Radiative Transfer Models of Attenuation Curves in Clumpy, Galactic Environments

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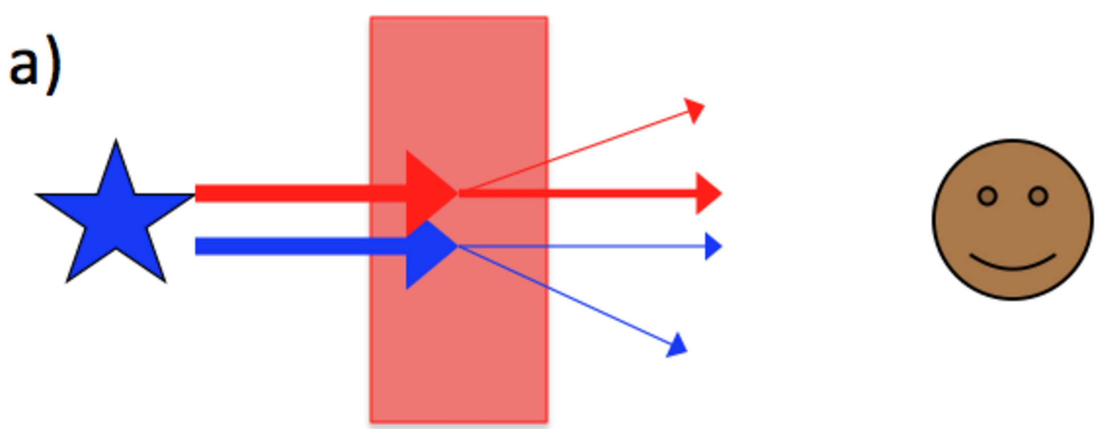
What is the attenuation curve?

extinction

individual point source



extinction = intrinsic property of dust

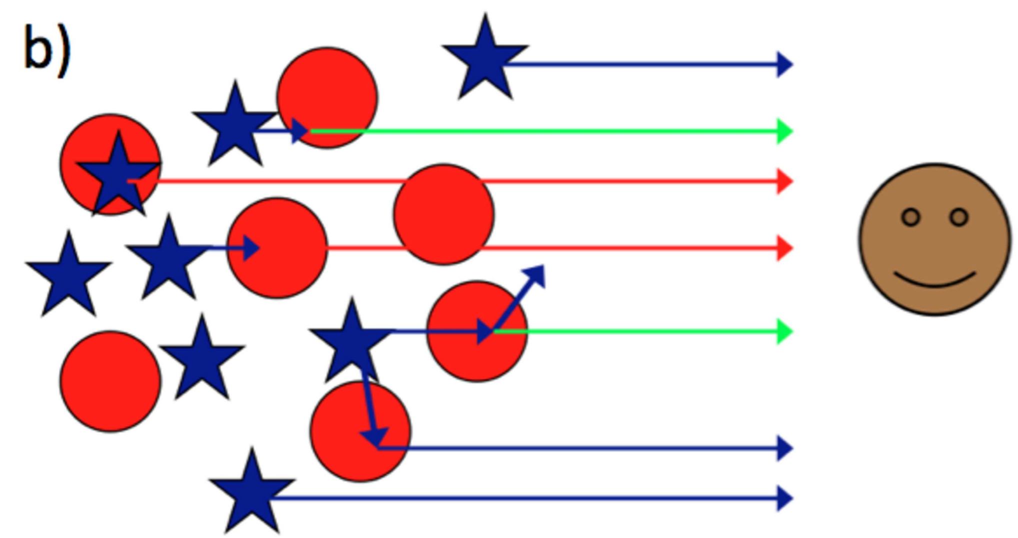
$$F_\lambda = F_\lambda^{\rm star} e^{-\tau_\lambda^{\rm ext}}$$

$$\tau_\lambda^{\rm ext} = -\ln\left(\frac{F_\lambda}{F_\lambda^{\rm star}}\right)$$

attenuation (or effective extinction)

extended source

Calzetti (2013)



attenuation = intrinsic property of dust
+ radiative transfer effect

$$F_\lambda = F_\lambda^{\rm galaxy} e^{-\tau_\lambda^{\rm att}}$$

$$\tau_\lambda^{\rm att} = -\ln\left(\frac{F_\lambda}{F_\lambda^{\rm galaxy}}\right)$$

Why the attenuation curve is important?

