Spectral Energy Distribution Fitting Techniques

Spectral Energy Distribution

The Spectral Energy Distribution (SED) is the energy emitted by an object as a function of the wavelength

- The flux detected by an observer on the ground can be altered because of
    1. The medium around the object (circumstellar material)
    2. The Interstellar Medium (ISM)
    3. The earth’s atmosphere

Spectral Energy Distribution

- Overview about SED fitting of Galaxies

  http://www.sedfitting.org/

- ARIADNE (spectrAl eneRgy dIstribution bAyesian moDel averagiNg fittEr): https://github.com/jvines/astroARIADNE
- sedkit: https://github.com/hover2pi/SEDkit
- VO SED Analyzer: http://svo2.cab.inta-csic.es/theory/vosa/

Spectral Energy Distribution - Fluxes

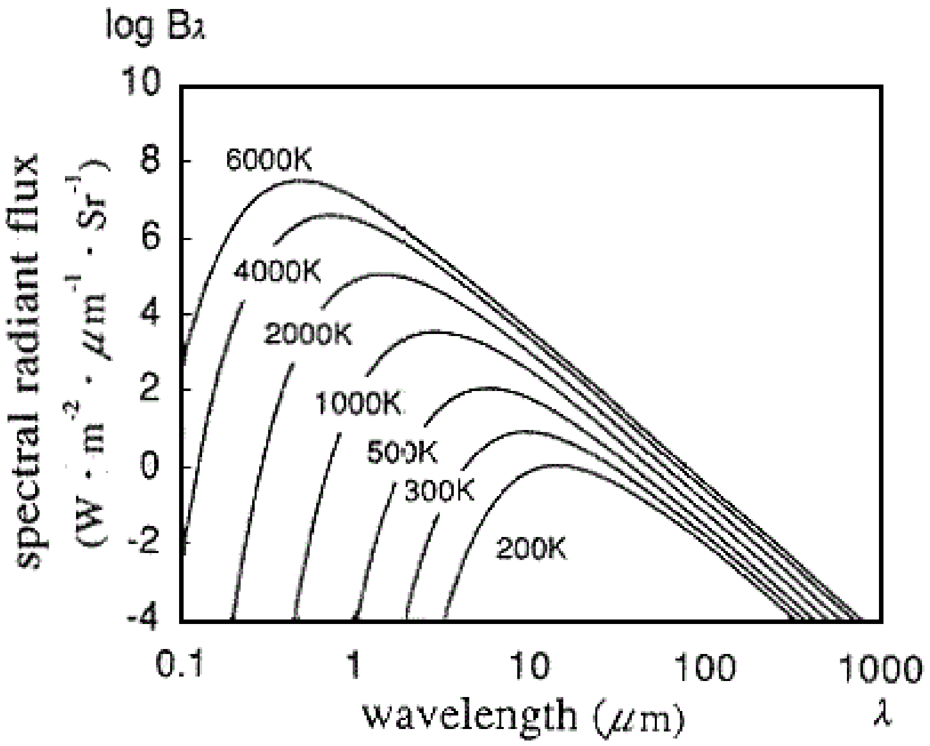
- To build the SED, we need fluxes, but we observe, normally magnitudes in a certain filter
- We need to transform the magnitudes to fluxes
- Our standard stars in this respect are the Sun, Vega and Sirius
- Review: Hayes, 1985, IAUS, 111, 225
- Cookbook: Gray, 1998, AJ, 116, 482S
- Also needed for Gaia: Altavilla et al., 2021, MNRAS, 501, 2848

Black Body Radiation

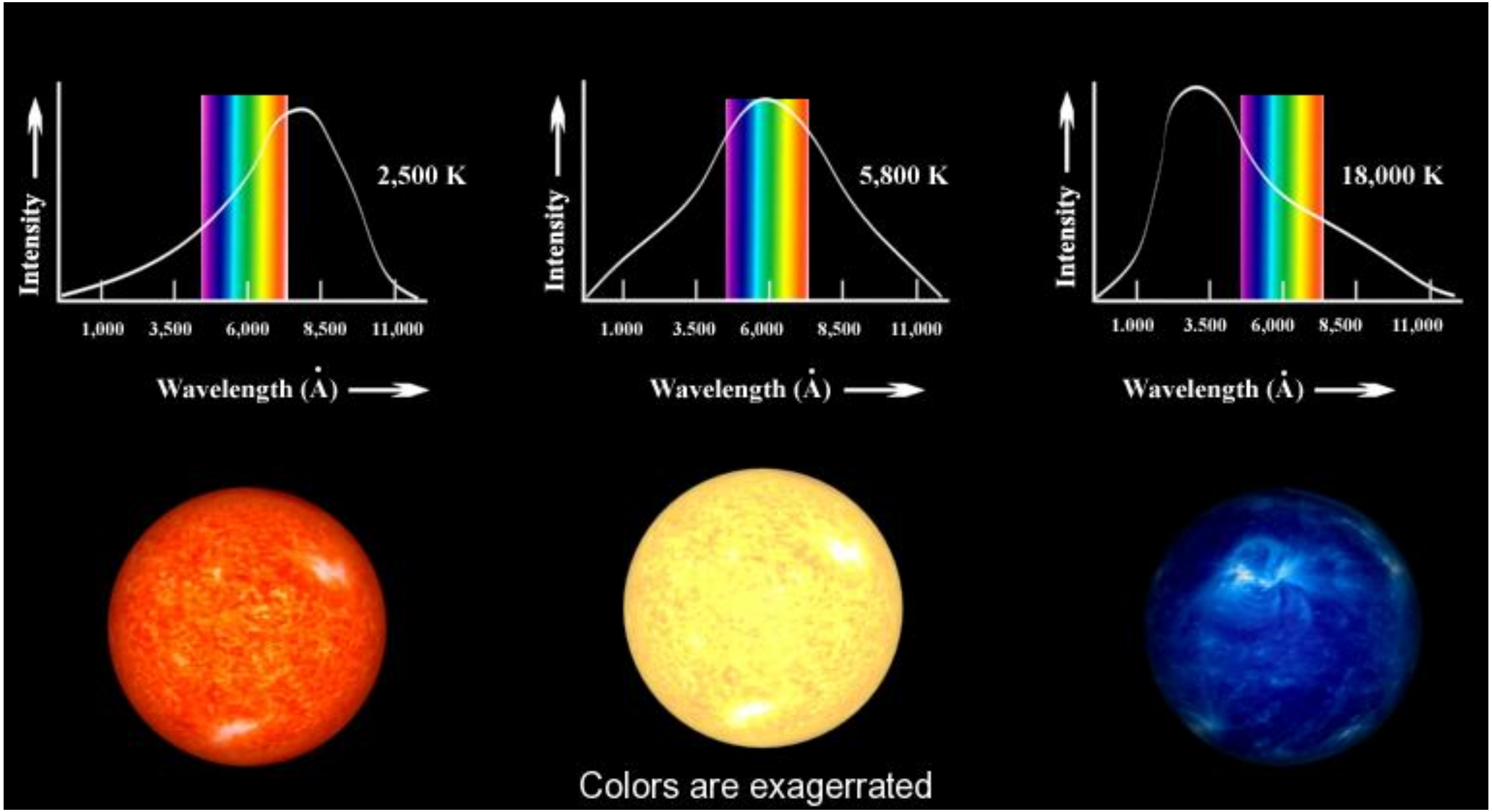
spectral radiance of black body $B\lambda$ is given as follows.

$$B\lambda = \frac{2hc^2}{\lambda^5} \cdot \frac{1}{exp(hc/k\lambda T) - 1}$$

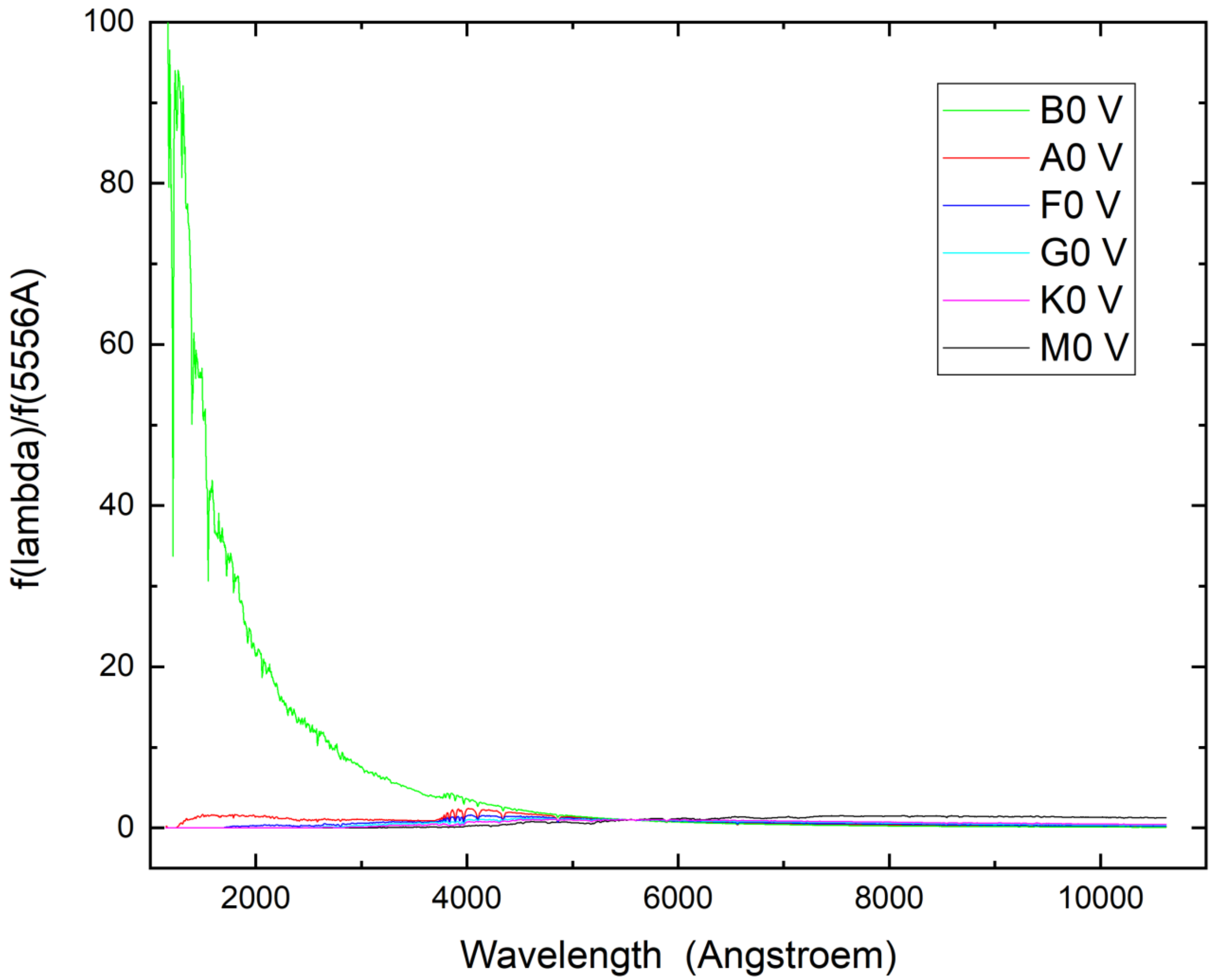
$B\lambda$	:	black body spectral radiance ($W \cdot m^{-2} \cdot sr^{-1} \cdot \mu m^{-1}$)		
T	:	absolute temperature of Black body (K)		
λ	:	wavelength (μm)		
c	:	velocity of light	2.998×10^8	($m \cdot s^{-1}$)
h	:	plank's constant	6.626×10^{-34}	($J \cdot s$)
k	:	Boltzmann's constant	1.380×10^{-23}	($J \cdot K^{-1}$)

