The effect of dust inside of the galaxies on their light

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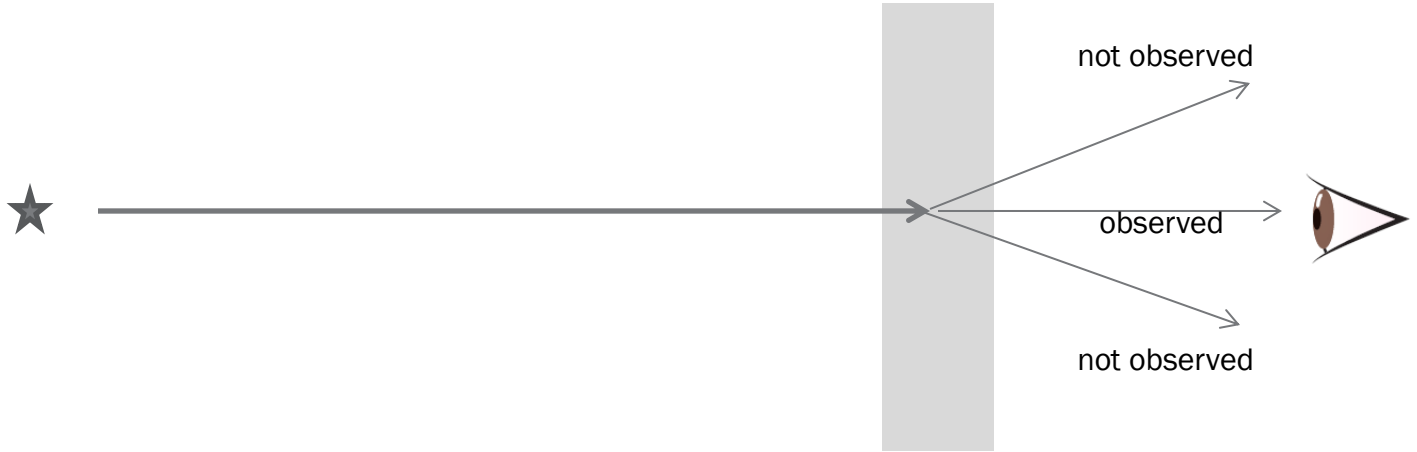
Dust in galaxies

- Diminishes the light of stars
- Affects our determinations of bulk:
  - ages of stars (look older)
  - star formation rates (looks lower)
  - stellar mass (looks lower)
  - metallicity (looks more metal rich)

- Dust content
  - understand galaxy evolution

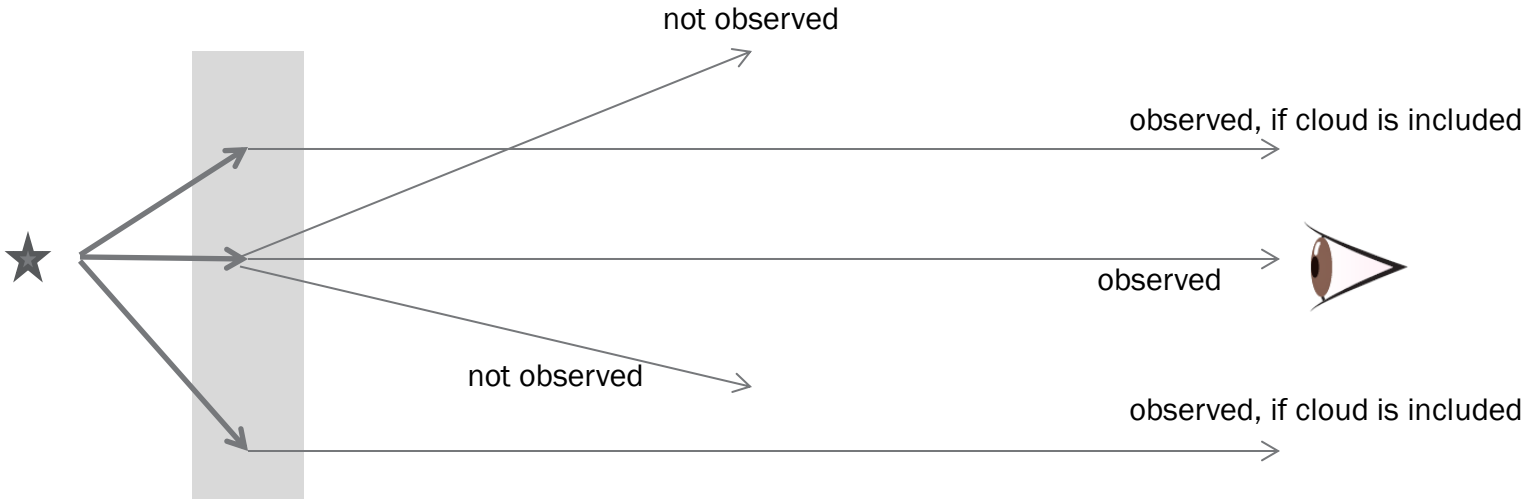
Extinction vs. attenuation

- Extinction = the effect of dust on a point source (a star)
- Distant star + foreground layer (cloud) of dust
  - part of the light is absorbed
  - part is scattered
- Extinction = absorption + scattering



Extinction vs. attenuation

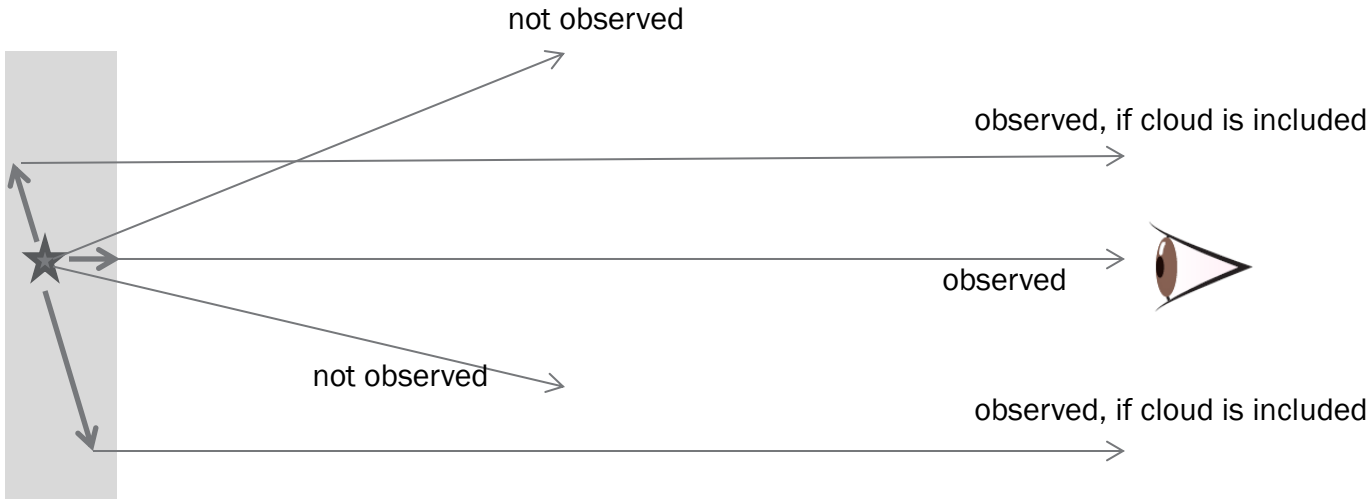
- Dust layer near the star, compared to us (star sees dust with large solid angle)
- If we measure only the light of star: extinction is same as before
- If we measure the light of star+cloud: some scattered light is recovered
  - star+cloud = extended object



  - received scattered light depends on the mutual position of star and dust cloud

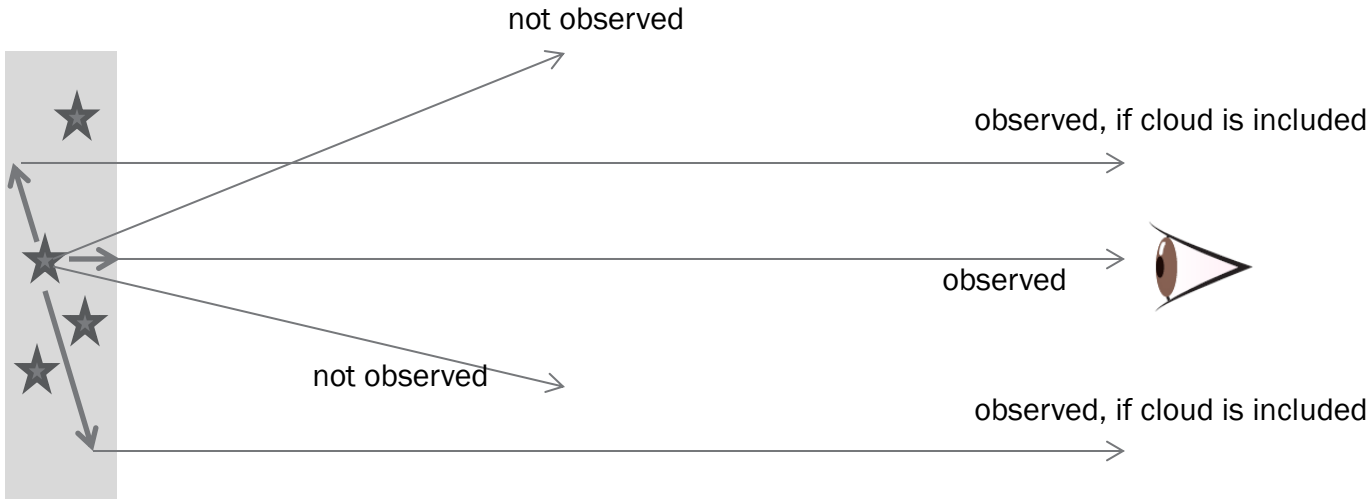
Extinction vs. attenuation

- Galaxy: star is imbedded in dust layer
  - light can scatter backwards and reach us
- We observe “a galaxy” = star+dust layer



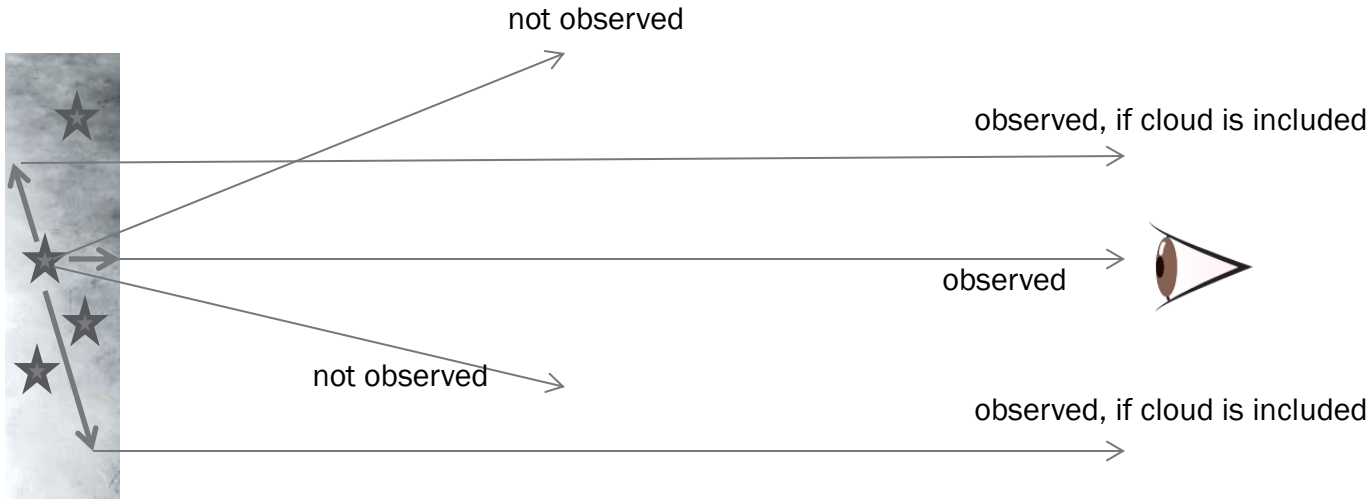
Extinction vs. attenuation

- Galaxy: there are many stars; stars with different luminosities
- We see combined effect of relative distribution of stars and dust (aka “geometry”)



