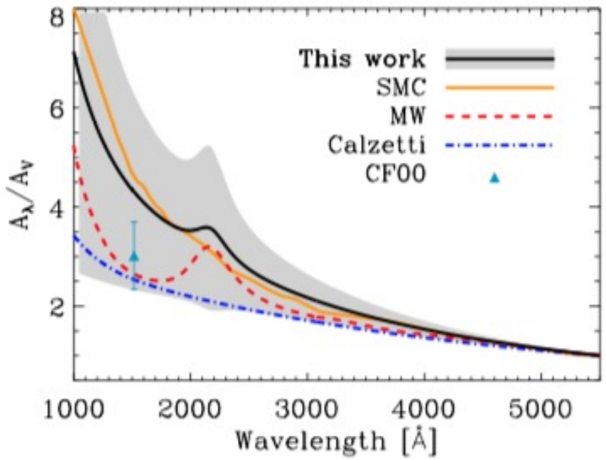
Corre+18

SDSS +GALEX+WISE z~0 CIGALE fits with Calzetti flexible att. Laws

Attenuation law flattens when A_v increases

Average curve steeper than the Calzetti law





Salim+18 (see also Battisti+20)

COSMOS field, **HELP/Herschel & 3D-HST data**

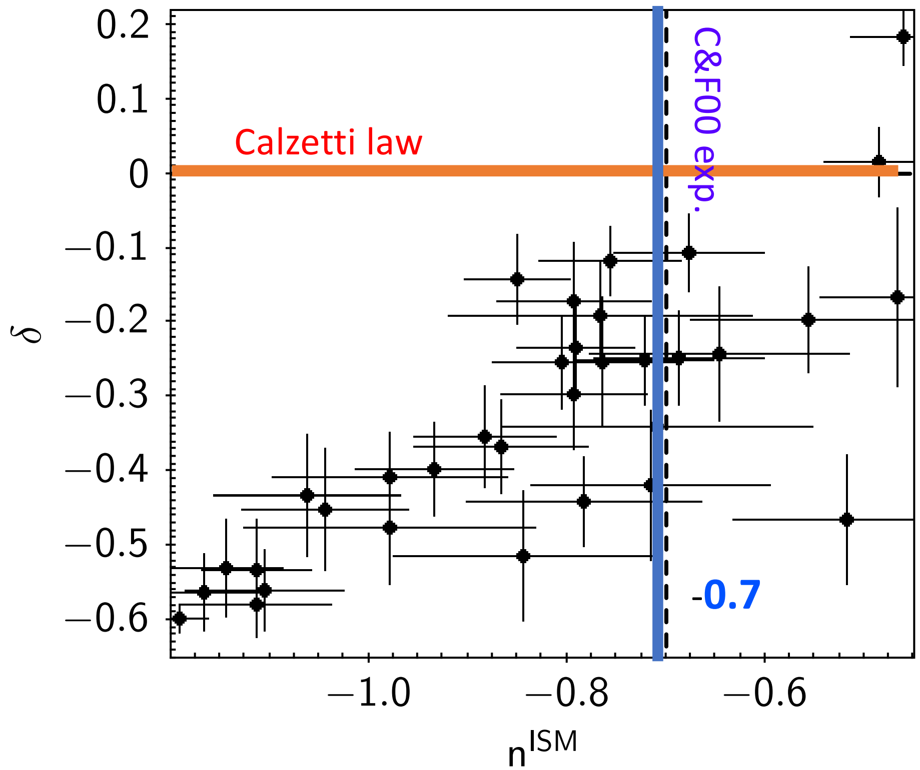
a sample of 34 IR sources all detected in Hα

