Modeling the Panchromatic Spectral Energy Distributions of Galaxies

Section 6,7,8

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Total Dust Attenuation

Four primary techniques:

- UV-to-NIR SED fitting (a known attenuation curve), constrain $E(B-V)_{\mathrm{star}}$;
- Balmer decrement (an intrinsic ratio), e.g., Hα/Hβ, constrain $E(B-V)_{\mathrm{gas}}$;
- Energy balance technique (statement), e.g., IRX-β relation;
- Using luminous background source with a known intrinsic spectrum, e.g., MW extinction (Fitzpatrick et al., 2019).

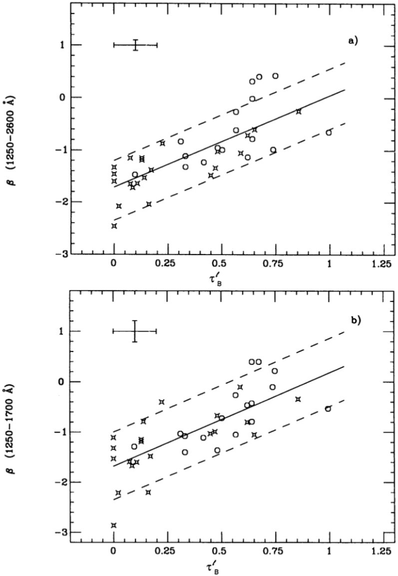
Commonly used parameterization: the total-to-selective attenuation curve

$$k_\lambda = \frac{A_\lambda}{E(B-V)},$$

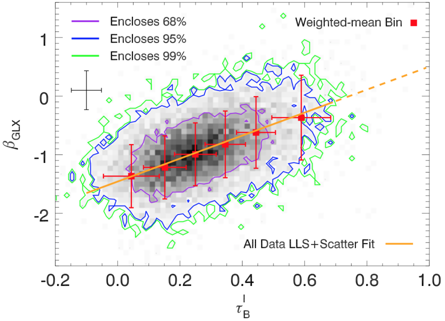
in which $E(B-V) = A_B - A_V$.

Nebular-to-stellar Attenuation Ratio

Calzetti et al. (1994)



Battisti et al. (2016)



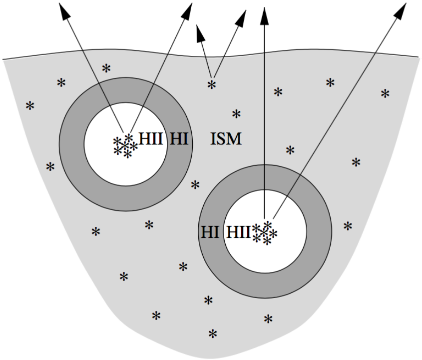
$$F(\lambda) \propto \lambda^{\beta}$$

$$\tau_B^l = \tau_{\mathrm{H}\beta} - \tau_{\mathrm{H}\alpha} = \ln\left(\frac{F(\mathrm{H}\alpha)/F(\mathrm{H}\beta)}{2.86}\right)$$

Calzetti (1997); Calzetti et al. (2000):

$$E(B-V)_{\mathrm{star}} = (0.44 \pm 0.03)E(B-V)_{\mathrm{gas}}$$

Two-component Dust Model



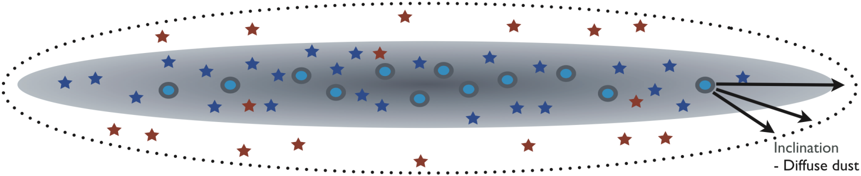
Charlot & Fall (2000)

$$\tau_\lambda^{\text{tot}}(t) = \begin{cases} \tau_\lambda^{\text{BC}} + \tau_\lambda^{\text{ISM}} & t \le t_{\text{BC}}, \\ \tau_\lambda^{\text{ISM}} & t > t_{\text{BC}}, \end{cases}$$