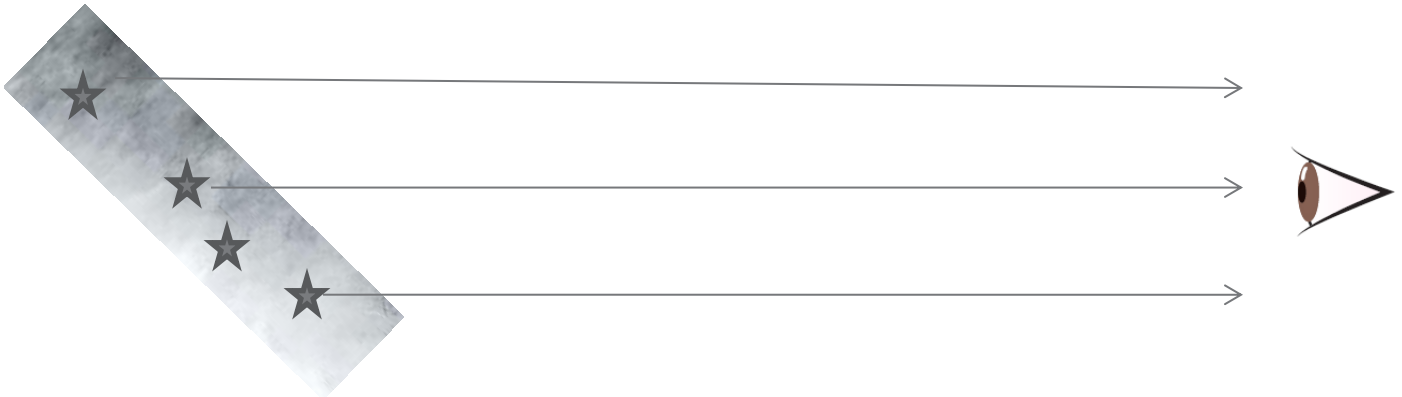
Extinction vs. attenuation

- Galaxy: dust can be patchy and have non-uniform density



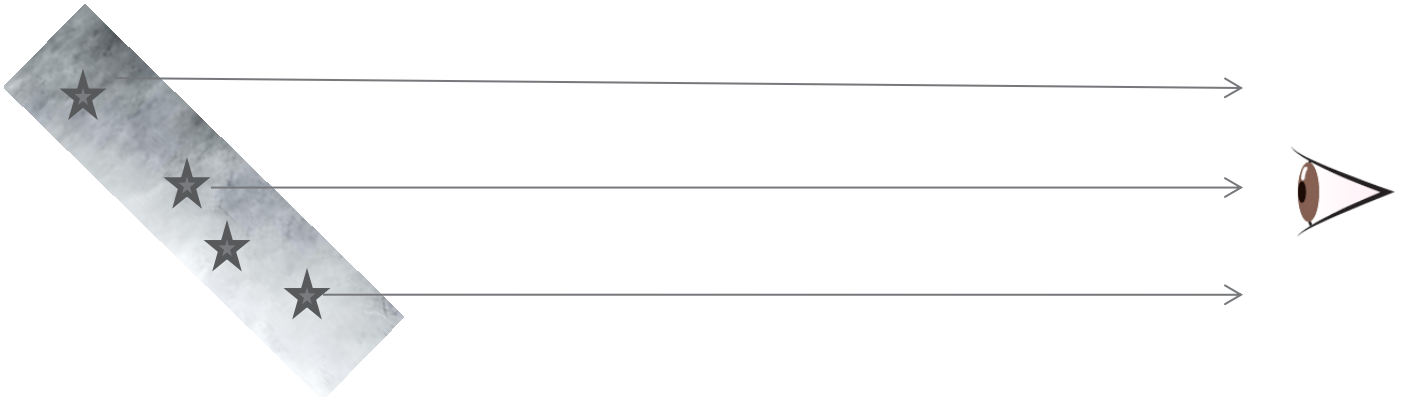
Extinction vs. attenuation

- Same galaxy seen from different angles => different geometry
  - local geometry = relative star/dust distribution (irrespective of viewing angle)
  - global geometry = viewing angle



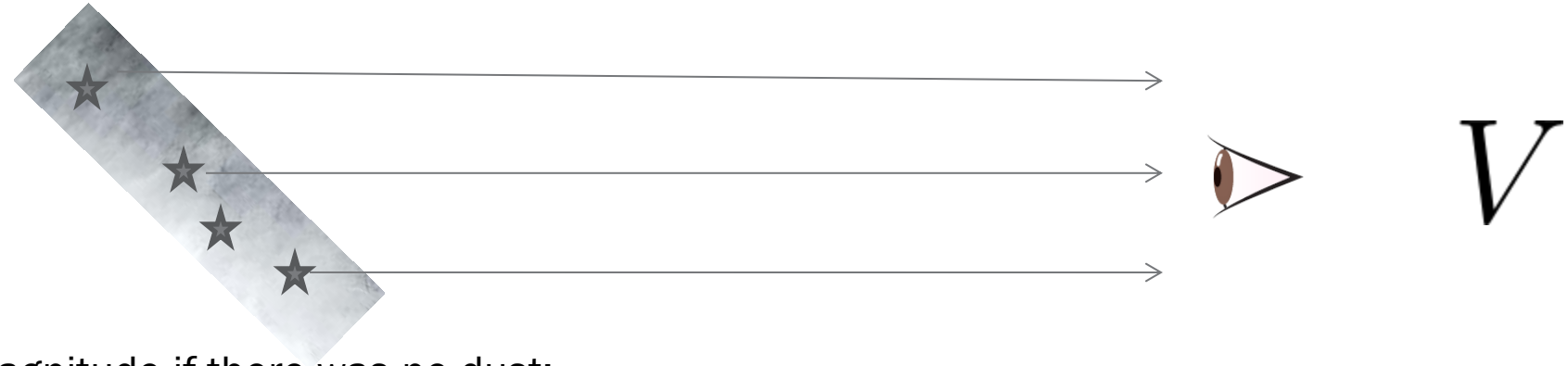
Extinction vs. attenuation

- Extinction = effect of dust on a point source
  - absorption + scattering loss
- Attenuation = effect of dust on an extended object
  = extinction + local & global geometry
  = (absorption + scattering loss) + scattering gain



Attenuation in a band: practical definition

- Magnitude of entire galaxy (integrated mag), as observed (e.g. in V band):



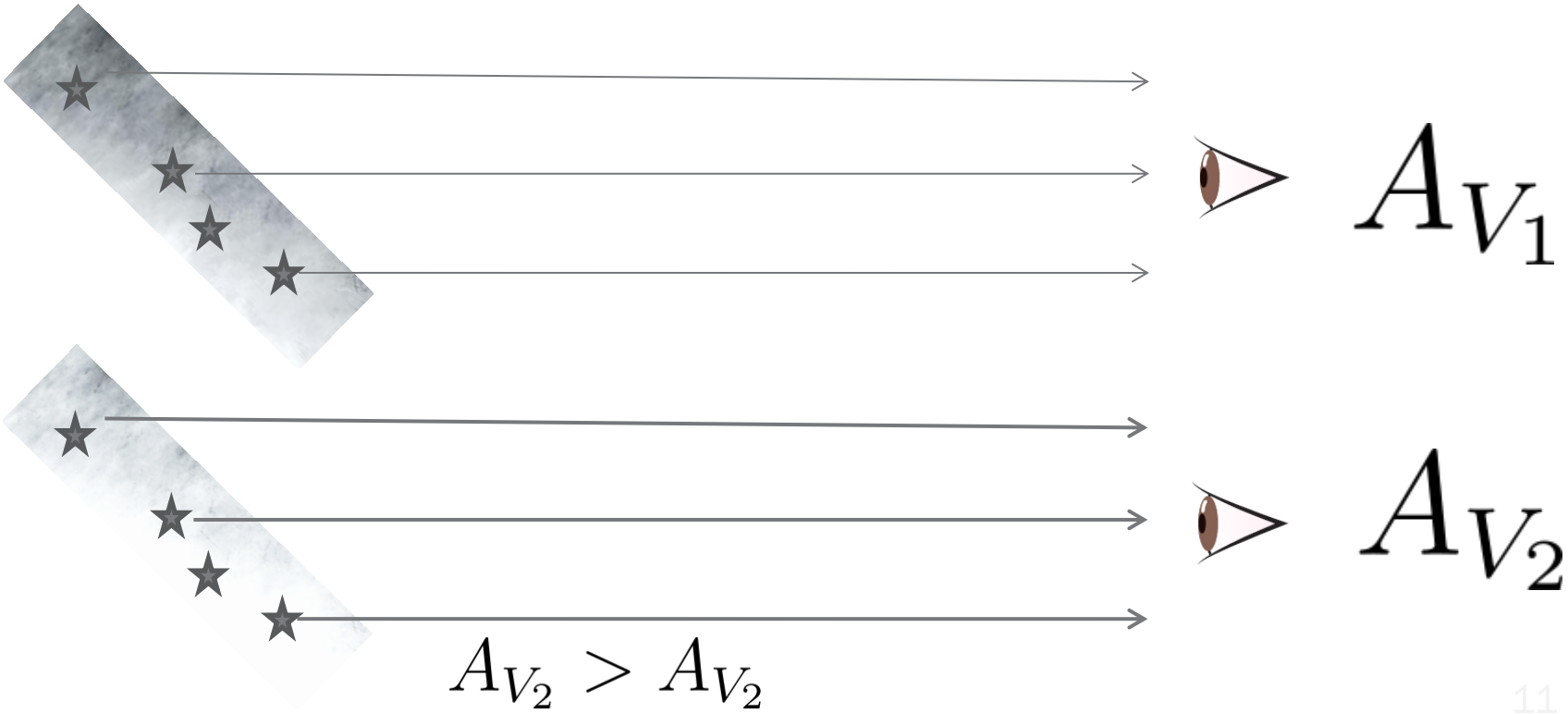
- Magnitude if there was no dust:

$$A_V = V - V_0 = -2.5 \log(f_0/f)$$

same definition as for extinction

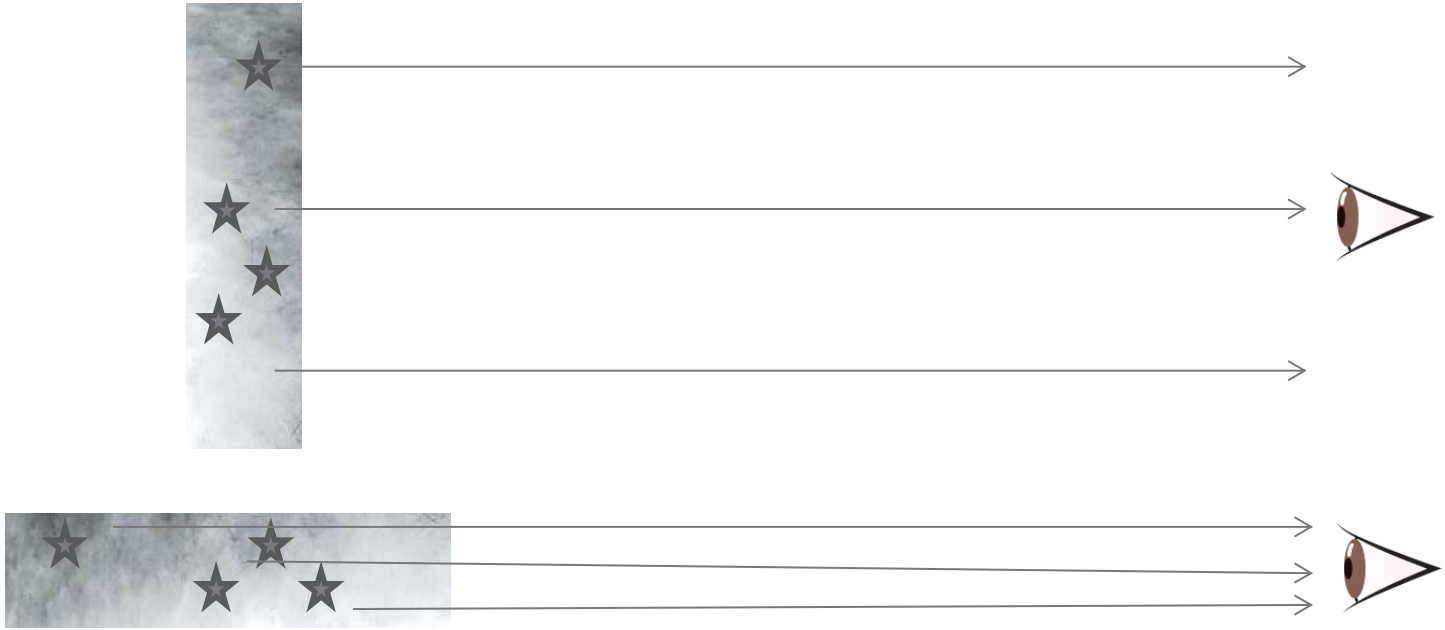
Factors affecting attenuation

- Dust content (dust density: grains per volume)



Factors affecting attenuation

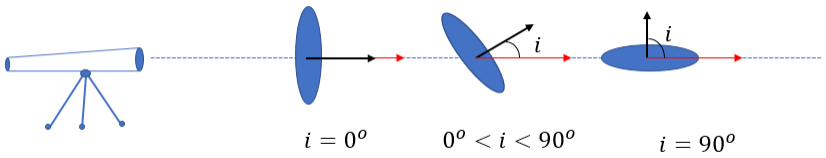
- Orientation (without changing dust content)

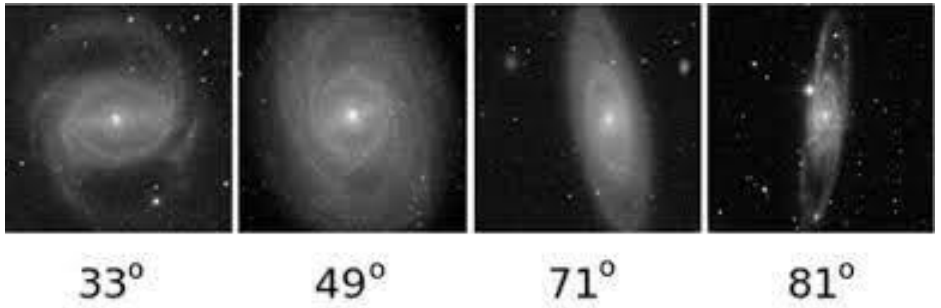


$$A_V(\text{face} - \text{on}) < A_V(\text{edge} - \text{on})$$

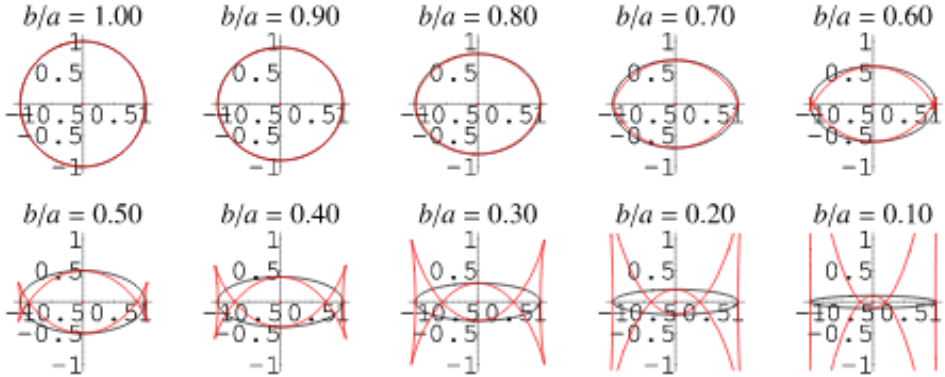
Factors affecting attenuation

- Orientation = galaxy inclination





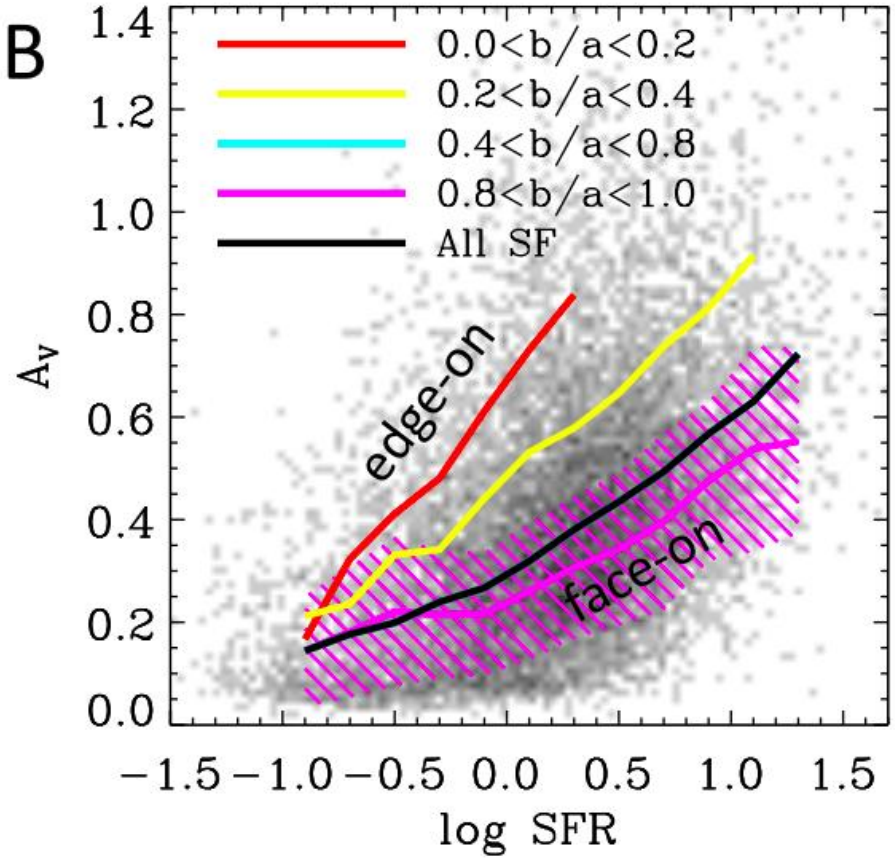
= axis ratio



$$0 < b/a < 1$$

Factors affecting attenuation

- Attenuation
  = dust content + orientation
  - dust content related to galaxy SFR (star formation rate)



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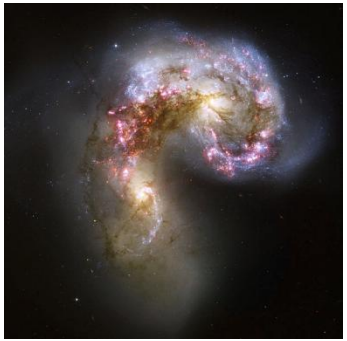
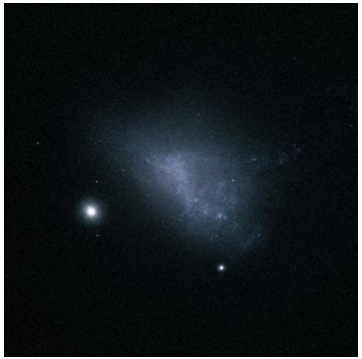


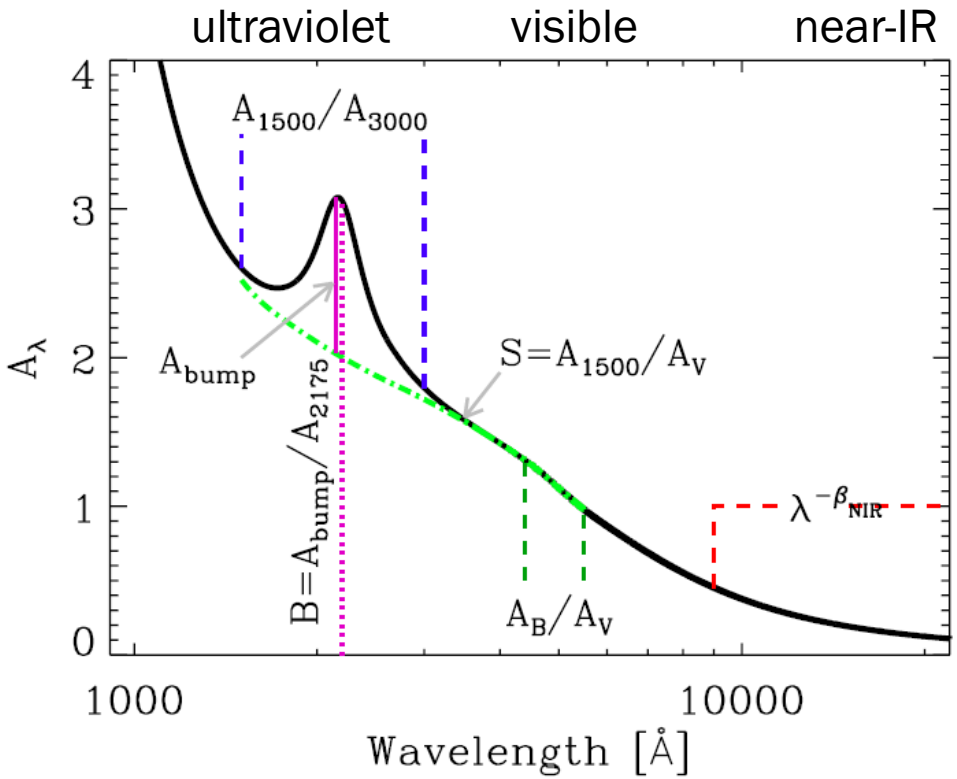


Dust attenuation curve

- Attenuation (like extinction) depends on wavelength
- Attenuation in different bands (V, B, R, UV)
  - more generally, attenuation at some wavelength