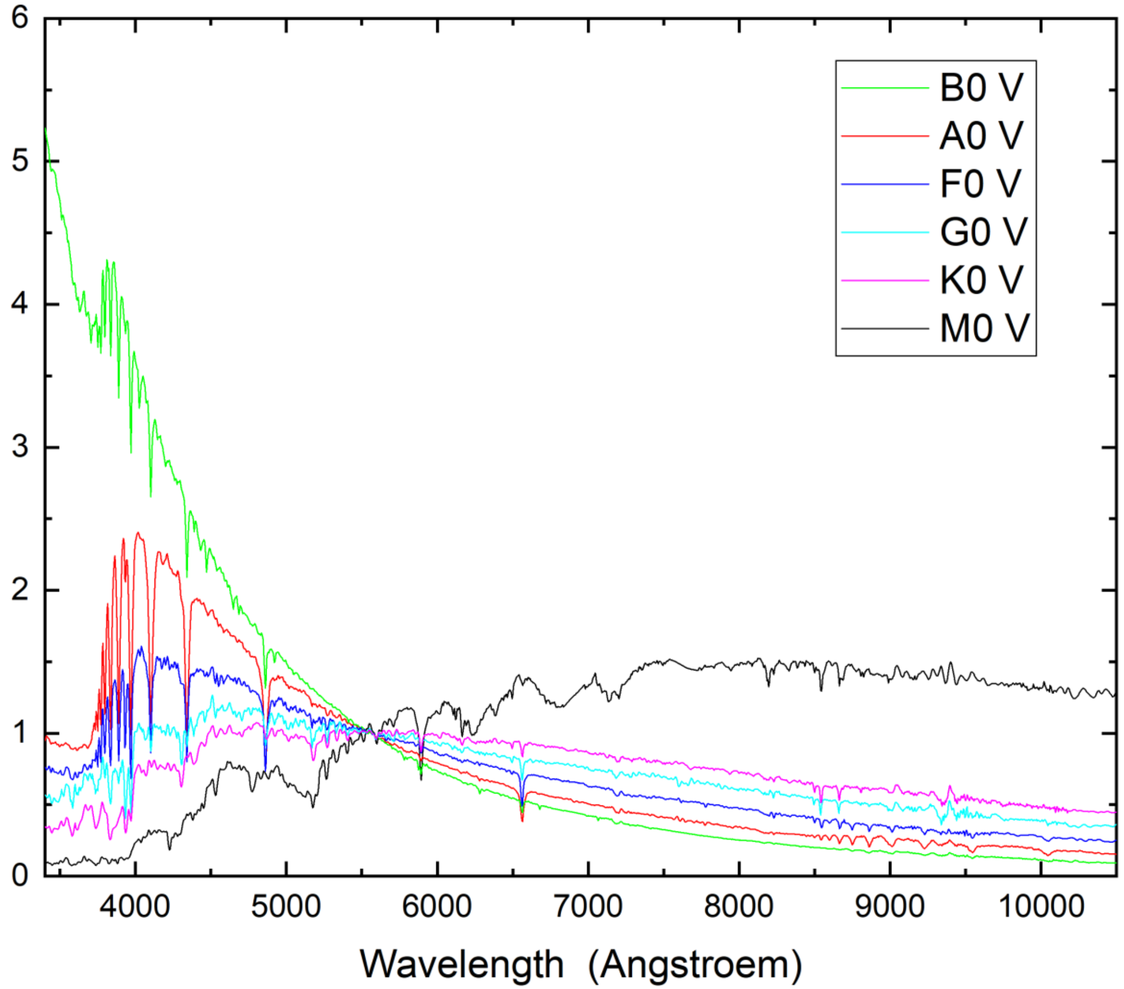


Black Body Radiation



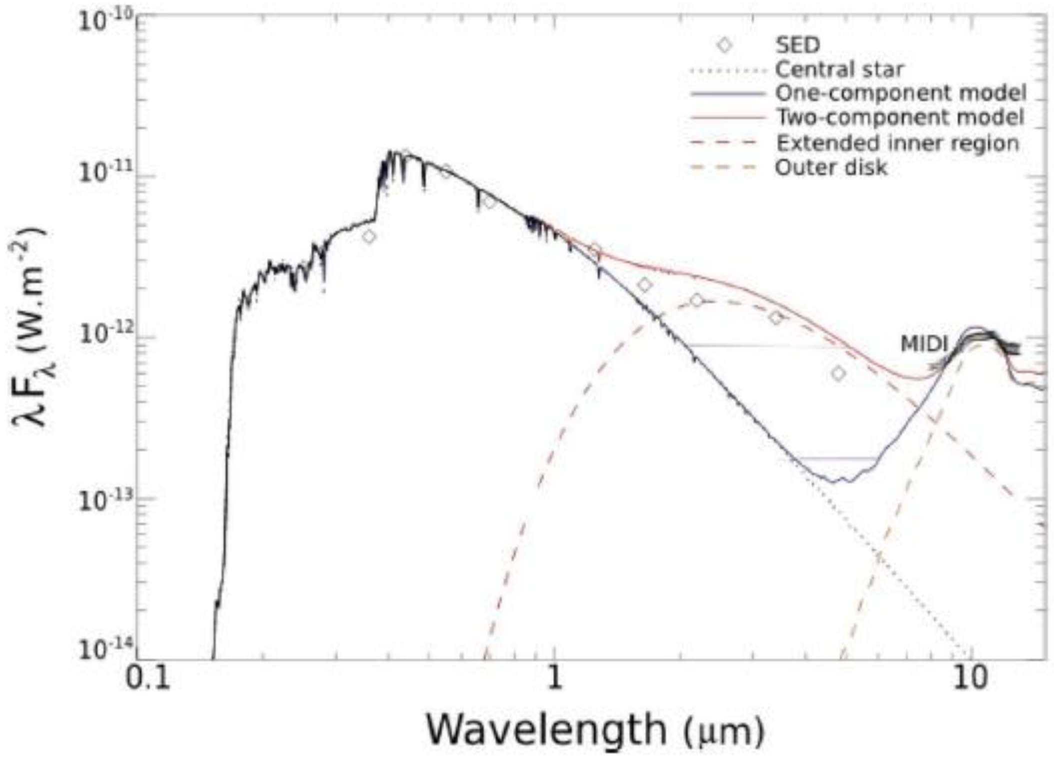
Spectral Energy Distribution - Stars

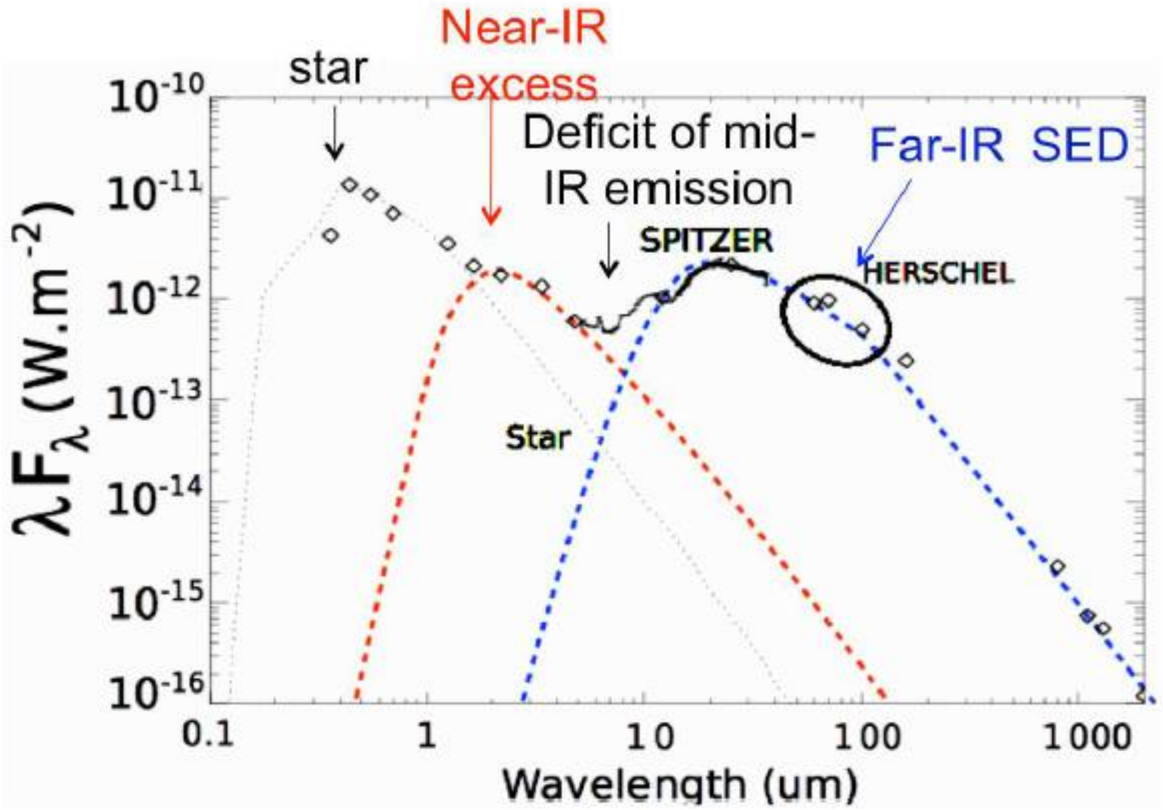




Pickles, 1998, PASP, 110, 863

Spectral Energy Distribution - Stars





Young star with a disk