0.6<z<1.6

Buat+18

n^{ISM} and δ correlate , steeper laws than the original ones

-->No universal values

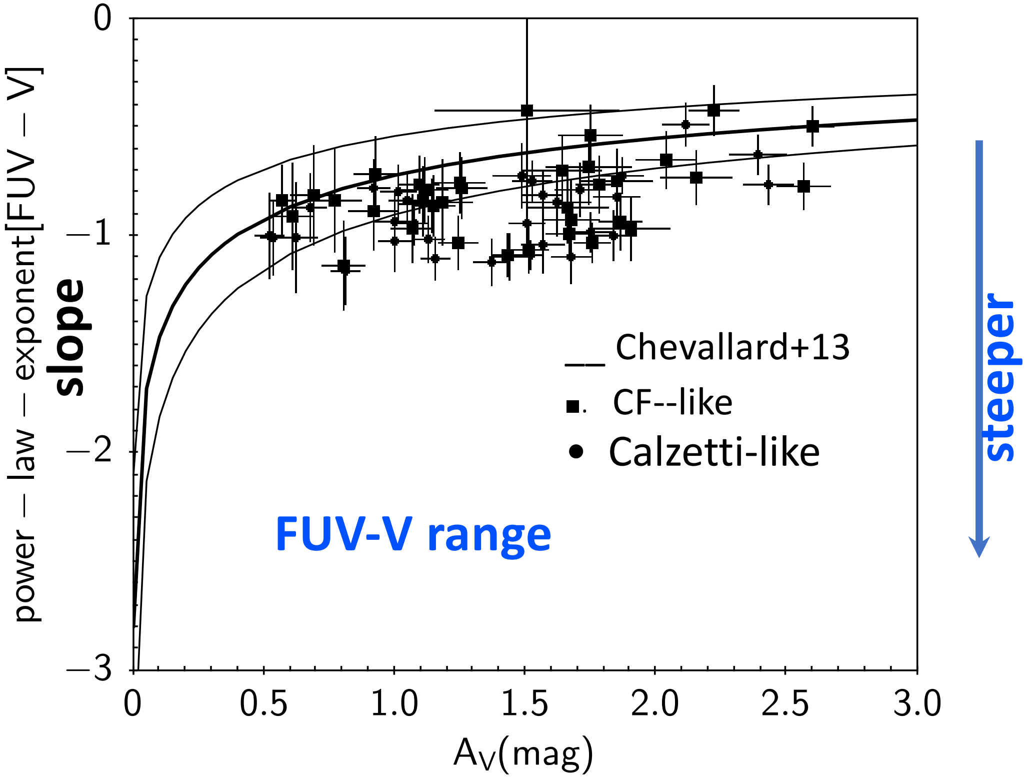