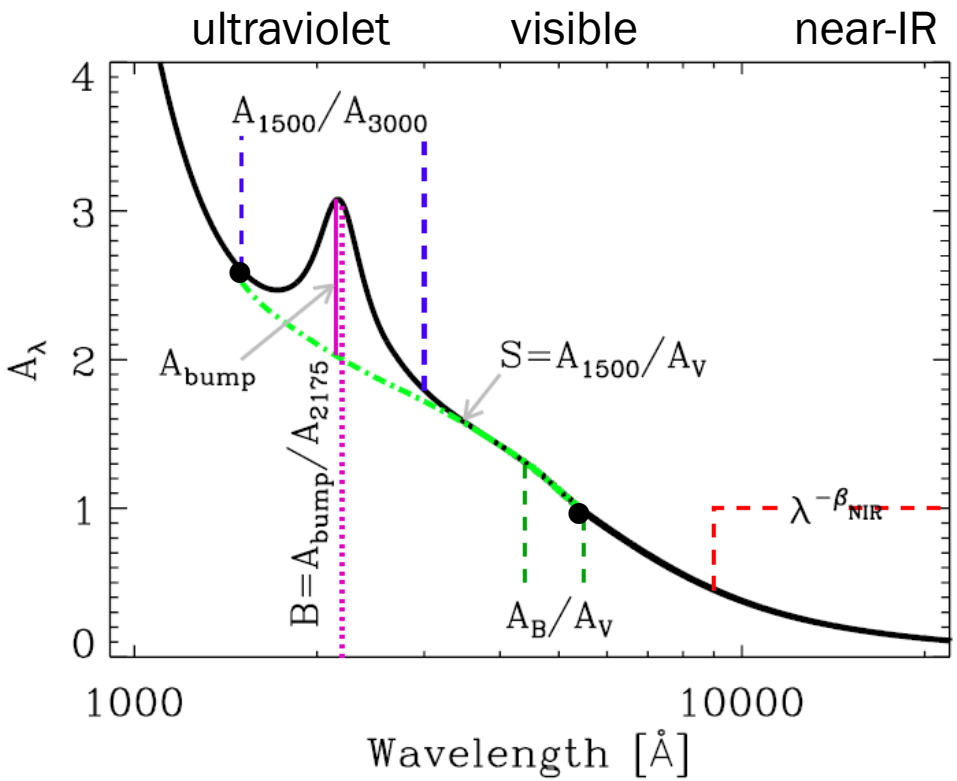
$$A_\lambda = m_\lambda - m_{\lambda,0}$$

- Shorter wavelength affected more => reddening
- A_λ = attenuation curve (or law)
- **A_λ/A_V = (normalized) attenuation curve**



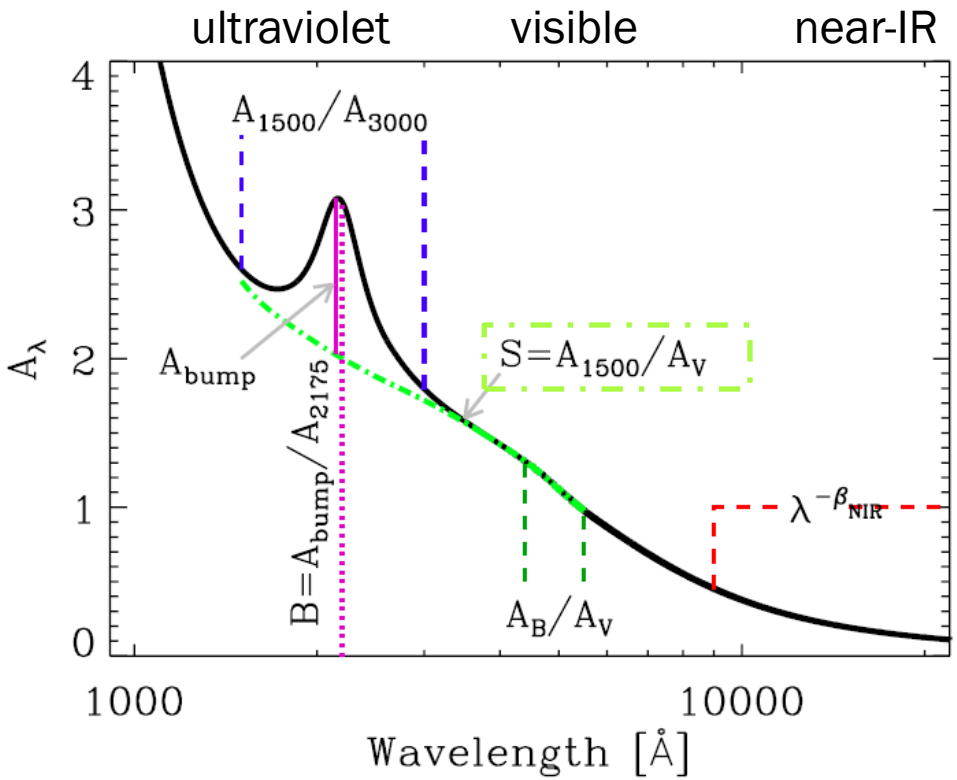
Dust attenuation curve

- E.g.
  - Av = 0.1, A_{1500} = 0.5
  - Av = 1, A_{1500} = 5
  - different normalization
  - same attenuation curve
  - normalization need not be in V



Dust attenuation curve

- Is attenuation curve universal?
- Is slope similar for all galaxies
  - e.g. UV to optical slope
  - S = A_{1500}/Av
- Is the strength of UV bump similar for all galaxies?
  - is it present at all?
- If not, how much variation is there?
- Does any galaxy property govern it?



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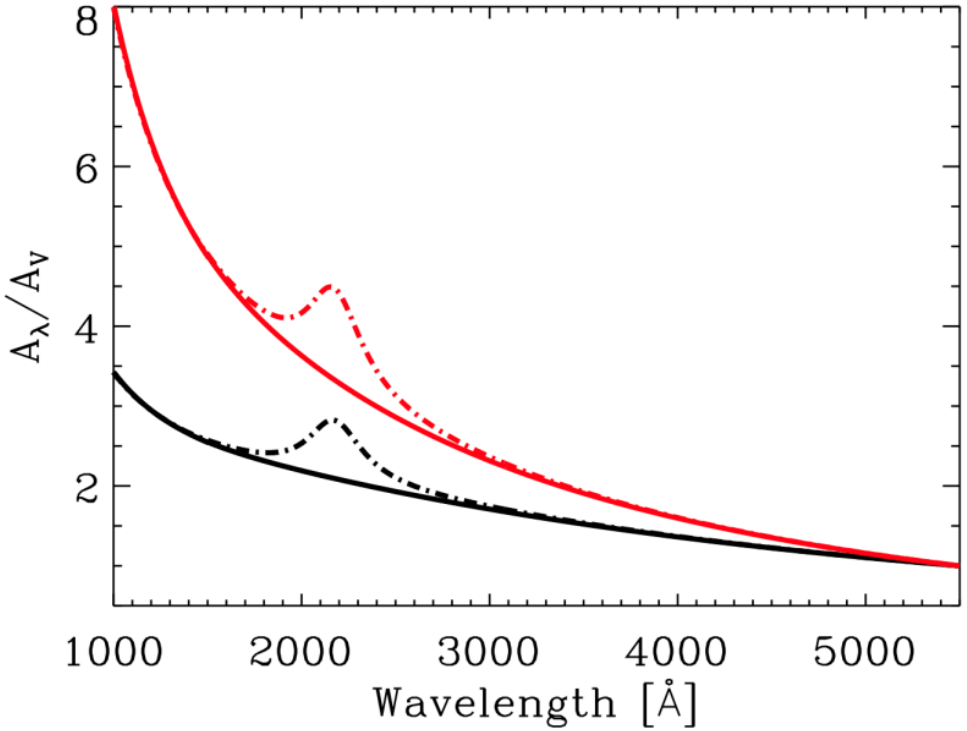
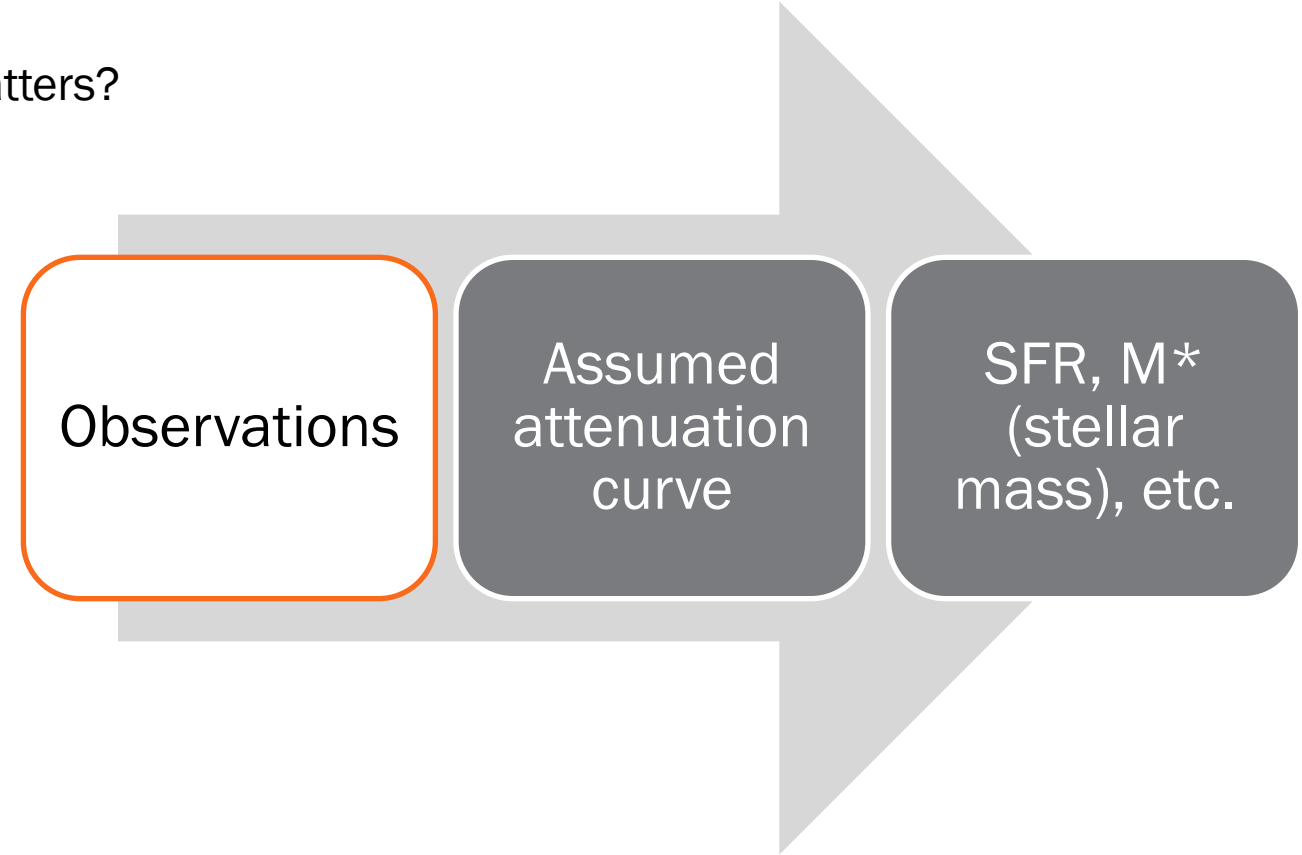