Labadie et al., 2014, Proceedings of the SPIE, Volume 9146, id. 91462T 11

Spectral Energy Distribution - Stars

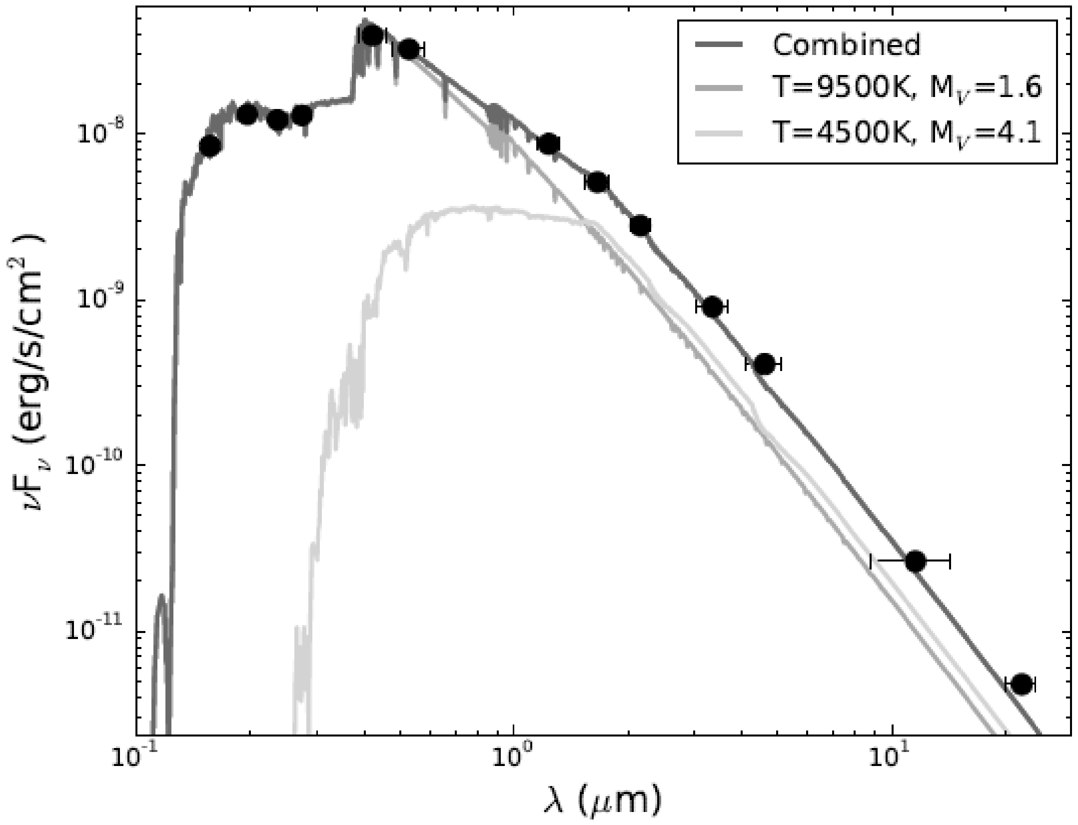
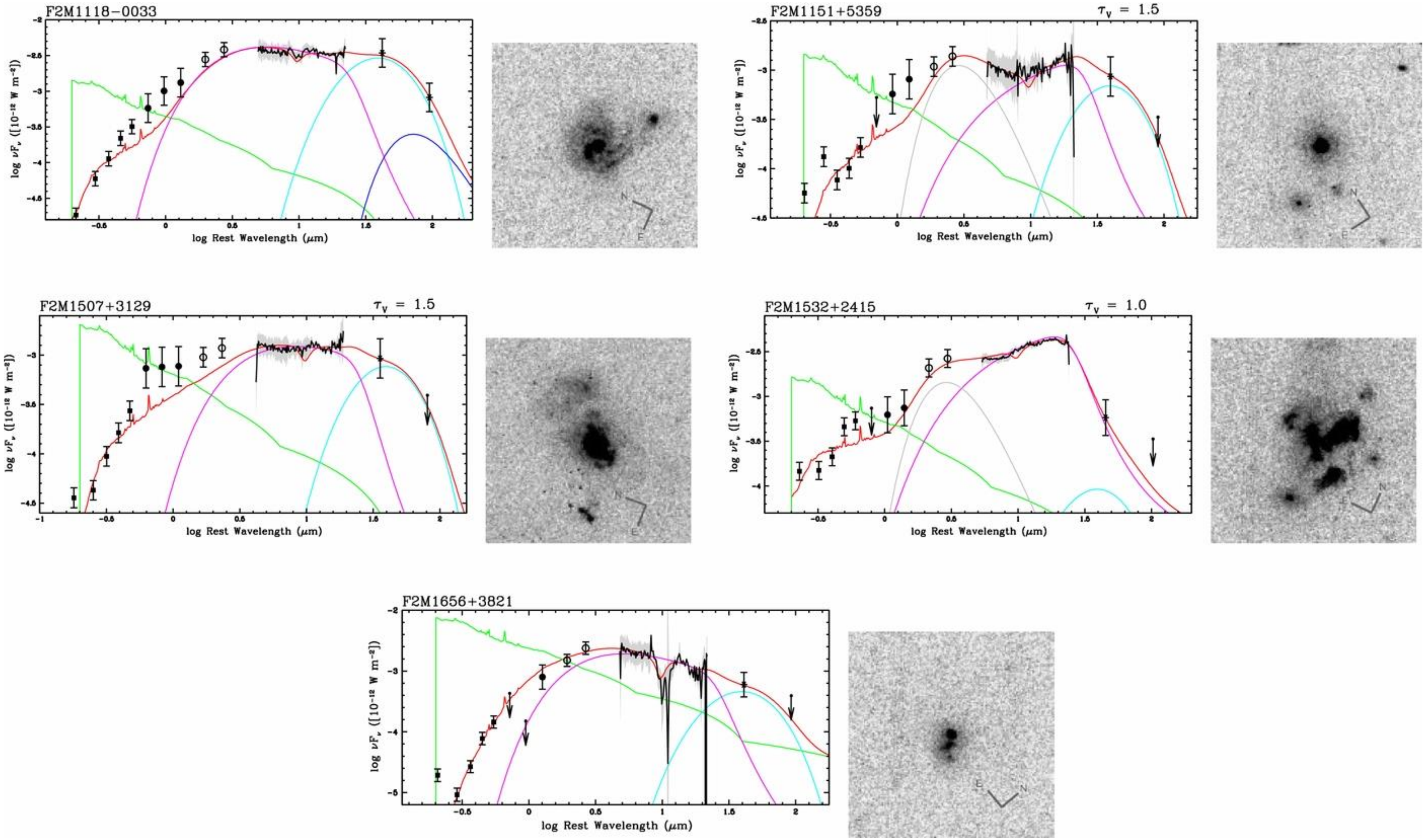


Figure 8. Spectral energy distribution (SED) for HD 63021 with model spectra co-added and matched in flux to the V-band.