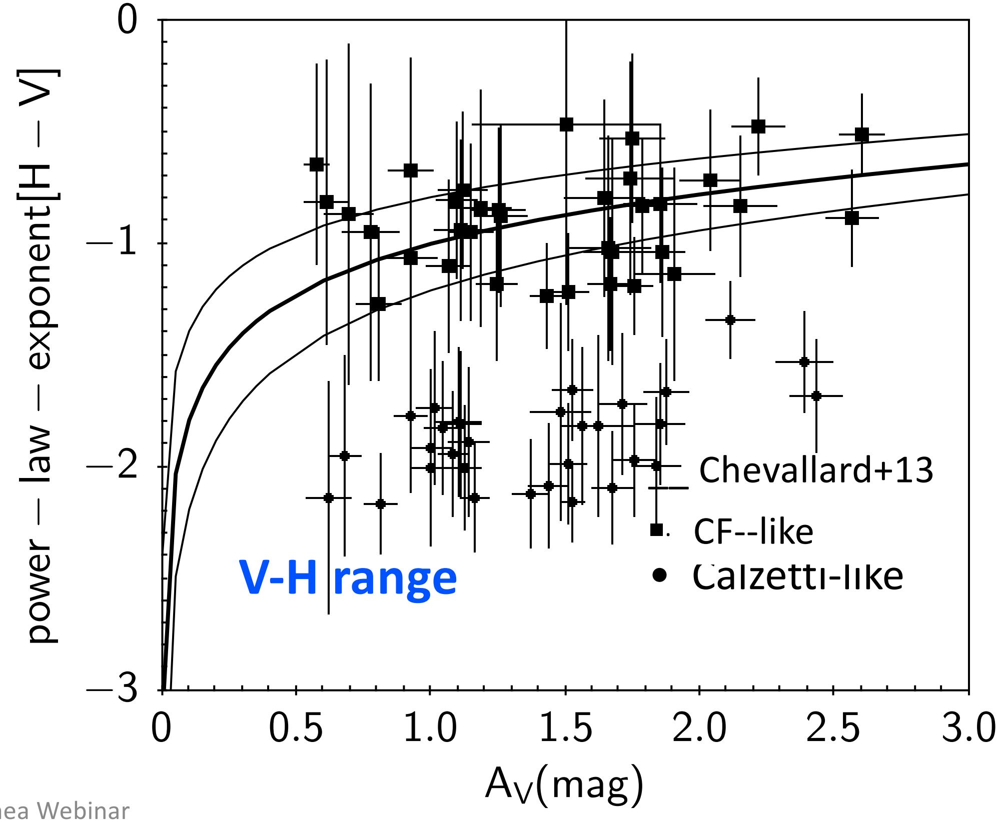
see also e.g. Buat+2012, Salmon+2016, Kriek & Conroy, 2013

Comparison with Radiation transfer modeling