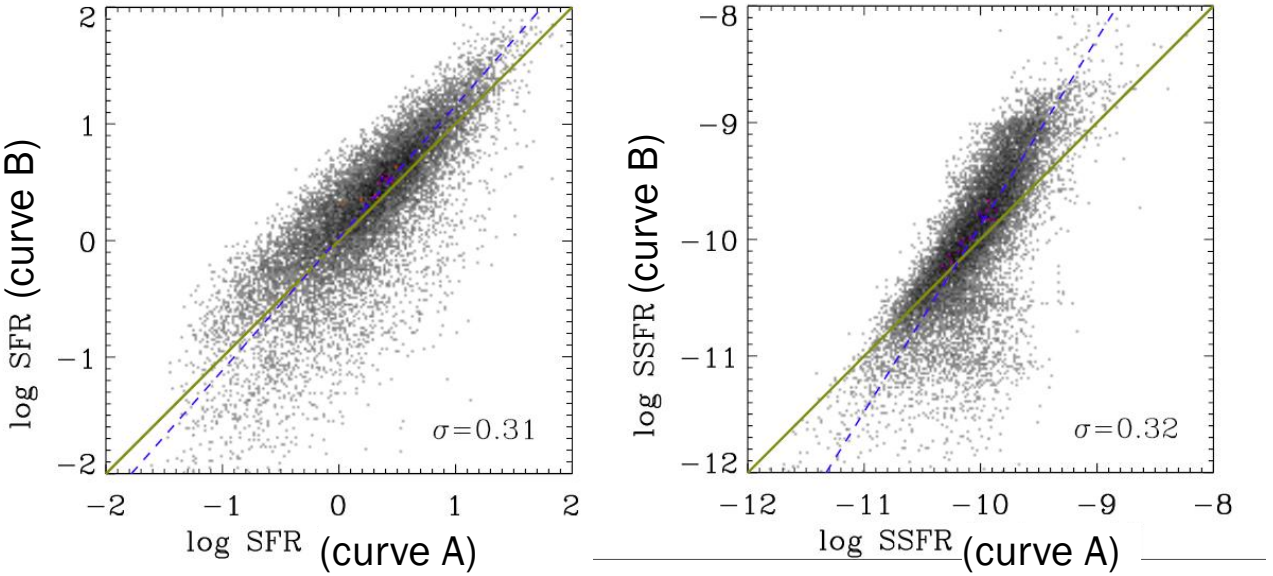
Dust attenuation curve

- Why it matters?



Dust attenuation curve

- Effect on SFR and on specific SFR (SFR/M*)
  - systematic effects and noise

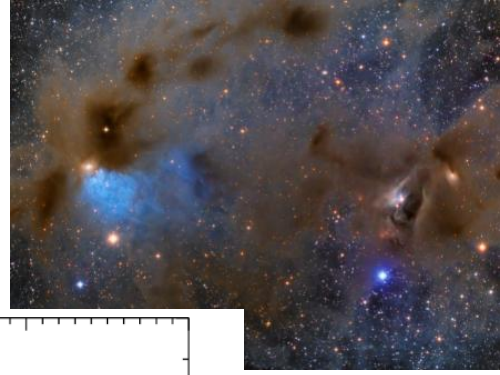


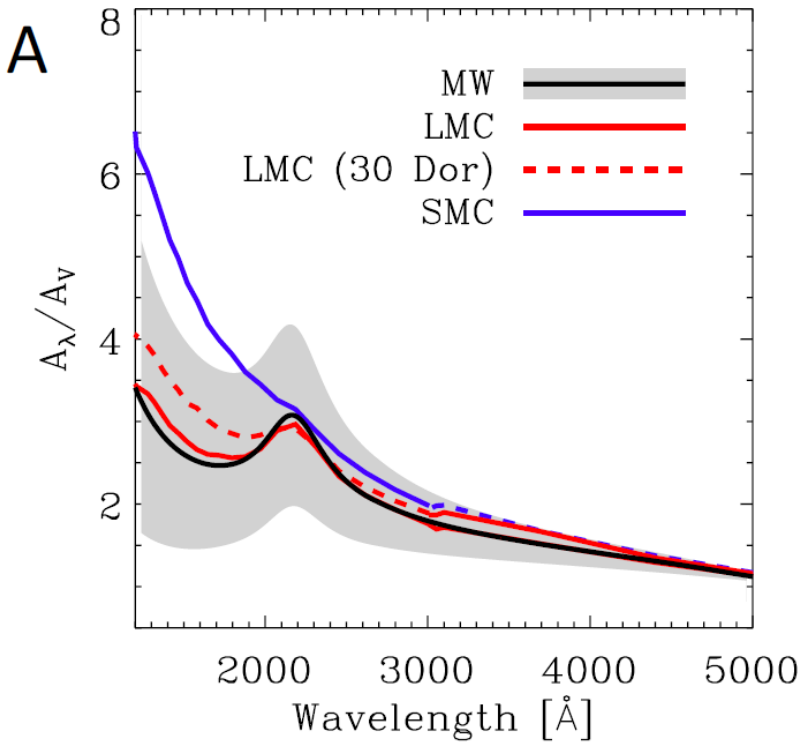
Dust extinction curves

- Attenuation = extinction + geometry

1. Average extinction curves differ among MW, LMC, SMC
2. Individual sightlines within MW differ: 1 < S < 3

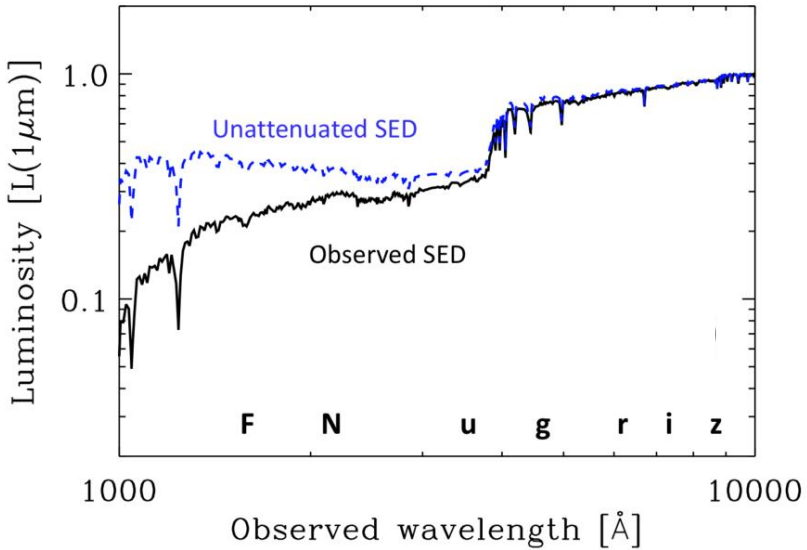
- Drivers:
  - differences in dust composition
  - differences is dust size distribution
- Extinction curves beyond local group not generally known





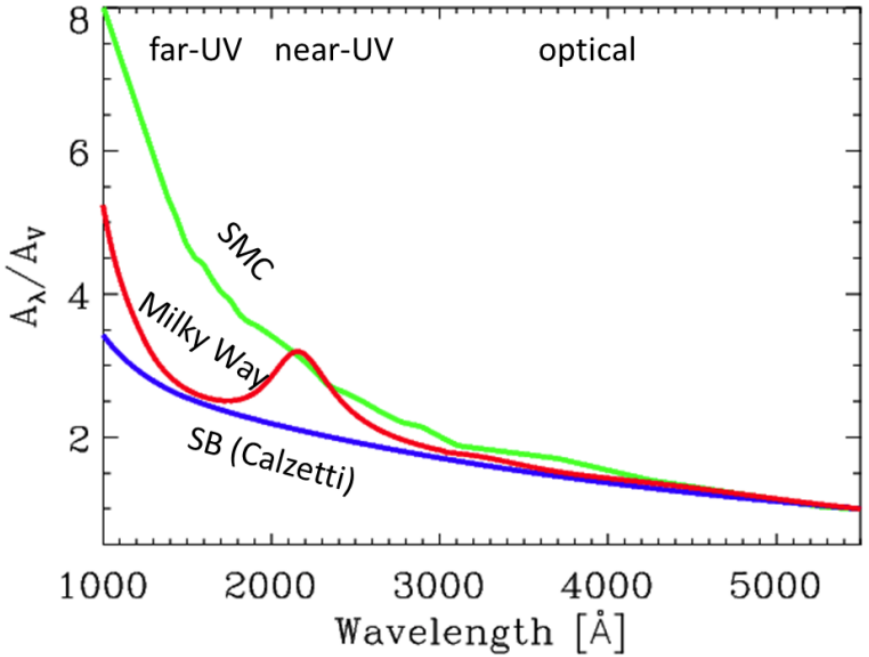
How to determine DAC?

- Extinction curve determination: pair method
  - observe two stars of (same spectral type), one behind dust, one dust free
- What is the dust-free SED of a galaxy?
  - SED (spectral energy distribution) = a spectrum or multi-band photometry



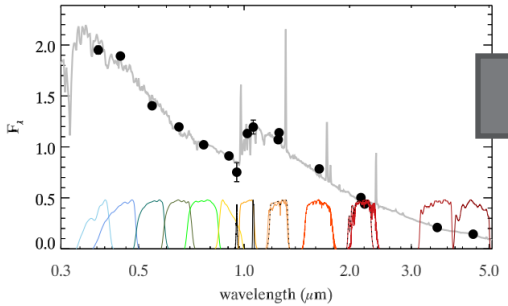
How to determine DAC?