Whelan et al., 2021, AJ, 161, 67

Spectroscopic binary system

Spectral Energy Distribution - Quasars

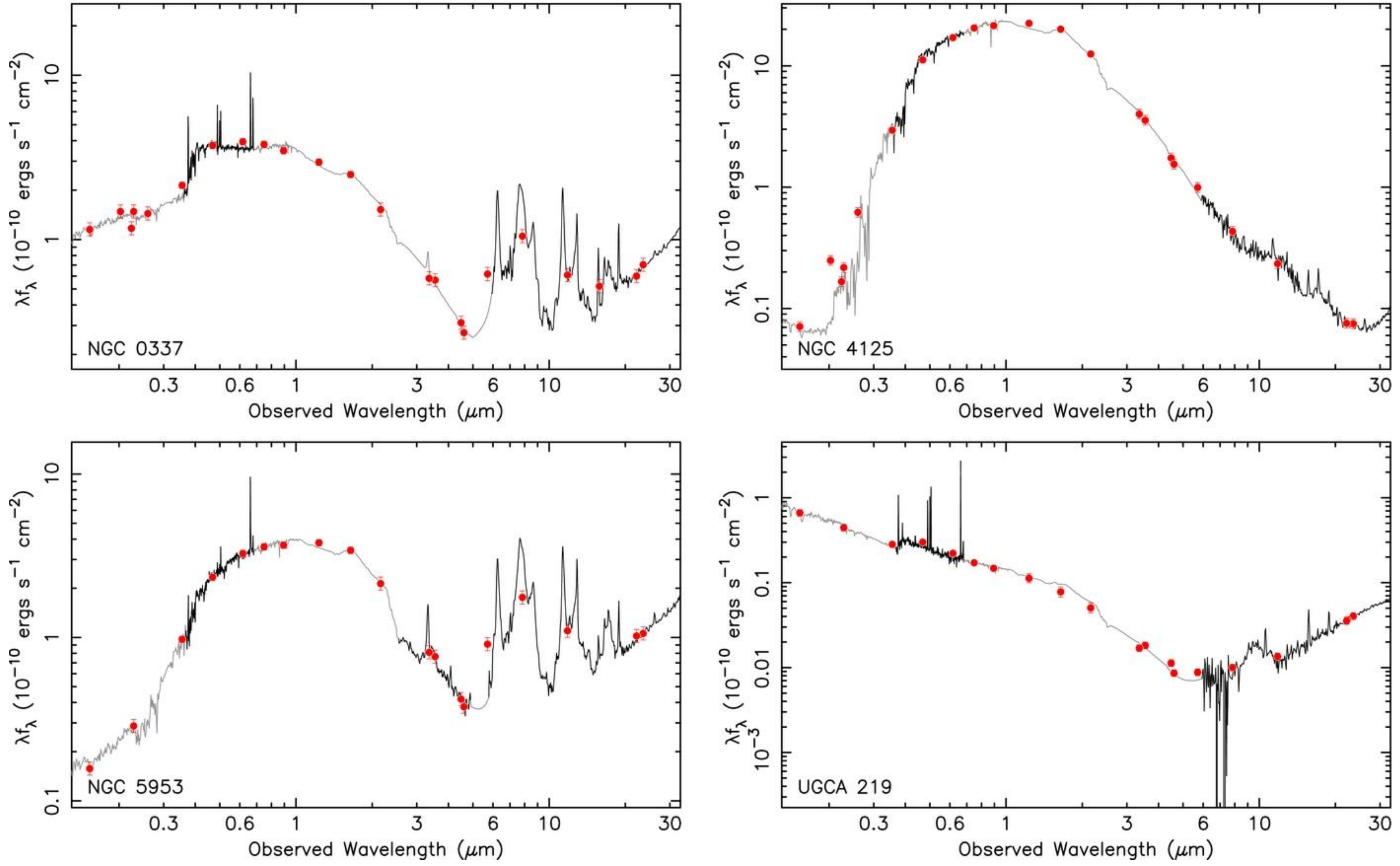


Circles are the observed values

Lines are different components of the models

Tanya Urrutia et al., 2012, ApJ, 757, 125

Spectral Energy Distribution - Galaxies



Brown et al., 2014, ApJS, 212, 18

Red circles are the observed values

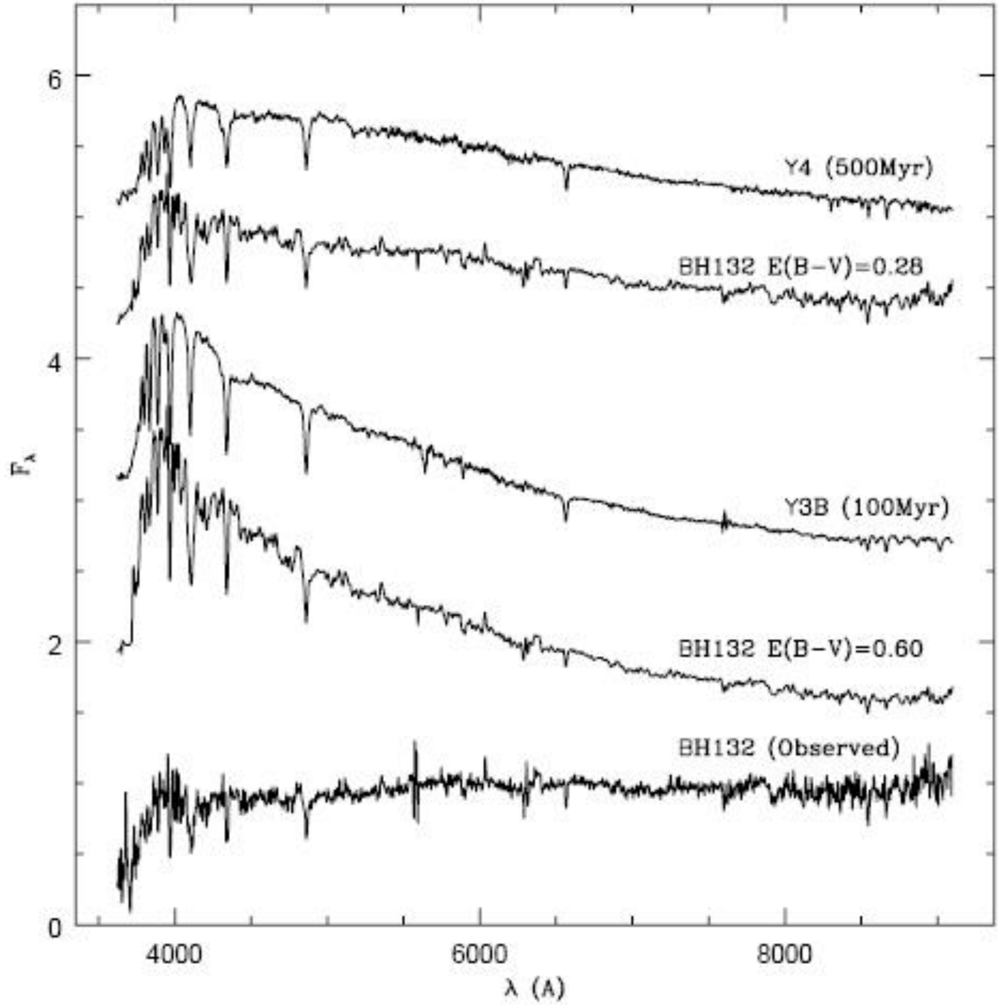
Black lines are the models

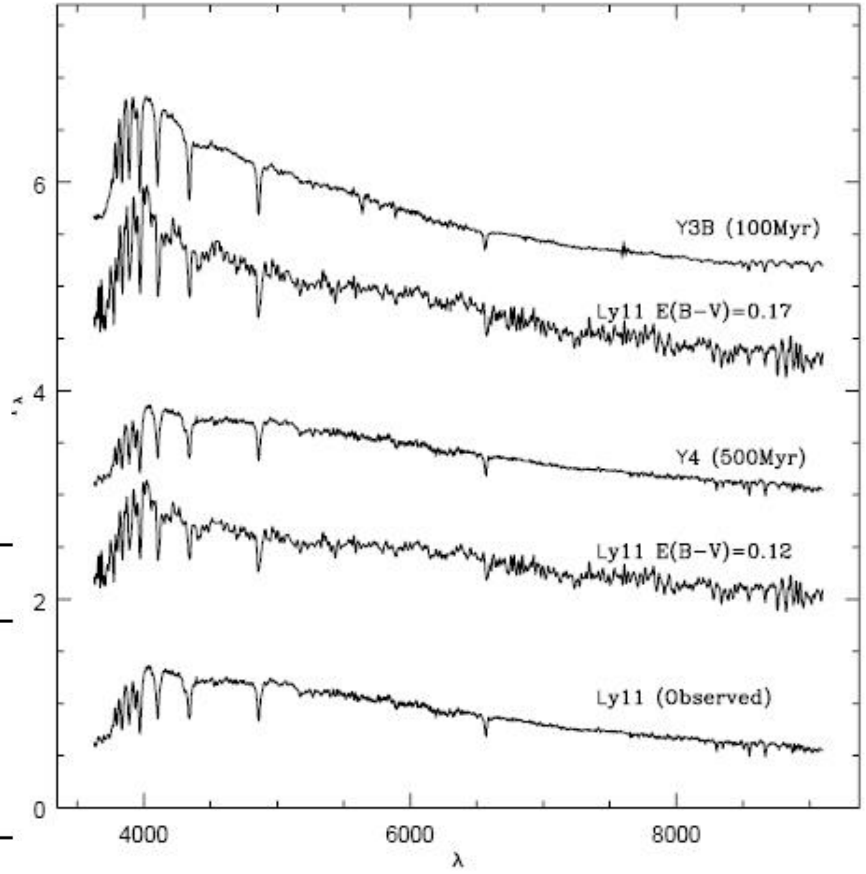
Spectral Energy Distribution - Galaxies

- Review articles:
  - Baes, 2020, IAUS, 341, 26
  - Leitherer, 2005, AIPC, 761, 39
  - Walcher et al., 2011, Ap&SS, 331, 1
- Ingredients:
  1. Stellar Population(s) – Initial Mass Function and Stellar Evolution
  2. ISM – dust and gas – composition, temperature, amount, emission
  3. Galaxy evolution
  4. Redshift