which predicts a flattening of attenuation laws with increasing obscuration.

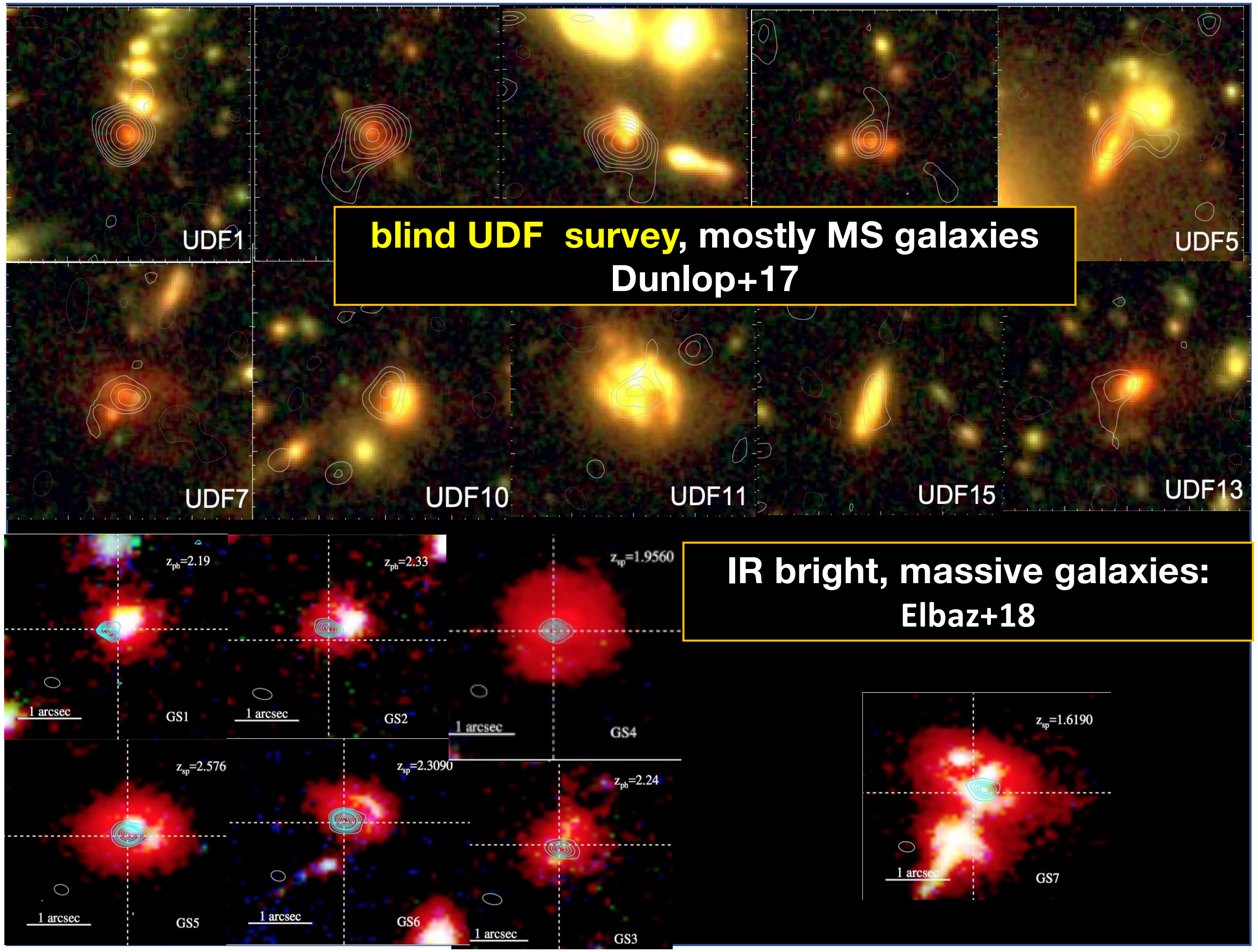
(Pierini+04, Tuffs+04, Law+18, Chevallard+13)