- Empirical approach
  - compare SEDs of galaxies with various amounts of dust as inferred from emission lines
  - Calzetti et al. 1994
    - aggregate curve of starbursting galaxies
    - shallow curve (S=2.5)
    - no UV bump
  - No other DAC until recently
- Theoretical (model) approach
  - SED fitting

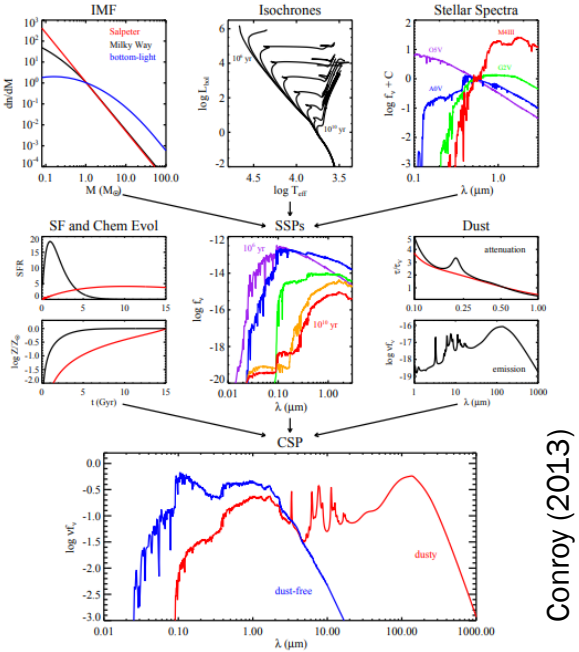


SED fitting

- Produce model (predicted) photometry based on stellar evolution + star formation history
- Standard approach: <u>assume</u> DAC with various amounts of dust
- Compare observed broad-band photometry with model predictions



observed SED
(UV+ optical photometry)



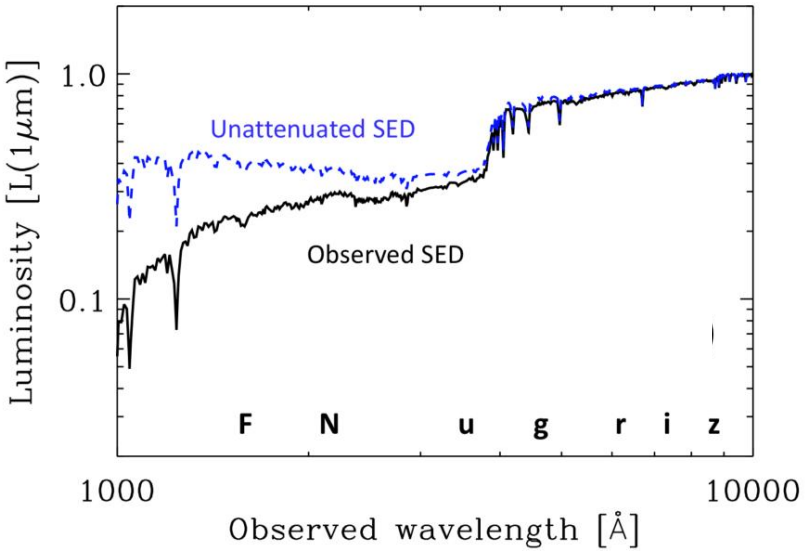
Conroy (2013)

SFR
M*
Z*
age
…

CIGALE
Code Investigating GALaxy Emission

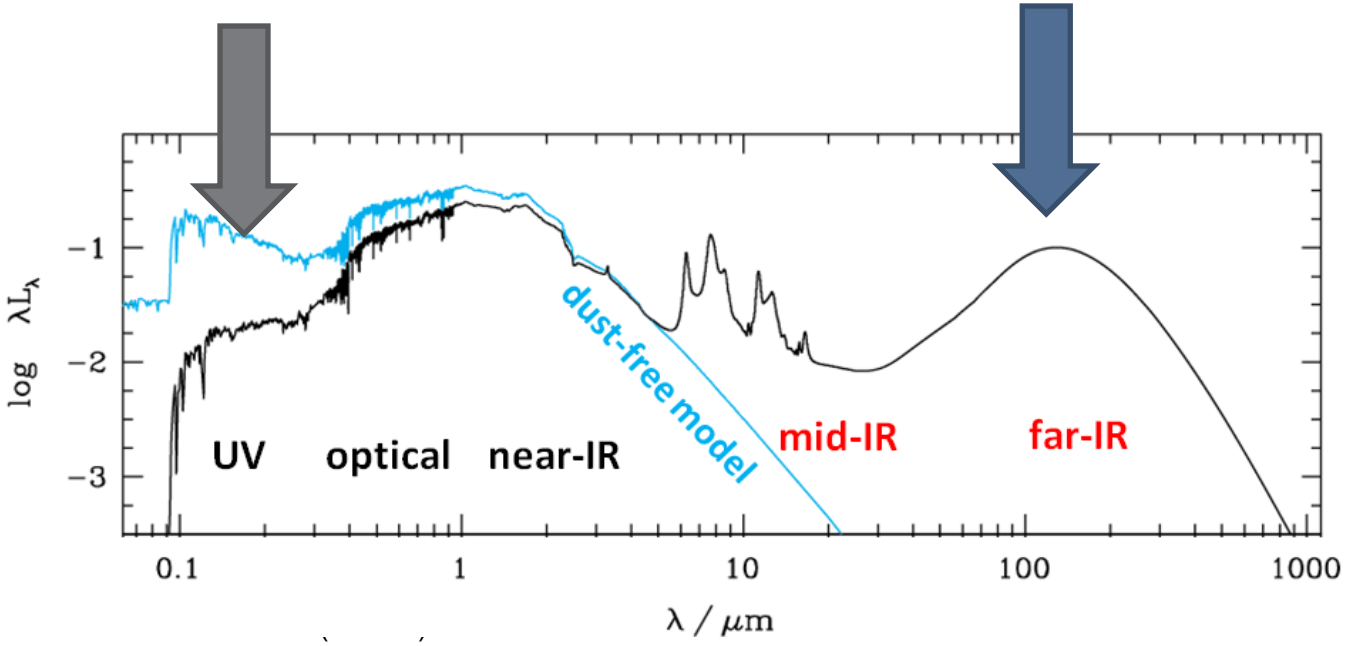
Attenuation curve from SED fitting?

- Why is DAC assumed in SED fitting?
- Dust-age-metallicity degeneracy
  - older age of stars or higher metallicity produce similar reddening as the dust
- Degeneracy can be broken with IR data



Attenuation curve from SED fitting?

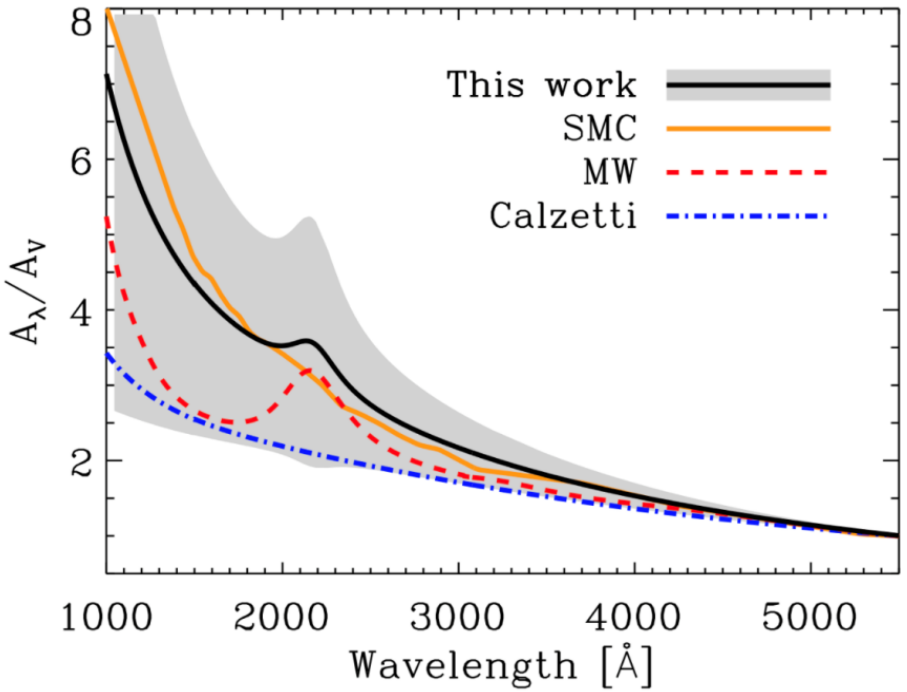
- UV/optical light absorbed by dust heats the grains => dust emits in the mid and far IR
- Energy balance: energy absorbed in UV+optical = energy emitted in IR



DAC at low redshift

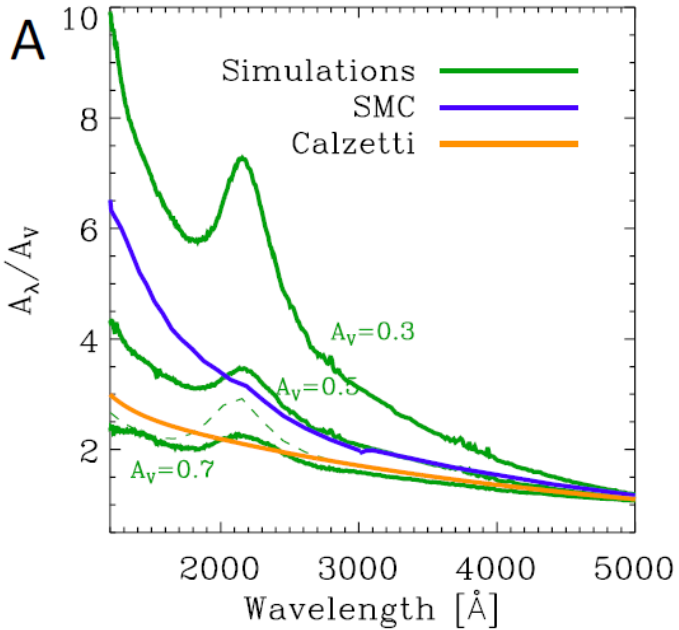
- Galaxy survey data
  - z < 0.3
  - GALEX UV
  - SDSS optical
  - WISE mid-IR
  - 230,000 galaxies

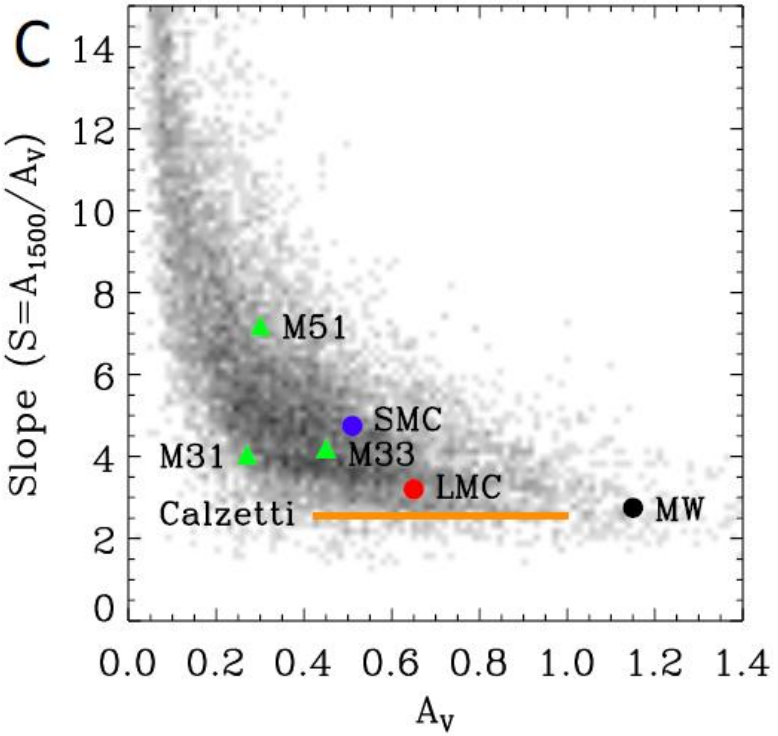
- Wide range of slopes
- 2 < S < 15
- (Calzetti: S = 2.5; SMC: 5)



What drives attenuation curve slopes?