Open cluster

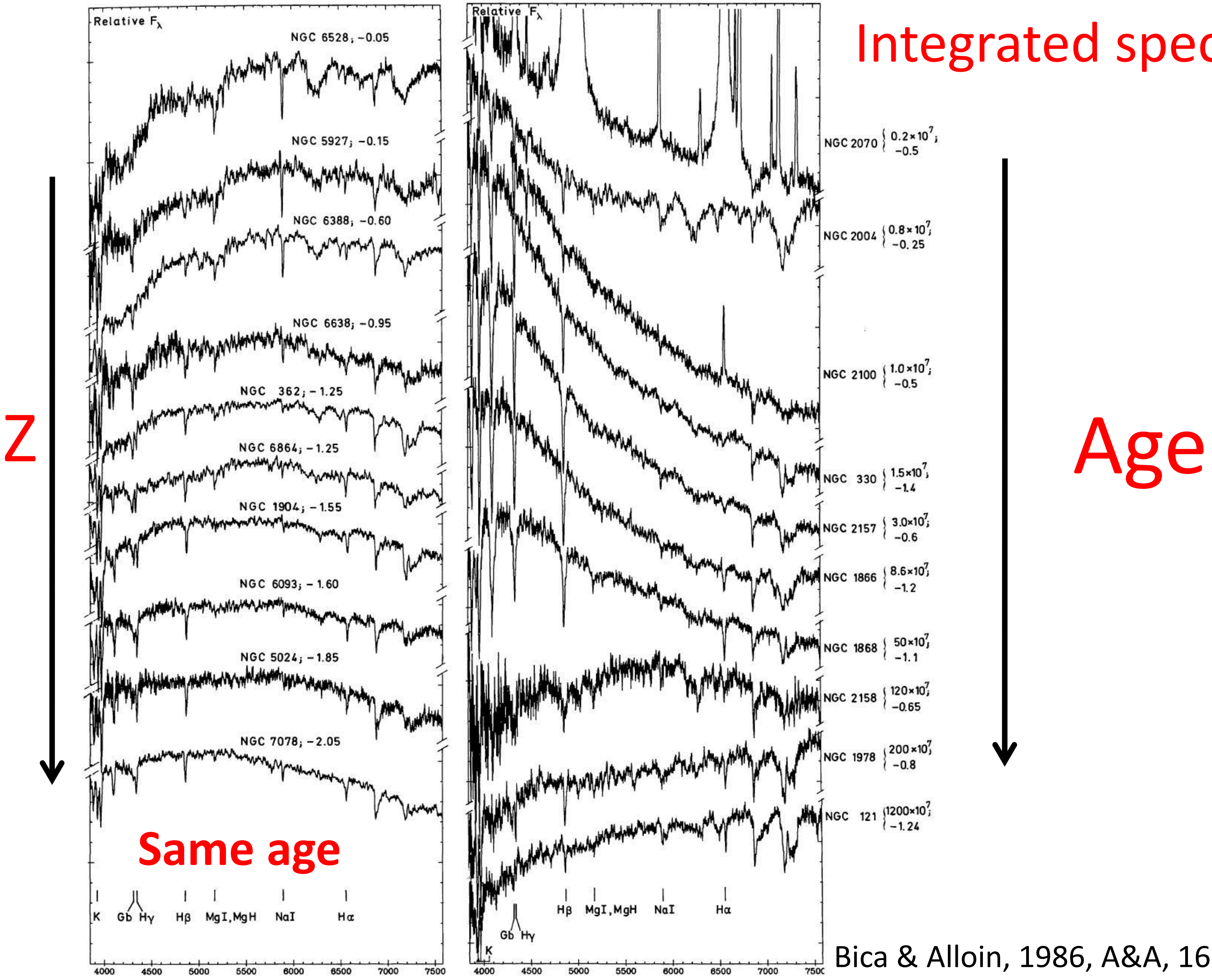
Ahumada et al., 2000, A&AS, 141, 79





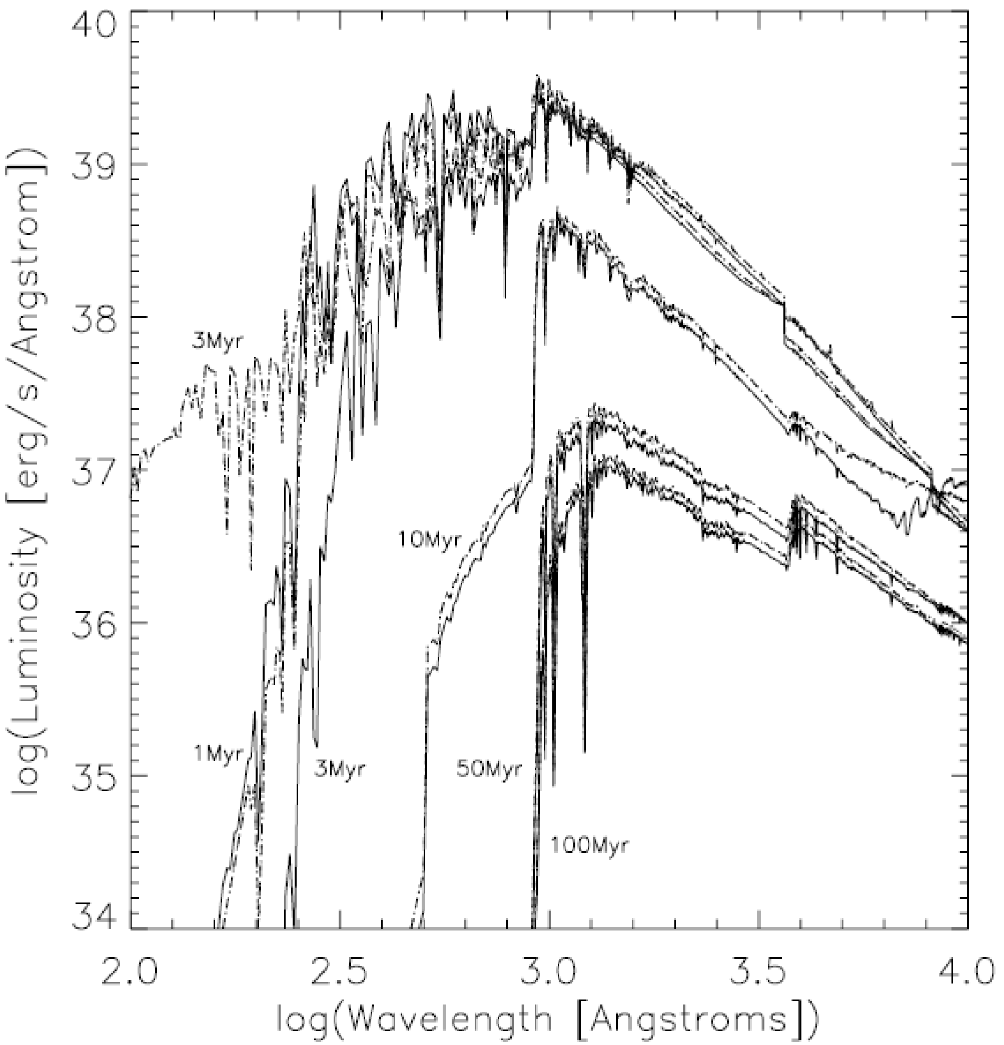
Cluster	$E(B-V)$	Age (Balmer) (Myr)	Age (template match) (Myr)	Adopted age (Myr)
Ruprecht 144	0.32 ± 0.02	200	100	150 ± 50
Melotte 105	0.31 ± 0.02	300	100	200 ± 100
BH 132	0.60 ± 0.05	200	100	150 ± 50
Hogg 15[a]	1.05 ± 0.05	30	3−6	5 ± 2
Pismis 21	1.50 ± 0.03	110	50	80 ± 30
Lyngå 11	0.12 ± 0.03	400	500	450 ± 50
BH 217	0.80 ± 0.03	20	50	35 ± 15