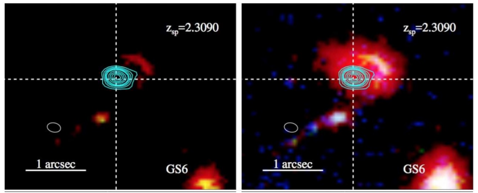
z~2 dust-rich sources as seen by ALMA: a challenge for SED fitting techniques

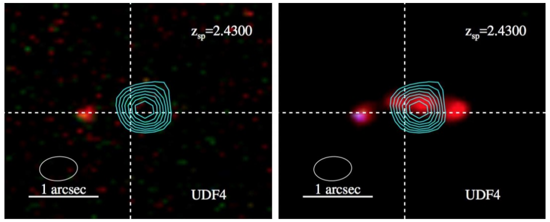
Buat+19



Fitting the SED with CIGALE

- UV-NIR rest frame data: stellar continuum → best fits with the Calzetti law for all but 1 galaxy
  → recovers at most half of the IR dust luminosty
- Fit of the full UV-submm: stellar and dust emission → various attenuation laws

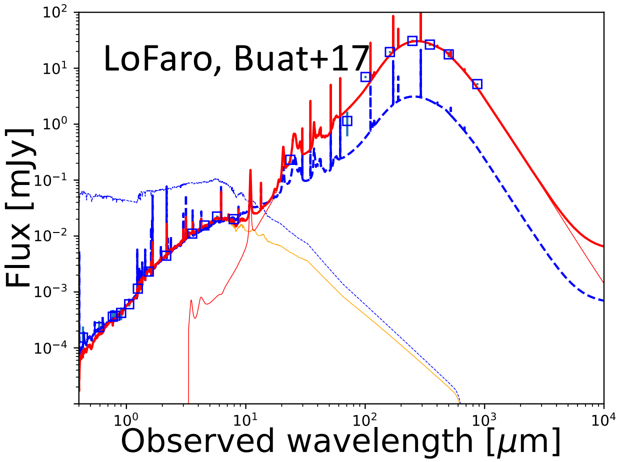




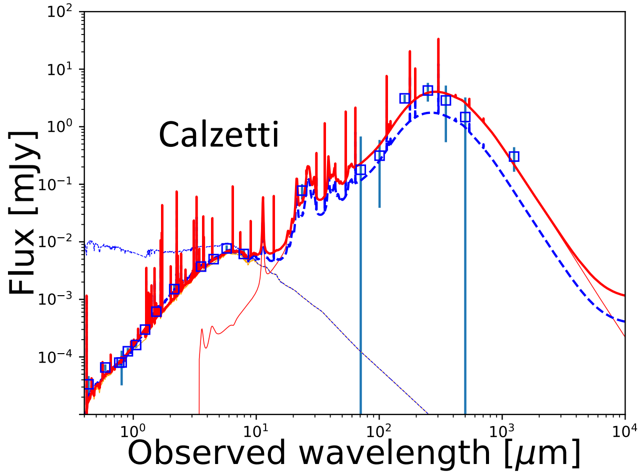
$L_{dust}^{UV\text{-}NIR}$ = 0.11 L_{dust}^{IR}

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

Best fit for GS6

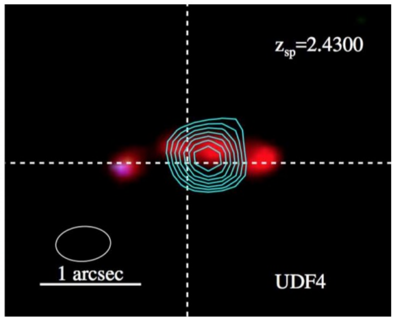


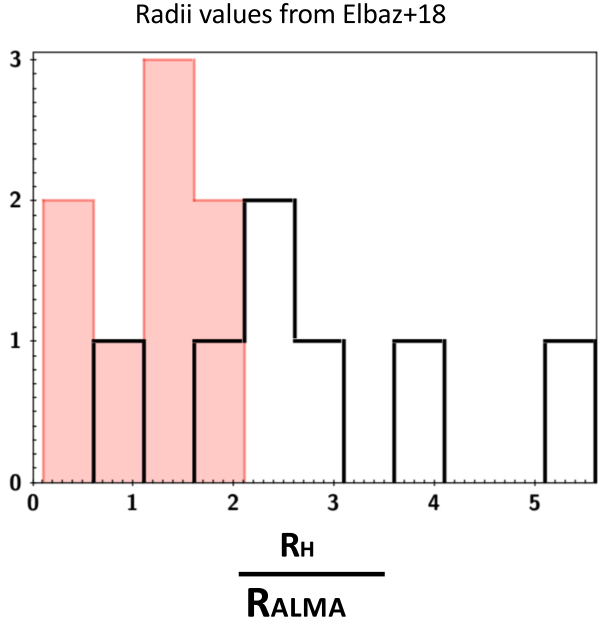
Best fit for UDF4



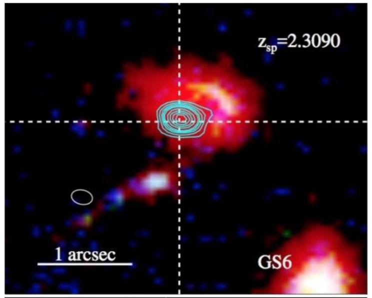
Dust attenuation law and compactness

Galaxies for which
Calzetti+00 is acceptable





Galaxies for which
a much flatter attenuation law
is needed



Suggests that sources with very compact dust distributions are better fitted with flatter attenuation laws than Calzetti+00