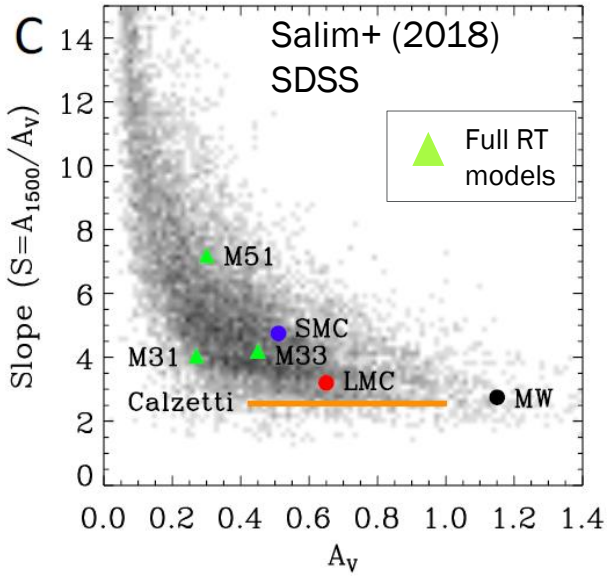
- Slope vs Av correlation
  - galaxies with higher Av have shallower DAC

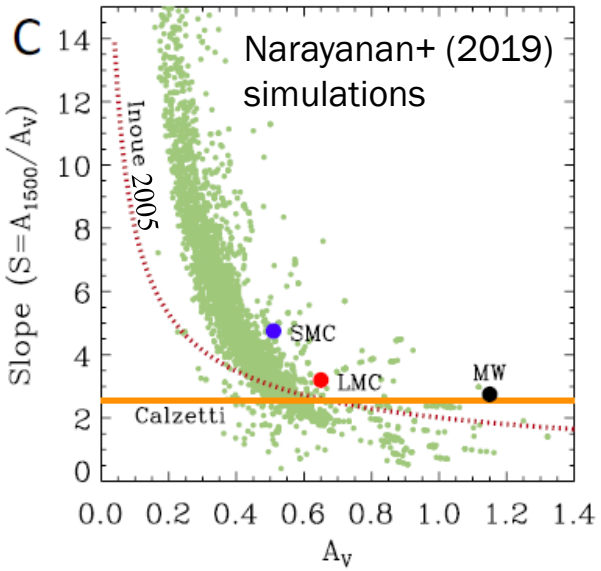




What drives attenuation curve slopes?

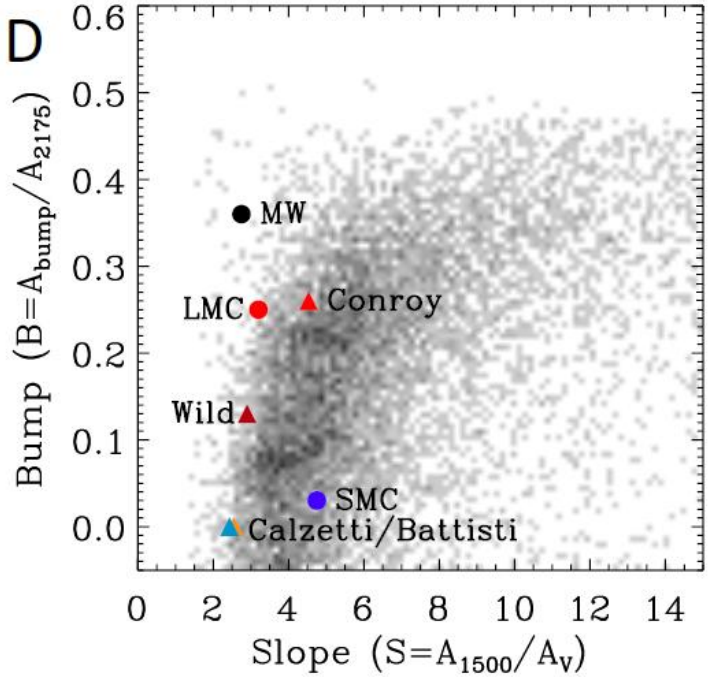
- Predicted by radiative transfer models (Pierini et al. 2004; Seon & Draine 2016)
  - Low opacity: scattering dominates (highly λ dependent)
  - High opacity: absorption dominates (grey)

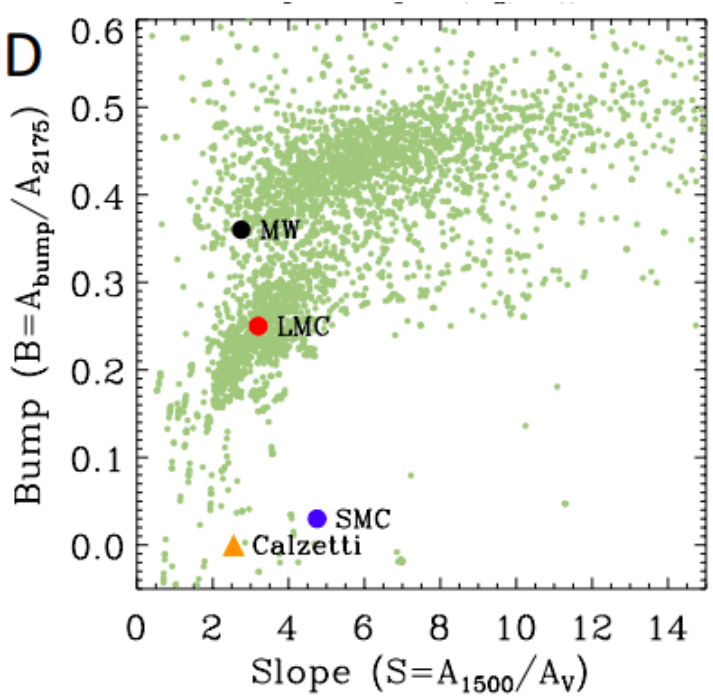




What drives attenuation curve slopes?

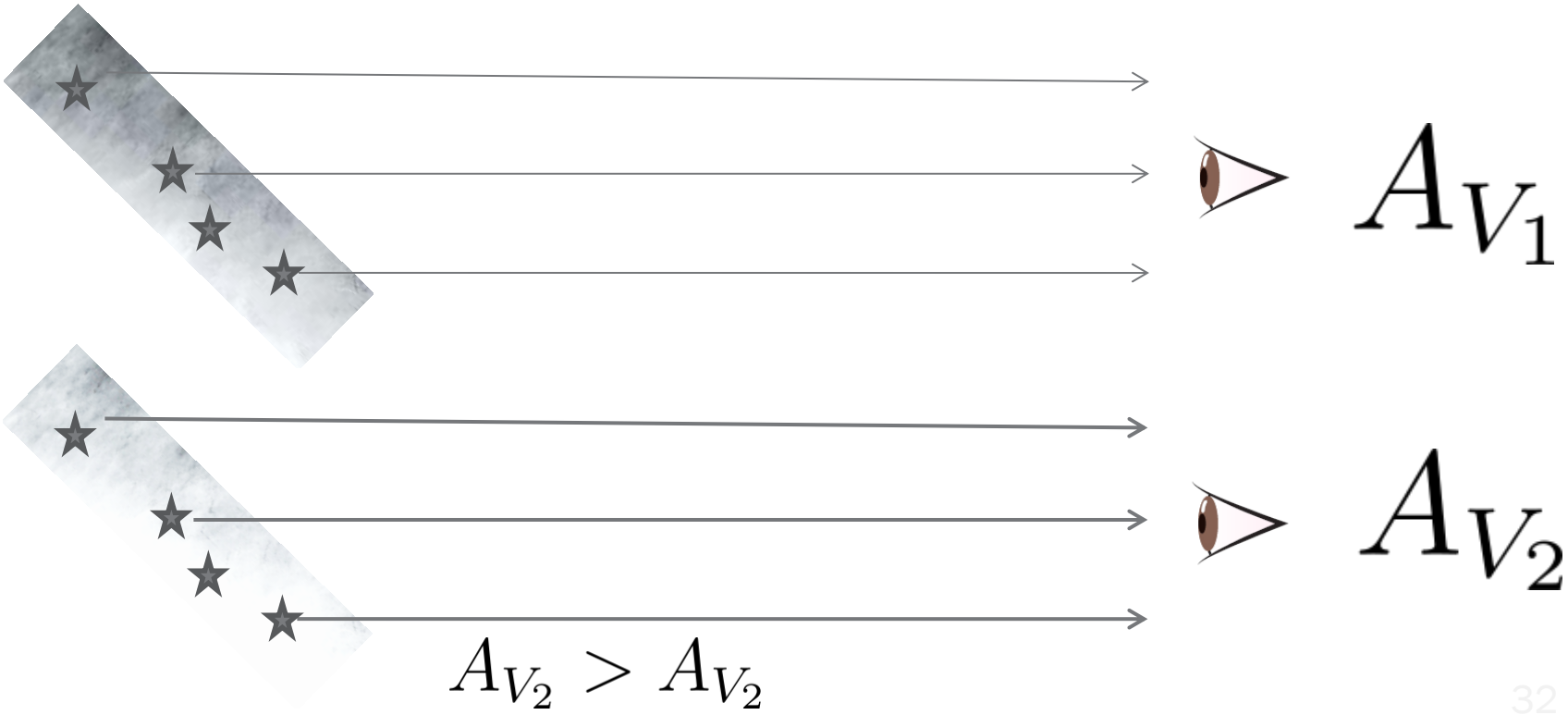
- Bump vs slope relation also seen in simulations





What drives attenuation curve slopes?

- Dust content (dust density: grains per volume)



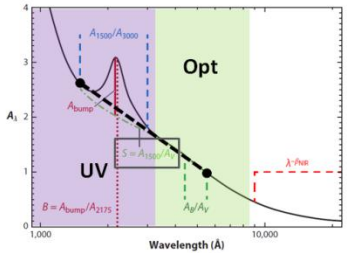
What drives attenuation curve slopes?

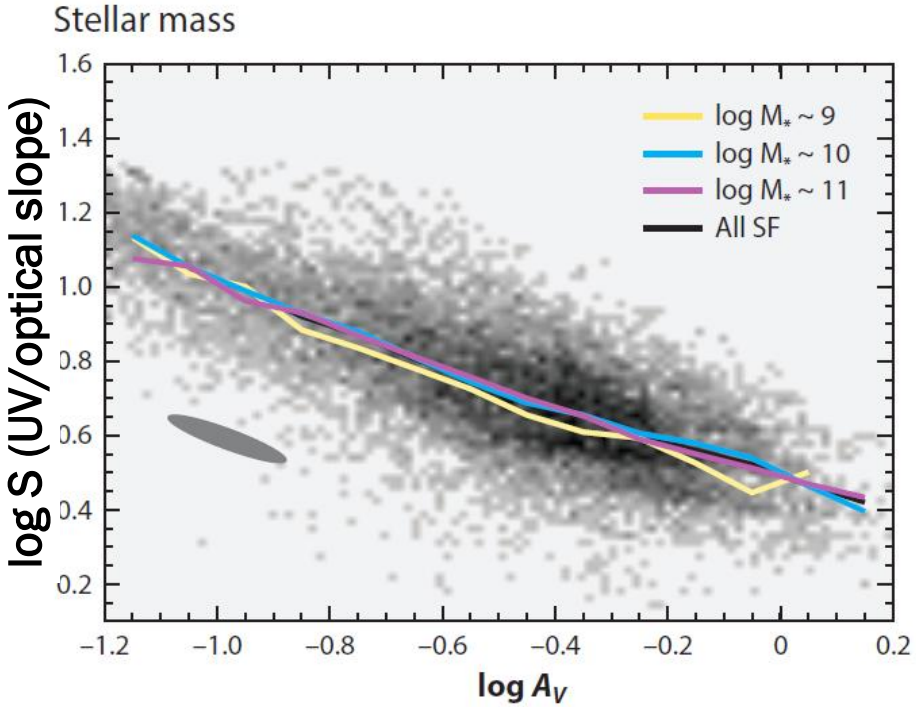
- Is dust opacity a factor independent of geometry?
  - depends on the definition
- Which factor is more important?