$\tau_\lambda^{\text{BC/ISM}} = \tau_V^{\text{BC/ISM}}(\lambda/0.55\mu\text{m})^{-n}$, $n = 0.7$, $t_{\text{BC}} = 10$ Myr.
da Cunha et al. (2008): $n_{\text{BC}} = 1.3$, $n_{\text{ISM}} = 0.7$.
Whitmore et al. (2014): $t_{\text{BC}} \lesssim 10$ Myr in NGC 4038/39.
Hollyhead et al. (2015): $t_{\text{BC}} < 4$ Myr in M83.
Grasha et al. (2019): $t_{\text{BC}} \lesssim 6$ Myr in M51.

Two-component Dust Model

Wild et al. (2011)



Inclination
- Diffuse dust increases
- Birth-cloud dust remains constant

Star-forming regions + Birth clouds
- OB stars produce nebular emission lines
- dust opacity dominated by birth clouds
- predominantly (spherical) screen-like extinction
- $\tau \sim \tau_{\mathrm{Birth\ Cloud}}$

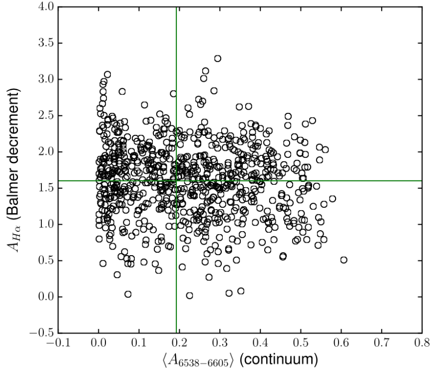
Intermediate-age stars
- mixed star-dust geometry
- attenuation primarily from diffuse ISM dust
- $\tau \sim \tau_{\mathrm{ISM}}$

Old stars (also in bulge, not pictured)
- predominantly responsible for NIR light
- higher fraction in bulge and/or thick disk
- screen-like extinction (far-side)
- no attenuation (near-side)
- observe extinction law in NIR ($\tau \sim \tau_{\mathrm{ext}}$)

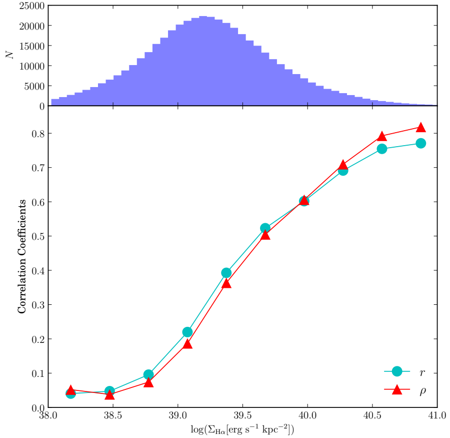
Diffuse ISM dust (with radial gradient)