Outline

❖**Dust and stellar interplay in galaxies**

- Definition of extinction and attenuation curves

  Extinction & attenuation in GRB hosts
- Radiation Transfer modelling

  Short description and few results

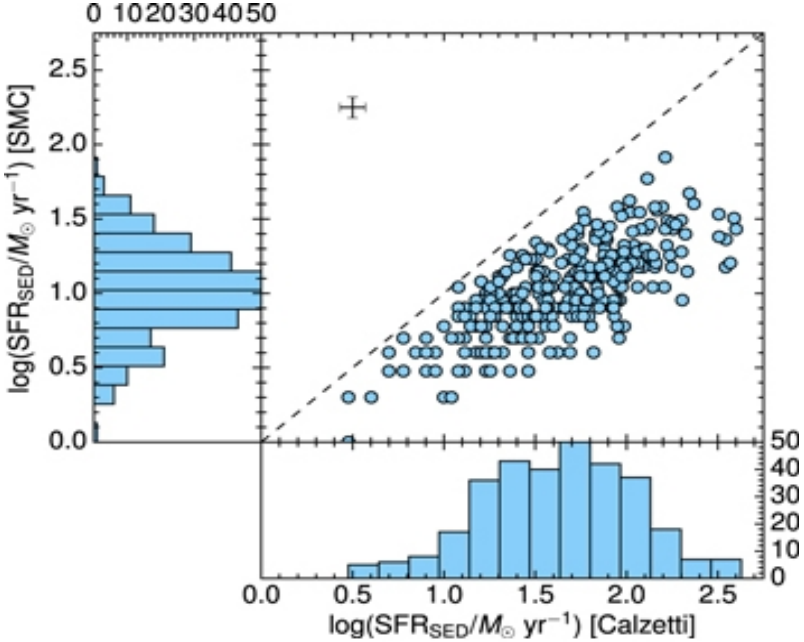
❖**The dust attenuation law from the local to the distant universe:**

- Formalisms and shapes of the attenuation law
- Attenuations laws from numerical simulations
- Measured attenuations laws

  From spectroscopy & from photometry and SED fitting

❖**Impact of attenuation on SFR and M_{star} measurements**

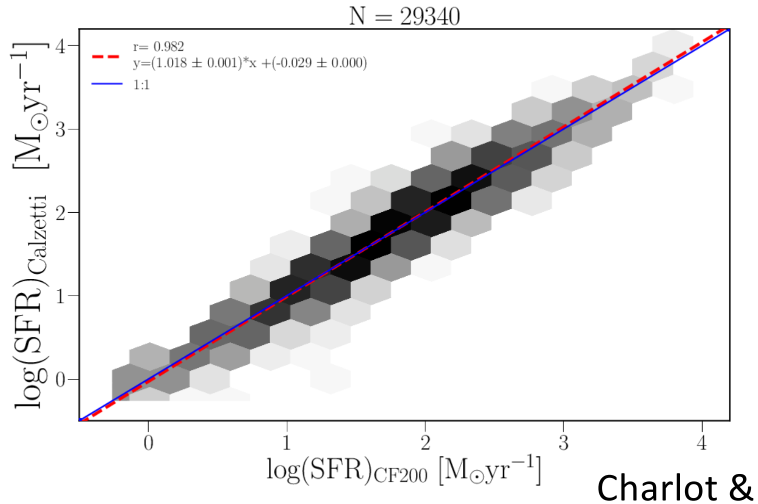
Impact of the dust attenuation law on the measure of physical quantities



Theios + 19

SMC (UV steep) and Calzetti (UV flat) curves

(no IR (dust) emission)