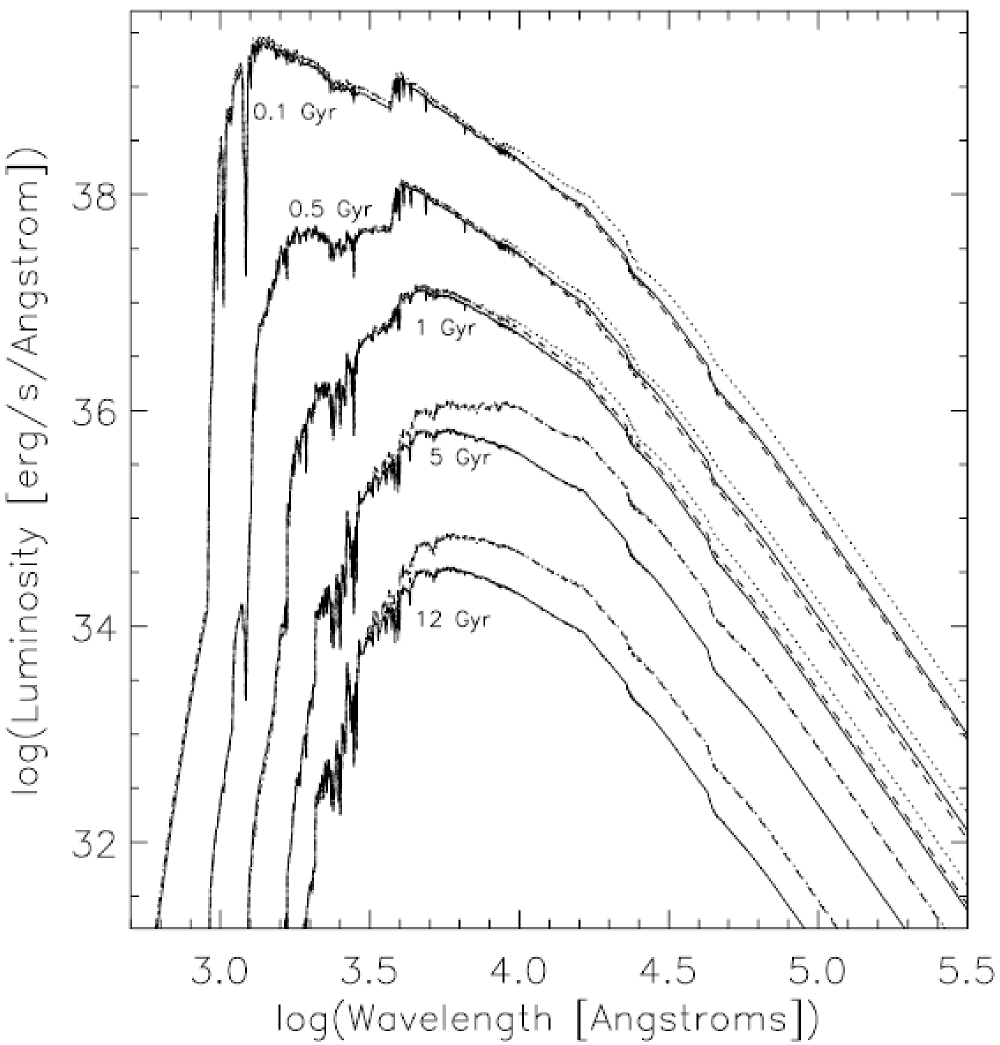
Integrated spectra



Bica & Alloin, 1986, A&A, 162, 21

Spectral Energy Distribution - Galaxies





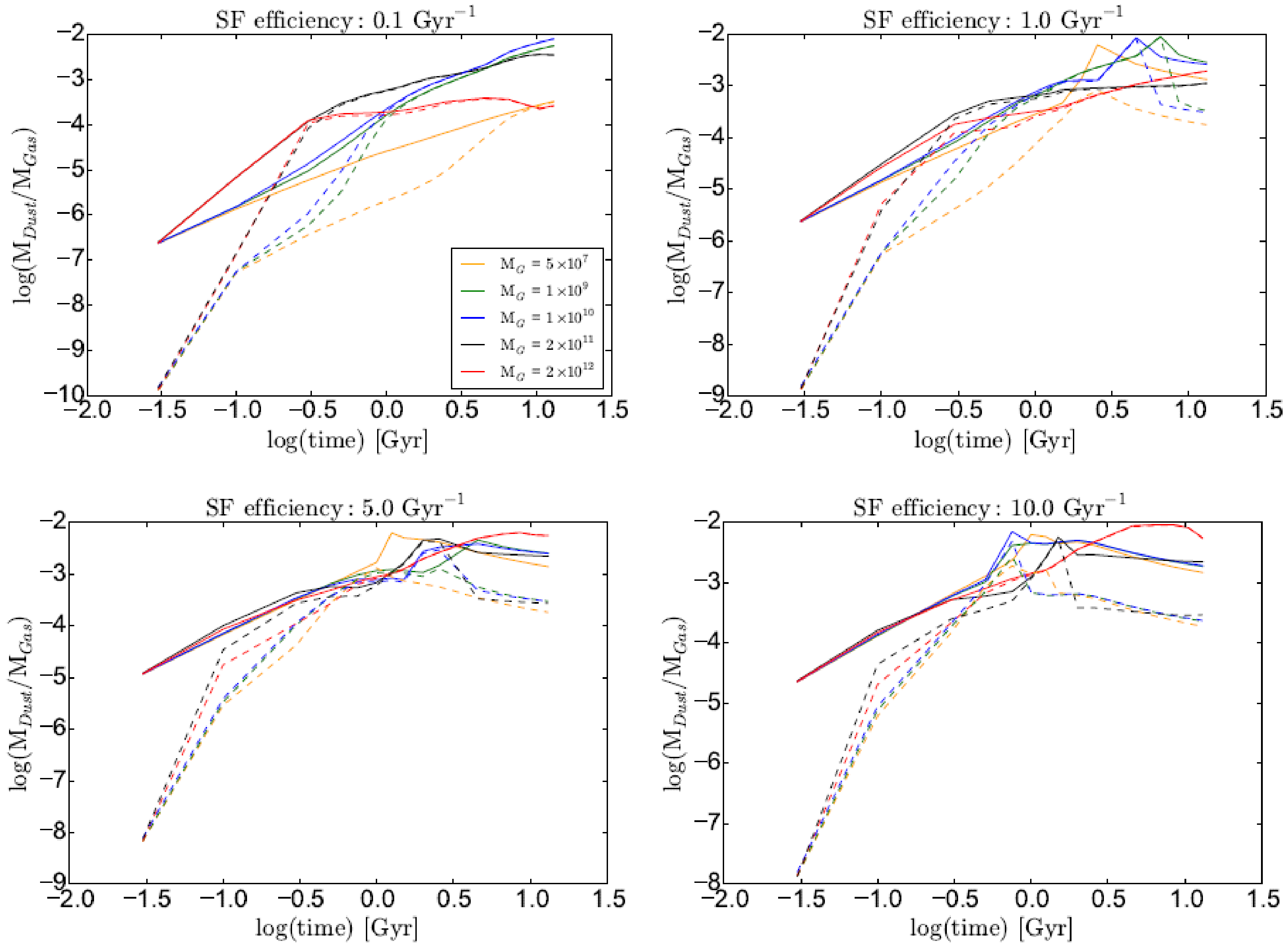
Two different isochrone grids uses

Vazquez & Leitherer, 2005, 621, 695

Spectral Energy Distribution - Galaxies

- Amount of dust in a galaxy regulates star formation
- Dust is also the most important contributor to extinction and reddening in the ISM due to absorption and scattering of the stellar light
- The absorbed light by dust is re-emitted in the infrared (IR) as thermal radiation (modified black body), reshaping the galaxy spectral energy distribution
- Massive star forming regions and starbursts galaxies are often observed in IR, enshrouded in dust cocoons, since the strong UV emission of young stars is reprocessed in dust clouds
- High mass galaxies have most of their star formation obscured by dust, while low mass ones tends to have most of the star formation unobscured
- So we need to know the composition, formation and evolution of the dust component in a galaxy

Spectral Energy Distribution - Galaxies



Change of the dust mass over time for different gas masses and star forming efficiencies

Barbosa-Santos et al, 2020, MNRAS, 499, 1701

Spectral Energy Distribution - Galaxies

- Some commonly used models:
  - Code for Investigating GALaxy Evolution (CIGALE) https://cigale.lam.fr/
  - GRAphite-SILicate approach (GRASIL) https://adlibitum.oats.inaf.it/silva/grasil/grasil.html
  - Multiwavelength Analysis of Galaxy PHYSical properties (MAGPHYS) http://www.iap.fr/magphys/

Spectral Energy Distribution - Galaxies

Hunt et al., 2019, A&A, 621, A51

Property	CIGALE	GRASIL[a]	MAGPHYS
SFH	SFR(t_{gal}) delayed+truncation (defined by Eq. (2)) with $t_{gal} = (8, 10, 12)$ Gyr; $\tau = (0.5, 1, 2, 4, 8)$ Gyr; $r_{SFR} = (0.01, 0.05, 0.1, 0.5, 1, 5, 10)$; age$_{trunc} = (10, 100, 1000)$ Myr[b].	SFR(t_{gal}) = $\nu M_{gas}(t_{gal})^k$ with primordial gas infall described as $\dot{M}_{gas} \propto \exp(-t/\tau_{inf})$; $k = 1$; (NSS)[c] $\nu = (0.3, 0.5, 0.8, 2.3, 8.0, 23.0)$ Gyr^{-1}; (NSS)[c] $\tau_{inf} = (0.01, 0.1, 0.5, 1, 2, 5, 10)$ Gyr; (NSS)[c] $t_{gal} = (0.01, 0.02, 0.05, 0.1, 0.2, 0.5, 1, 2, 4, 7, 10, 13)$ Gyr.	SFR(t_{gal}) = $\exp(-\gamma\, t_{gal})$ with random bursts potentially occurring at all times with amplitude $A = M_{burst}/M_{const}$, the ratio of the stellar masses in the burst and exponentially declining component; $t_{gal} \in [0.1, 13.5]$ Gyr; burst duration $\in [3, 30]$ Myr.
Geometry	None	Two geometries: (NSS) spheroid with King profiles for stars and dust, and (NSD) disk radial+vertical exponential profiles for stars and dust; GMCs are randomly embedded within each of these structural components; stellar radial scalelength (NSS)[c] $R_{gal} = (0.04, 0.14, 0.52, 1.9, 7.2, 26.6)$ kpc; (NSD) inclination angle i such that $\cos(i) = (1, 0.8, 0.6, 0.4, 0.2, 0)$.	None
Stellar populations	Bruzual & Charlot (2003) SSPs with Chabrier (2003) IMF, and solar metallicity ($Z = Z_\odot$).	Bruzual & Charlot (2003) SSPs with Chabrier (2003) IMF, and metallicities ranging from $Z = 0.01\,Z_\odot$ to $Z = 2.5\,Z_\odot$.	Bruzual & Charlot (2003) SSPs with Chabrier (2003) IMF, and metallicities ranging from $Z = 0.02\,Z_\odot$ to $Z = 2\,Z_\odot$.
Ionized gas?	Yes[d]	No	No