$\tau_\lambda^{\mathrm{BC+ISM}}/\tau_\lambda^{\mathrm{BC}}$ Ratio

Viaene et al. (2017):
dust-lane ETGs

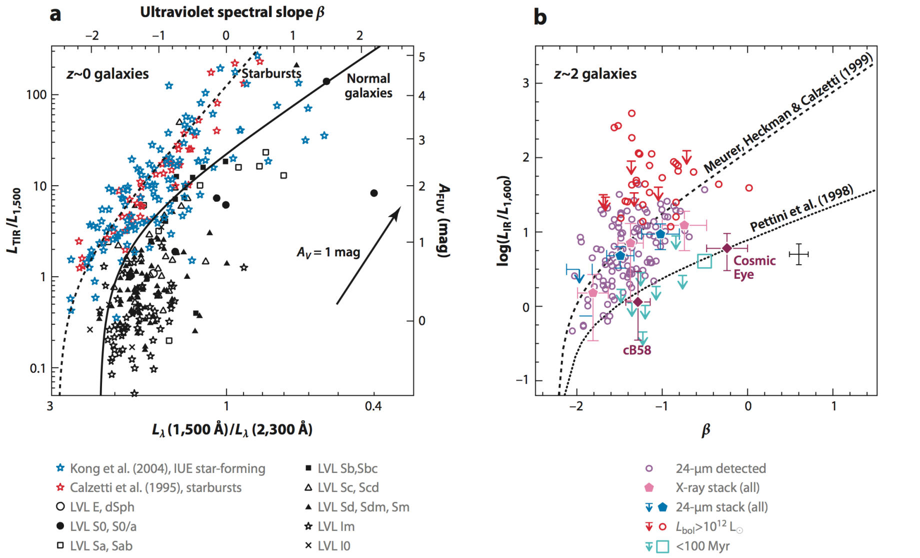


Lin & Kong (2019)



$\tau_\lambda^{\mathrm{BC+ISM}}/\tau_\lambda^{\mathrm{BC}}$ or $E(B-V)_{\mathrm{star}}/E(B-V)_{\mathrm{gas}}$ may be not a constant for all type of galaxies (Wild et al., 2011; Zahid et al., 2017; Koyama et al., 2019; Qin et al., 2019; Lin & Kong, 2019).

IRX-β Relation



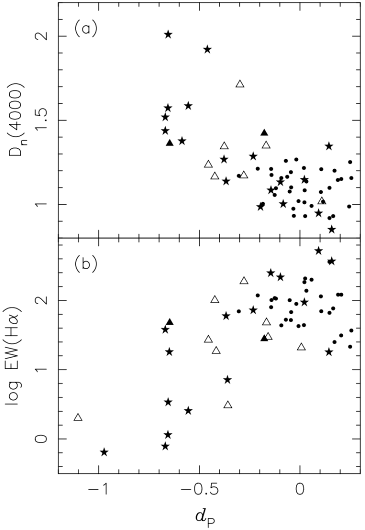
Second Parameter

- Kong et al. (2004): stellar population parameters (SFH)
- Boquien et al. (2009) (H II regions): dust geometries and extinction curves
- Casey et al. (2014): SFR (or L_{IR})

Disadvantage:

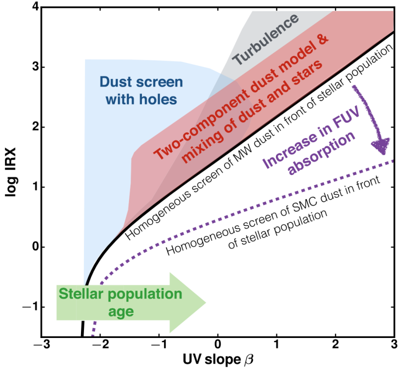
- Large uncertainties on IRX (Johnson et al., 2007)
- Energy balance statement might be broken at scale $\lesssim$ 1.5 kpc (Williams et al., 2019)

Estimation of dust attenuation from the IRX-β will give way to more robust techniques.