Calzetti+00

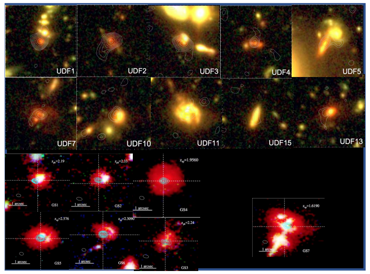
Charlot & Fall 03

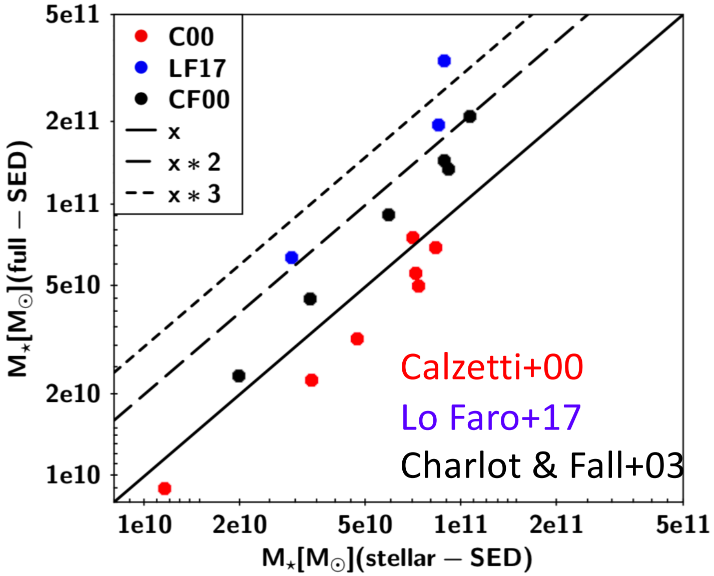
Malek, Buat+18; with **HELP/Herschel data**

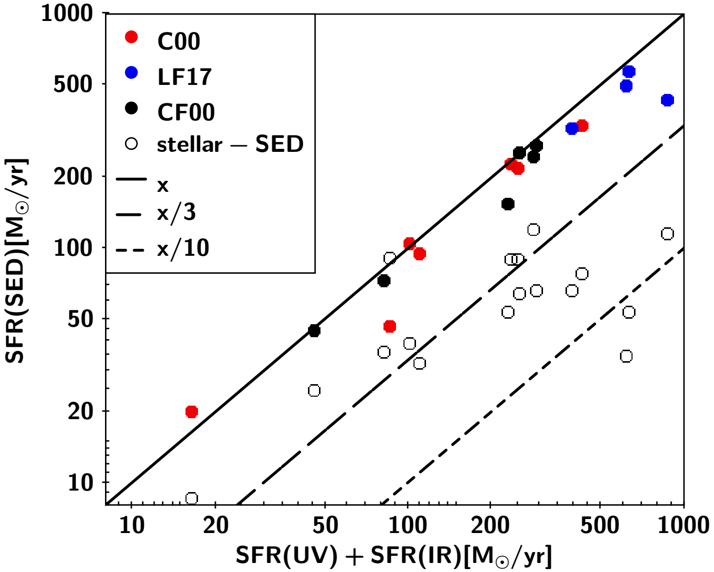
Strong impact on SFR determinations when IR (dust) emission is not available.
SFR robustly measured when IR data are available

SFR and stellar mass determinations in dust-rich ALMA galaxies

Buat+2019







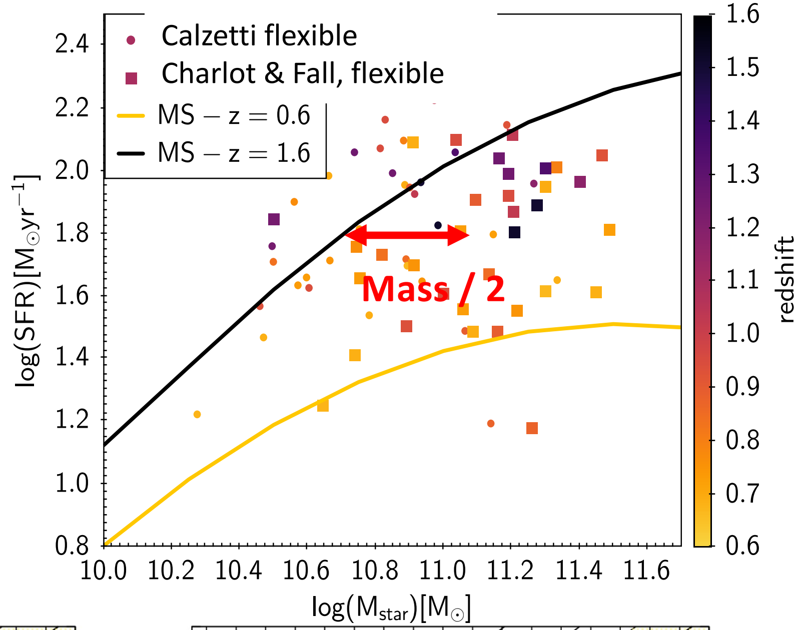
- **Stellar masses** depend on the attenuation law:

increase when the attenuation law flattens a factor ~2 of uncertainty

- **SFR** are recovered as long as IR data are taken into account:

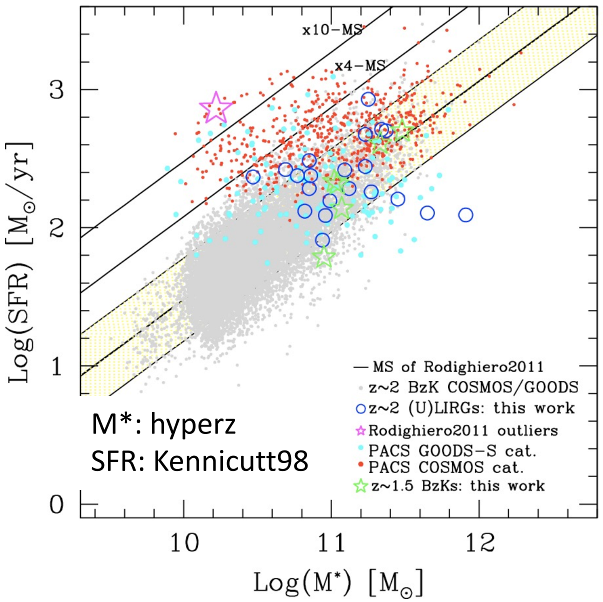
and if young populations are dominant to heat the dust.

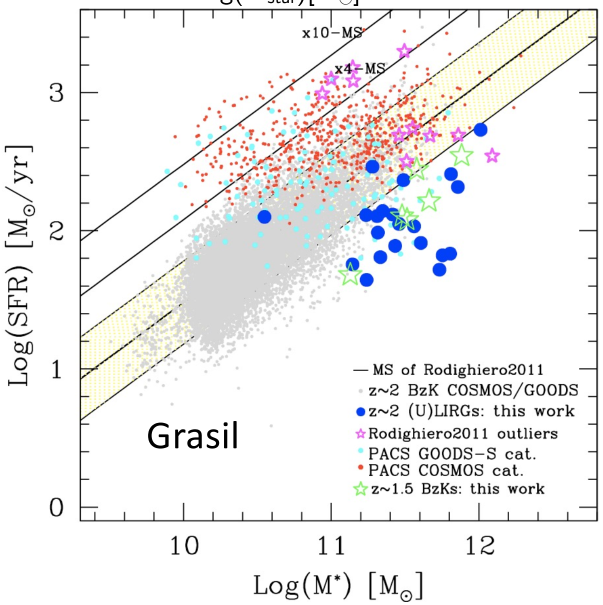
Impact on Main Sequence (MS) determinations



CiGALE fits with flexible attenuation laws: SFR similar and M_{star} vayring with a factor ~2

Buat+18





ULIRG at z~2

lower SFR and higher M_{star}

Lo Faro et al. 2015

Few important results to take away…

- Dust attenuation in galaxies is modeled with an ‘effective’ **attenuation law which is found not to be universal** but flattens when the amount of attenuation increases.
- **Radiation Transfer modeling** based on either simple geometries or numerical simulations give the framework to interpret measurements and **predict the variety of attenuation curves and their flattening of up to the NIR when attenuation increases,** confirmed in dusty galaxies.
- **Variations of the attenuation law has an impact on measured stellar mass and SFR** (if no IR data) and on the Main Sequence