Dust attenuation	Modified starburst attenuation law with power-law slope $\delta = (-0.5, -0.4, -0.3, -0.2, -0.1, 0.0)$; normalization $E(B-V)$ for stars younger than 10 Myr $\in$[0.01,0.60] mag; differential $E(B-V)$ factor $E(B-V)_{\rm old}/E(B-V)_{\rm young} = (0.25, 0.50, 0.75)$; variable 0.2175 μm bump with strength of 0.0 (no bump), 1.5, 3.0 (Milky-Way-like).	Attenuation law as a consequence of geometry, grain opacities from Laor & Draine (1993) mediated over grain size distributions from 0.001 μm to 10 μm, and radiative transfer of the GMC and diffuse dust components. Free parameters are: $R_{\rm gmc} = (6.1, 14.5, 22.2, 52.2)$ pc; $f_{\rm mol} = (0.1, 0.3, 0.5, 0.9)$; $t_{\rm esc} = (0.001, 0.005, 0.015, 0.045, 0.105)$ Gyr.	Two-component (BC, ambient ISM) dust attenuation (Charlot & Fall 2000) as in Eq. (4) with $\mu \in$[0,1], drawn from the probability density function $p(\mu) = 1 - \tanh(8\mu - 6)$; $\hat{\tau}_V$ parametrized according to the probability density function $p(\hat{\tau}_V) = 1 - \tanh(1.5\hat{\tau}_V - 6.7)$. Optical depth $\hat{\tau}_V$ is time-dependent as in Eq. (3).
Dust emission	Overall dust luminosity defined by energy-balance considerations with SED shape governed by the dust models of Draine et al. (2007, 2014). With the exception of one ($\alpha \equiv 2.0$), parameters of these models are left to vary: $q_{\rm PAH} = (0.47, 2.50, 4.58, 6.62)$%; $U_{\rm min} = (0.10, 0.25, 0.50, 1.0, 2.5, 5.0, 10, 25)$; $\log\gamma = [-3.0, -0.3]$ in 10 steps. Dust emission is assumed to be optically thin; the DL07 models used in `CIGALE` have $\kappa_{\rm abs} = 0.38$ cm^2 g^{-1} at 850 μm.	Overall dust luminosity and SED shape governed by geometry, grain opacities from Laor & Draine (1993) mediated over grain size distributions from 0.001 μm to 10 μm, and radiative transfer of the GMC and diffuse dust components. The dust column is assumed to be proportional to the metallicity of the given SFH, and the consistent relation between extinction and emission ensures energy conservation. The same variable parameters for dust extinction govern dust emission through radiative transfer. Dust opacity $\kappa_{\rm abs} = 0.56$ cm^2 g^{-1} at 850 μm (Laor & Draine 1993).	Overall dust luminosity defined by energy-balance considerations with SED shape governed by four species of dust emitters in two environments (BC, ambient ISM), with both having PAH+hot+warm grains ($\xi^{\rm BC}_{\rm PAH}$, $\xi^{\rm BC}_{\rm MIR}$, $\xi^{\rm BC}_{\rm W}$, $\xi^{\rm ISM}_{\rm PAH}$, $\xi^{\rm ISM}_{\rm MIR}$, $\xi^{\rm ISM}_{\rm W}$), but an additional cold-dust component for the ambient ISM ($\xi^{\rm ISM}_{\rm C}$). In addition to ensuring unity ($\xi^{\rm BC}_{\rm PAH} + \xi^{\rm BC}_{\rm MIR} + \xi^{\rm BC}_{\rm W} = 1$, $\xi^{\rm ISM}_{\rm PAH} + \xi^{\rm ISM}_{\rm MIR} + \xi^{\rm ISM}_{\rm W} + \xi^{\rm ISM}_{\rm C} = 1$) fixed parameters are: $\xi^{\rm ISM}_{\rm PAH} = 0.550(1 - \xi^{\rm ISM}_{\rm C})$; $\xi^{\rm ISM}_{\rm MIR} = 0.275(1 - \xi^{\rm ISM}_{\rm C})$; and $\xi^{\rm ISM}_{\rm W} = 0.175(1 - \xi^{\rm ISM}_{\rm C})$. Parameters left to vary are: $\xi^{\rm BC}_{\rm W} \in$[0,1]; $\xi^{\rm BC}_{\rm MIR} \in [0, 1 - \xi^{\rm BC}_{\rm W}]$; $\xi^{\rm ISM}_{\rm C} \in$[0,1]; $T^{\rm BC}_{\rm W} \in$[30,70] K; $T^{\rm ISM}_{\rm W} \in$[30,70] K; $T^{\rm ISM}_{\rm C} \in$[10,30] K. Dust emission is assumed to be optically thin; dust opacity $\kappa_{\rm abs} = 0.77$ cm^2 g^{-1} at 850 μm (Dunne et al. 2000).

Spectral Energy Distribution - Galaxies

Hunt et al., 2019, A&A, 621, A51

Property	CIGALE	GRASIL[a]	MAGPHYS
Free parameters	11 with SFH ($t_{\rm gal}$, τ, $r_{\rm SFR}$, age$_{\rm trunc}$); dust attenuation (δ, normalization $E(B-V)$, differential $E(B-V)$, variable 0.2175 μm bump strength); dust emission ($q_{\rm PAH}$, $U_{\rm min}$, γ).	7 for NSS templates with SFH ($t_{\rm gal}$, $\tau_{\rm inf}$, ν); geometry ($R_{\rm gal}$); dust attenuation ($R_{\rm gmc}$, $f_{\rm mol}$, $t_{\rm esc}$); dust emission (same as for dust attenuation). 8 for NSD templates with the addition of galaxy inclination (viewing angle).	12 with SFH (γ, $t_{\rm gal}$, A, $Z_{\rm star}$); dust attenuation (μ, and $\hat{\tau}_V$); dust emission ($\xi^{\rm BC}_{\rm W}$, $\xi^{\rm BC}_{\rm MIR}$, $T^{\rm BC}_{\rm W}$, $\xi^{\rm ISM}_{\rm C}$, $T^{\rm ISM}_{\rm C}$, $T^{\rm ISM}_{\rm W}$).

NSD … New Star-forming Disks
NSS … New Star-forming Spheroids
SFH … Star Formation History
SFR … Star Formation Rate

Spectral Energy Distribution - Galaxies

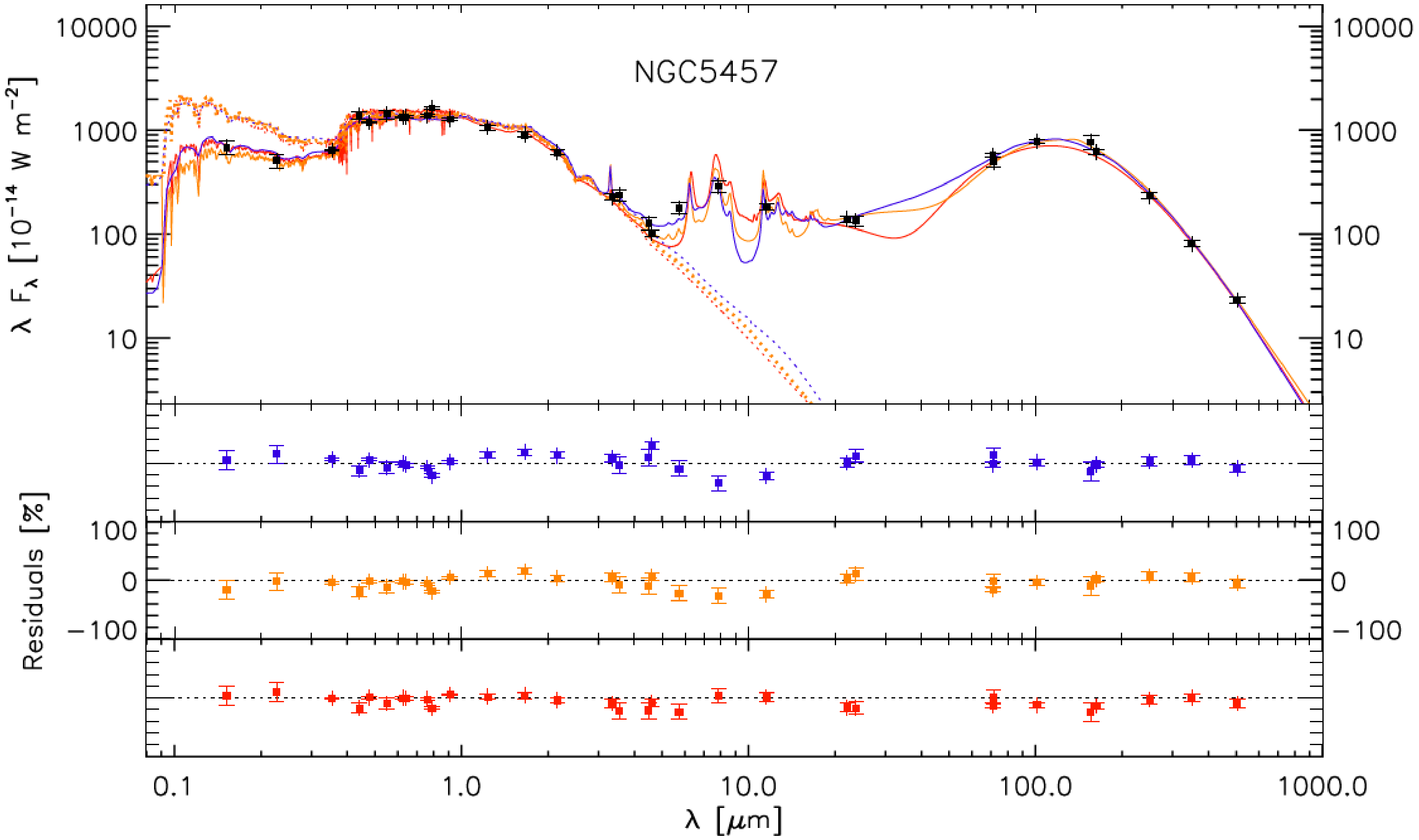


Fig. 1. Panchromatic SED for NGC 5457 (M 101) based on the photometry measurements from Dale et al. (2017) overlaid with the best-fitting SED model inferred from the SED fitting tools `MAGPHYS` (red curve), `CIGALE` (dark-orange curve) and `GRASIL` (blue curve). The dashed curves represent the (unattenuated) intrinsic model emission for each SED fitting method (using the same color coding). The bottom part of each panel shows the residuals for each of these models compared to the observed fluxes in each waveband.