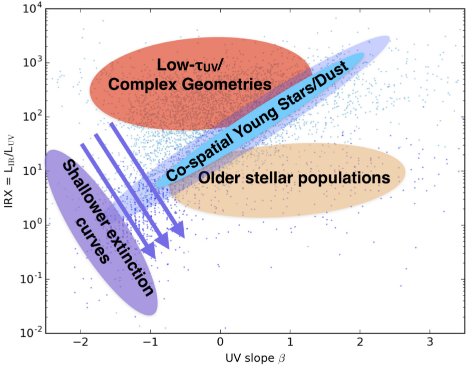


Origin of Scatter

Popping et al. (2017): `Starburst99`+dust models



Narayanan et al. (2018): Cosmological zoom galaxy formation simulations

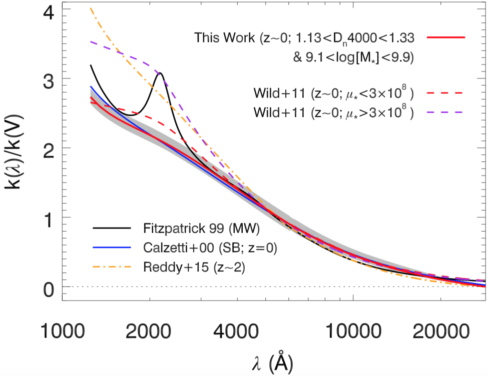


UV-to-NIR SED fitting

- Age–dust degeneracy: poorly constrained dust attenuation from UV-NIR broadband SEDs
- Break the degeneracy: spectroscopic or FIR data
- Narrow spectroscopic features: stellar age and metallicity, e.g., $D_n(4000)$ and Hδ (Kauffmann et al., 2003)
- FIR data: measurement of the total L_{IR} (Noll et al., 2009a)

Constraints on the Attenuation Curve

- Calzetti et al. (1994, 2000): assuming the same underlying stellar populations, compare galaxies with different τ_B^l $\rightarrow$ average attenuation curve for SB galaxies, shallower than the MW or LMC extinction curve, without 2175 Å bump
- Wild et al. (2011): pairs of galaxies with similar gas-phase metallicities, sSFRs, b/a but different τ_B^l
- Battisti et al. (2016); Battisti et al. (2017): local SFGs
- CIGALE fit for individual galaxies: Buat et al. (2018); Salim et al. (2018)
- High-z: Kriek & Conroy (2013); Reddy et al. (2015); Scoville et al. (2015); Zeimann et al. (2015); Cullen et al. (2018)



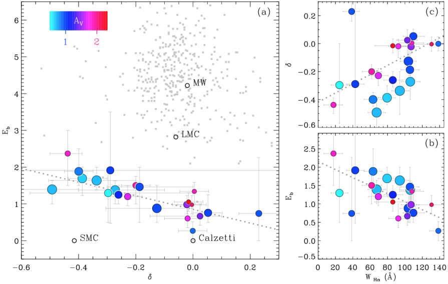
2175-Å dust feature

Expectation: normal SFGs should show evidence for the 2175 Å dust feature. Parameterize dust attenuation curve with a bump (Noll et al., 2009b):

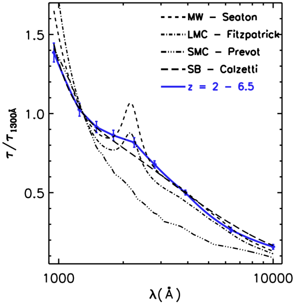
$$A(\lambda) = \frac{A_V}{4.05}(k_{\mathsf{Cal}}(\lambda) + D(\lambda))\left(\frac{\lambda}{\lambda_V}\right)^{\delta}$$

$$D(\lambda) = \frac{E_b(\lambda\Delta\lambda)^2}{(\lambda^2 - \lambda_0)^2 + (\lambda\Delta\lambda)^2}.$$

Kriek & Conroy (2013)

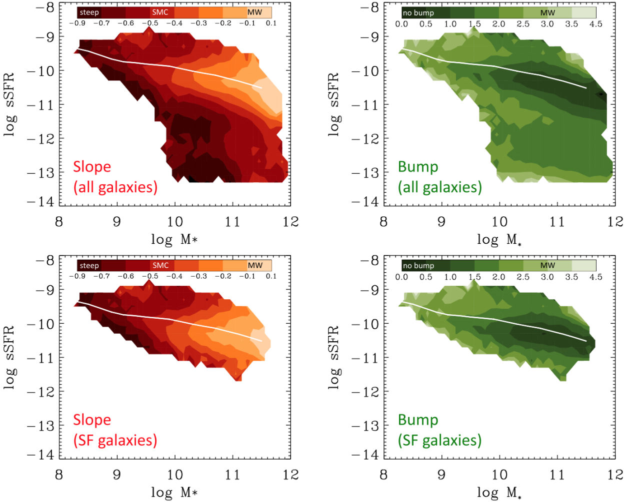


Scoville et al. (2015)