Attenuation curves - diversity

Primary dependence is on the dust column

- At fixed Av (dust column) curve slope does not depend on stellar mass

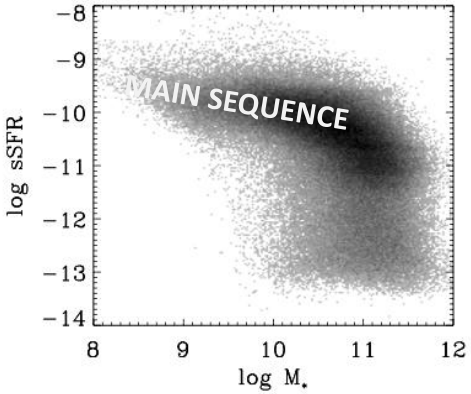


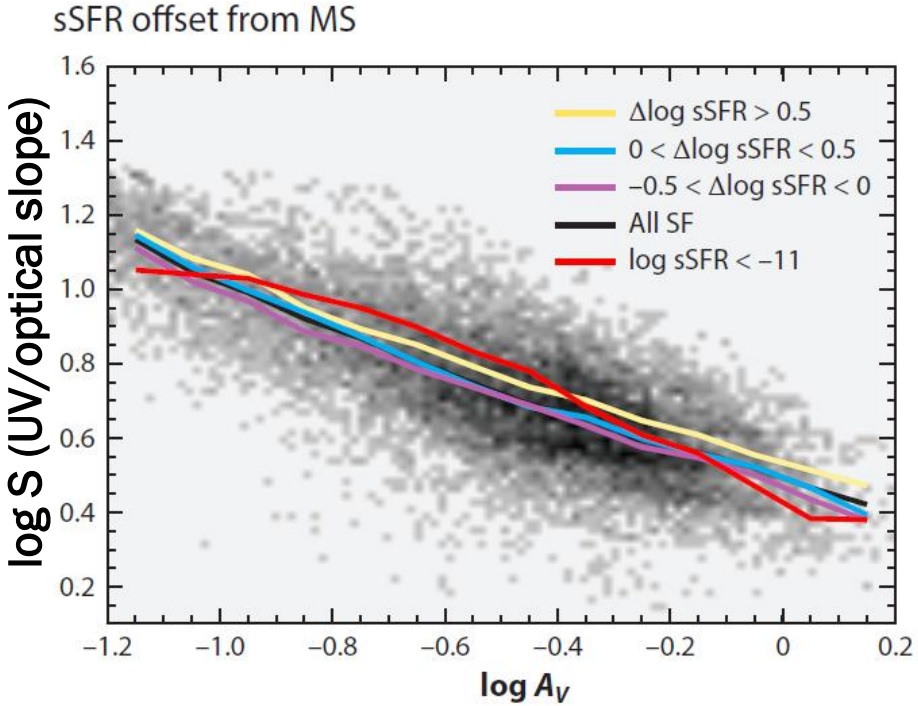


Attenuation curves - diversity

Primary dependence is on the dust column

- At fixed Av (dust column) curve slope does not depend on sSFR

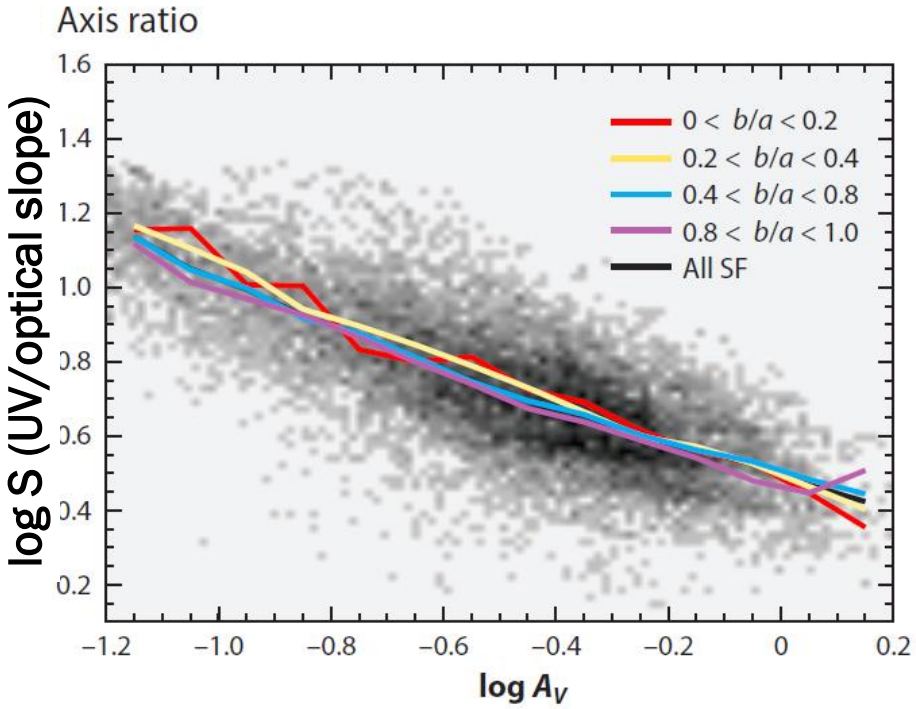


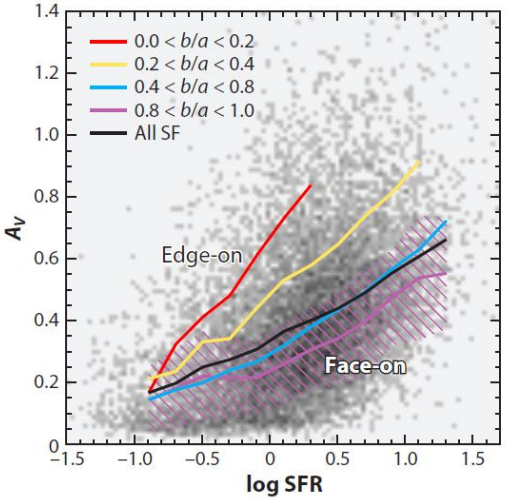


Attenuation curves - diversity

Primary dependence is on the dust column

- At fixed Av (dust column) curve slope does not depend on the axis ratio

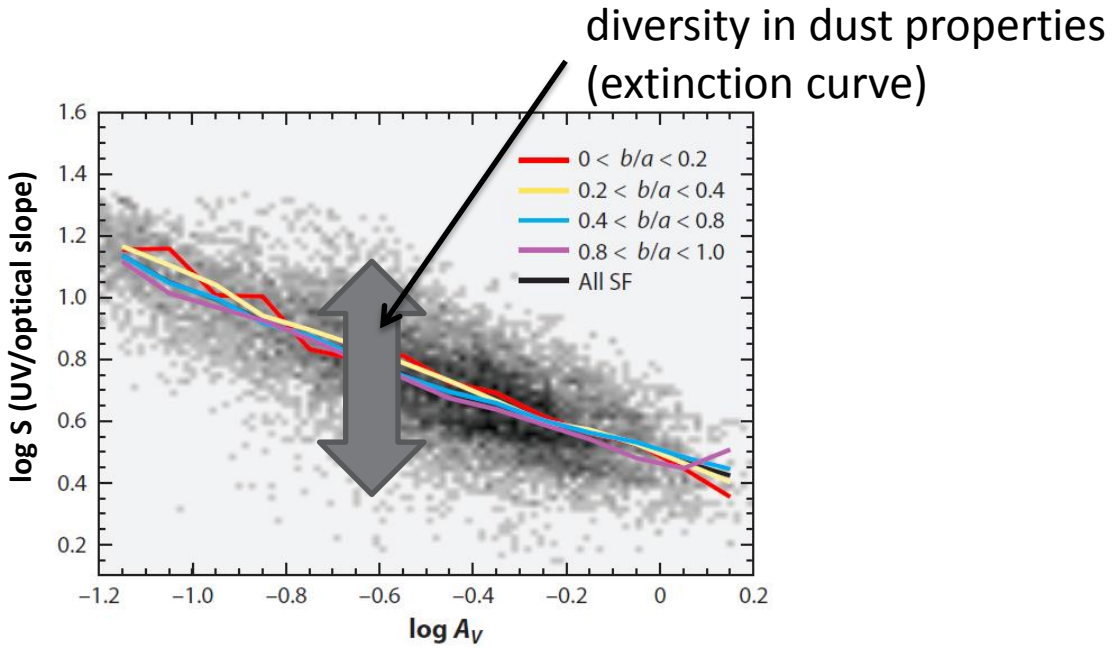




Disentangling attenuation and extinction curves?

Residual scatter in slope-Av relation

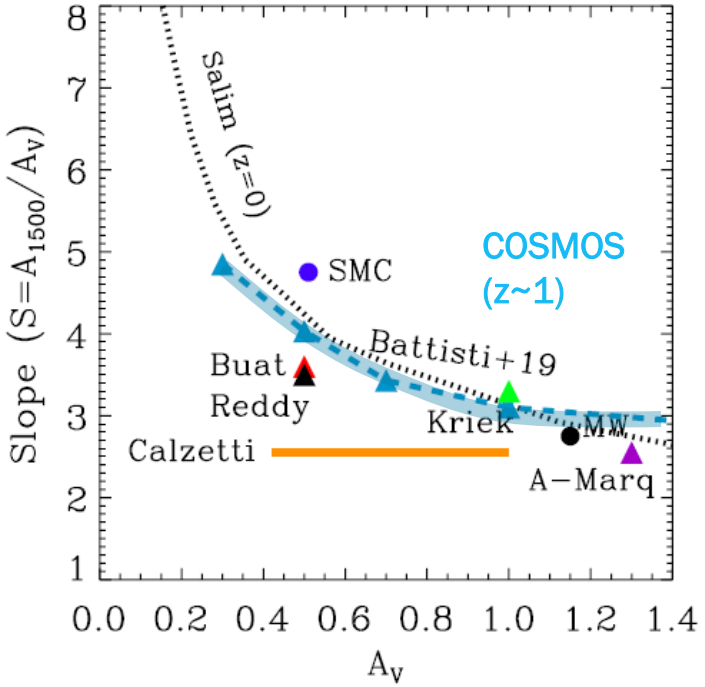
- Observed slope-Av relation is broader than the simulated one



Evolution of the attenuation curve?

High-z results often inconsistent

- Important: compare all studies at the same Av
- DAC may not evolve much



Summary

- Extinction vs. attenuation
- Is there a diversity of attenuation curves?
- What is the average curve?
- What does the slope depend on?
- What does it not depend on?
- Evolution