Hunt et al., 2019, A&A, 621, A51

Spectral Energy Distribution - Methods

Machine Learning algorithm

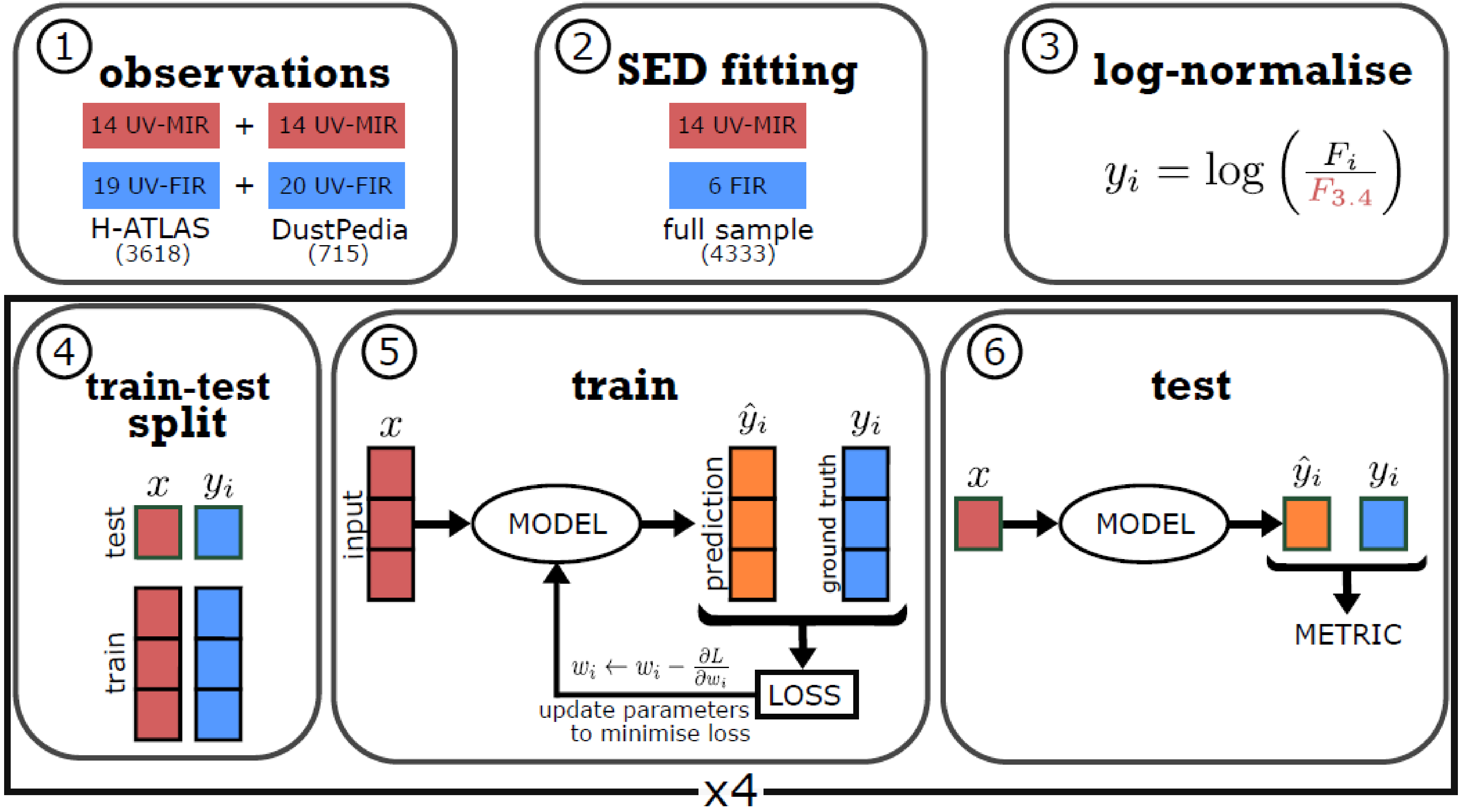
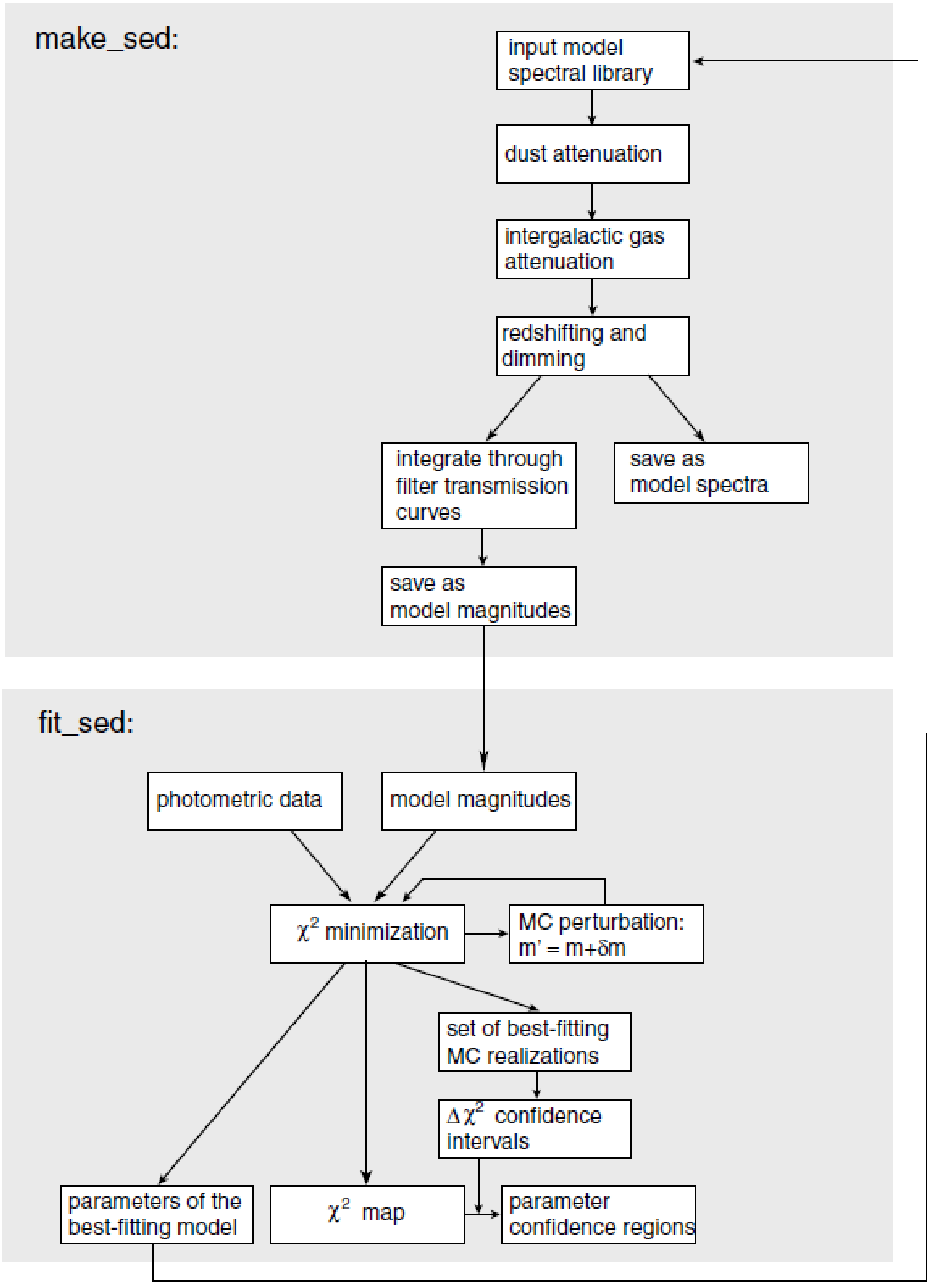
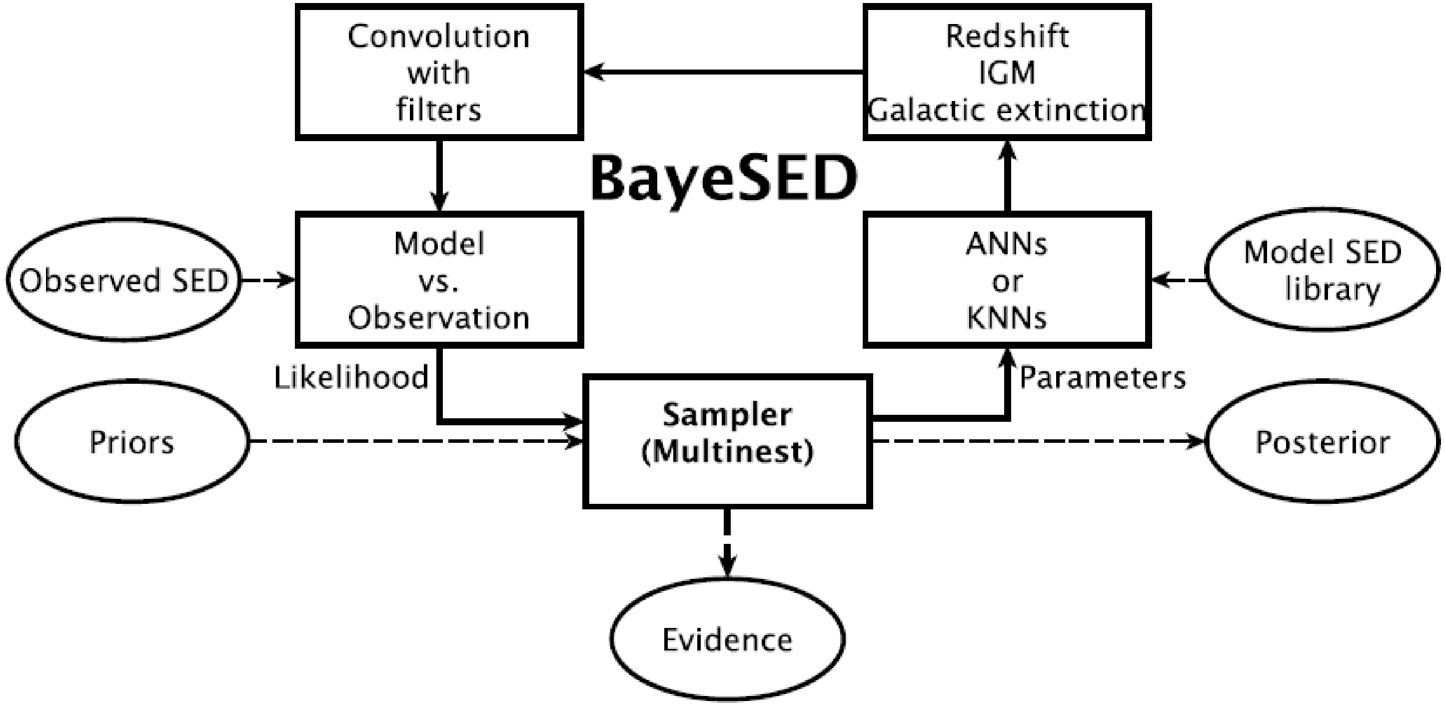


Fig. 1. Diagram of the pipeline, split into six steps. The red boxes are used for input data, which do not make use of *Herschel*. The blue boxes do require *Herschel* observations and are used to derive the ground truth (i.e. prediction target). The orange boxes are model predictions. Steps 4 to 6 are repeated for the four folds, in order to use the full data set as a test set.

Dobbles et al., 2020, A&A, 634, A57



Sawicki, 2012, PASP, 124, 1208



Han & Han, 2014, ApJS, 215, 2