2175-Å dust feature

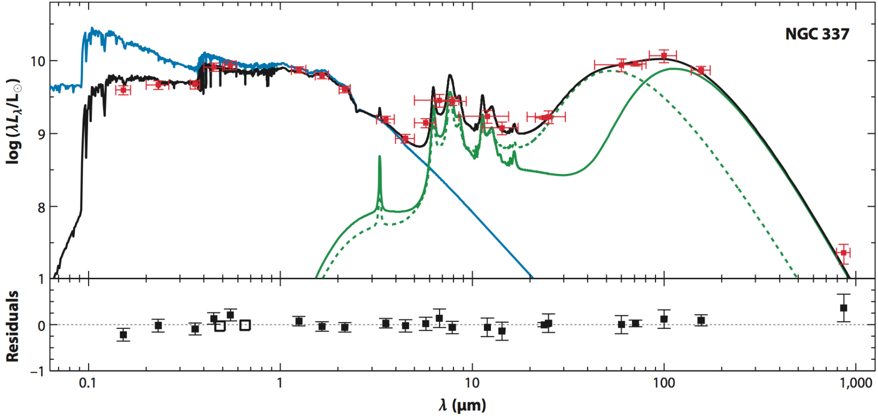
Salim et al. (2018): local galaxies, a wide range of UV bump amplitudes with an average strength of 1/3 of the MW bump.



Physical Dust Properties

Constraints on the M_{dust} and T_{dust} require data beyond the peak in the thermal dust emission spectrum at $\sim 100\ \mu$m.

da Cunha et al. (2008) (`MAGPHYS`)



Physical Dust Properties

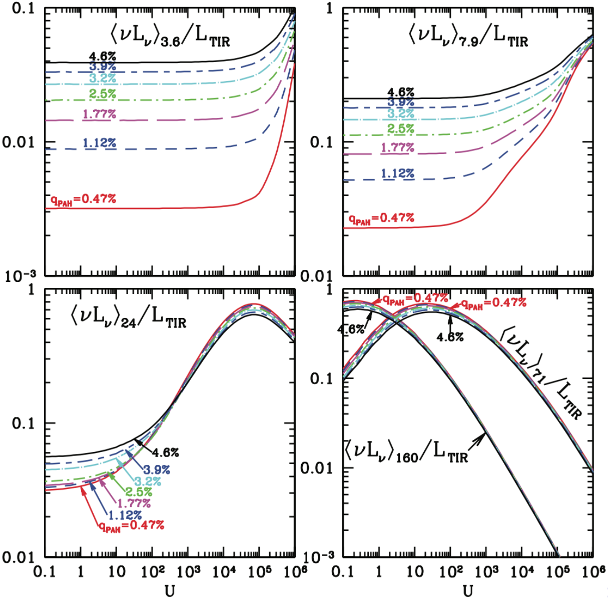
IR SED models:

Draine & Li (2007) (e.g., `CIGALE`)

- grain populations exposed to a variety of starlight intensities
- thermal emission and single photon heating of dust particles
- dust size distributions of MW (q_{PAH}) + emissivity for a dust mixture heated by U + dM_{dust}/dU
- free parameters: q_{PAH}, U_{min}, $\gamma(U > U_{\mathrm{min}})$ (fixed $\alpha = 2$, $U_{\mathrm{max}} = 10^6$, Draine et al. 2007)

With *Herschel* data: simplistic, modified blackbody dust models are no longer capable of providing adequate fits to the data.

Physical Dust Properties



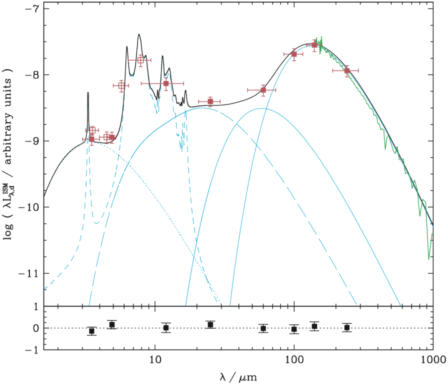
Physical Dust Properties

IR SED models:

da Cunha et al. (2008) (`MAGPHYS`)

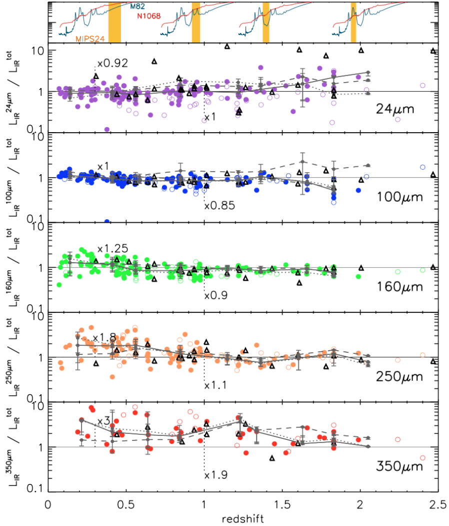
- an empirical spectrum for the PAH emission
- emission from stochastically heated grains
- warm and cold thermal dust

New update of `MAGPHYS`:
add 2175 Å bump to attenuation curve (Battisti et al., 2019)

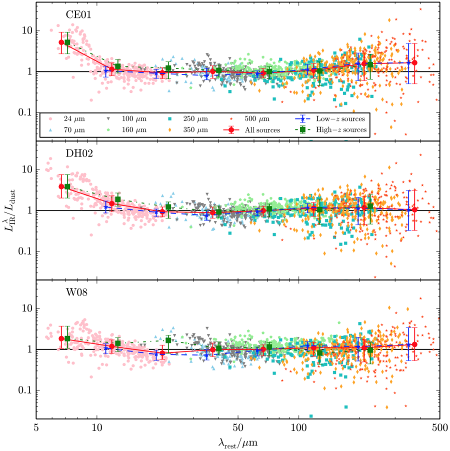


Cosmic Evolution of IR SEDs

MIR-excess problem (Elbaz et al., 2010)



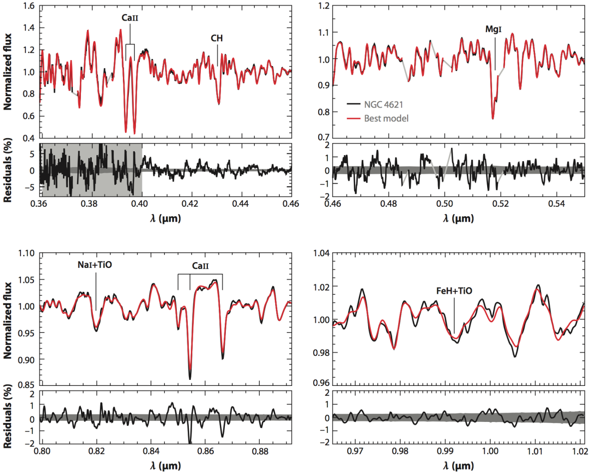
Lin et al. (2016)



Elbaz et al. (2011): local ULIRGs, a depressed emission component from PAHs due to hotter T_{dust}.

Constraints from SEDs

Problem: whether the IMF has had the same form over all of cosmic time and in all environments



- IMF-sensitive features: NaI doublet (0.82 μm), CaII triplet (0.86 μm), FeH band head (0.99 μm)
- Extremely dwarf-rich IMFs are now routinely ruled out.
- More modest IMF variations appear to be supported by the data, at the level of a factor of 2–3 in M/L.

Concluding Remarks

- Combining broadband data with moderate resolution spectra: IFU, narrow-band photometry, grism data (e.g., 3D-HST)
- Uncertainties in the SPS models are becoming a critical limiting factor to the interpretation of galaxy SEDs: include contributions from nebular emission and dust around AGB stars; FUV-FIR models, stellar evolution uncertainties
- A more sophisticated approach: derive the full posterior distributions via (e.g.,) MCMC techniques
- Understanding what is knowable from the modeling of galaxy SEDs

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