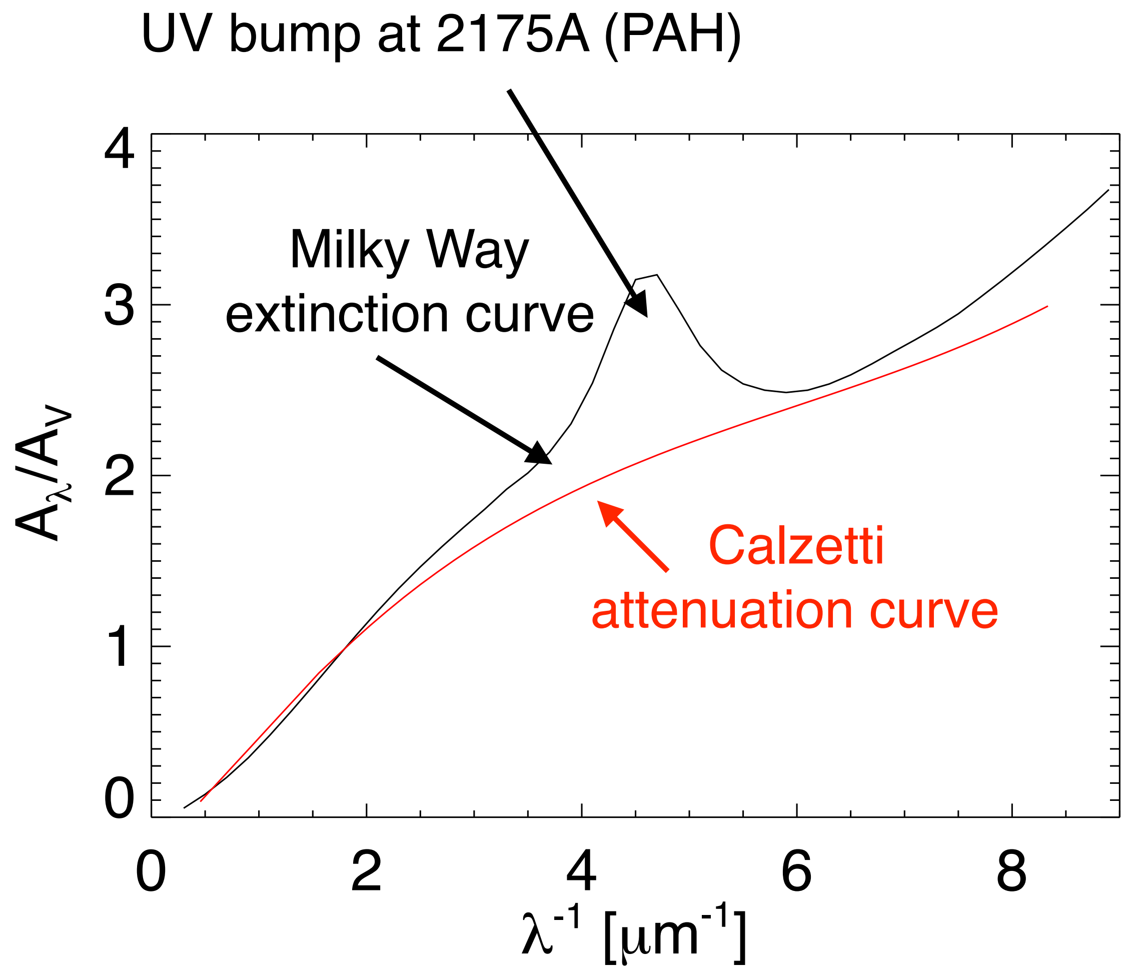
- Most of our knowledge about the SFRs of high-redshift galaxies is obtained using observations in the rest-frame UV and/or SEDs.
- SEDs of galaxies provide crucial information on stellar population, metal content and star formation history.
- However, internal dust absorbs and scatters starlight, and hampers our ability to directly measure the intrinsic SEDs, especially at UV.
- We need to correct the dust attenuation effect.

Calzetti Law

- Calzetti Law (1994, 2000) was derived from the IUE observations of local starburst galaxies.

Three Questions:

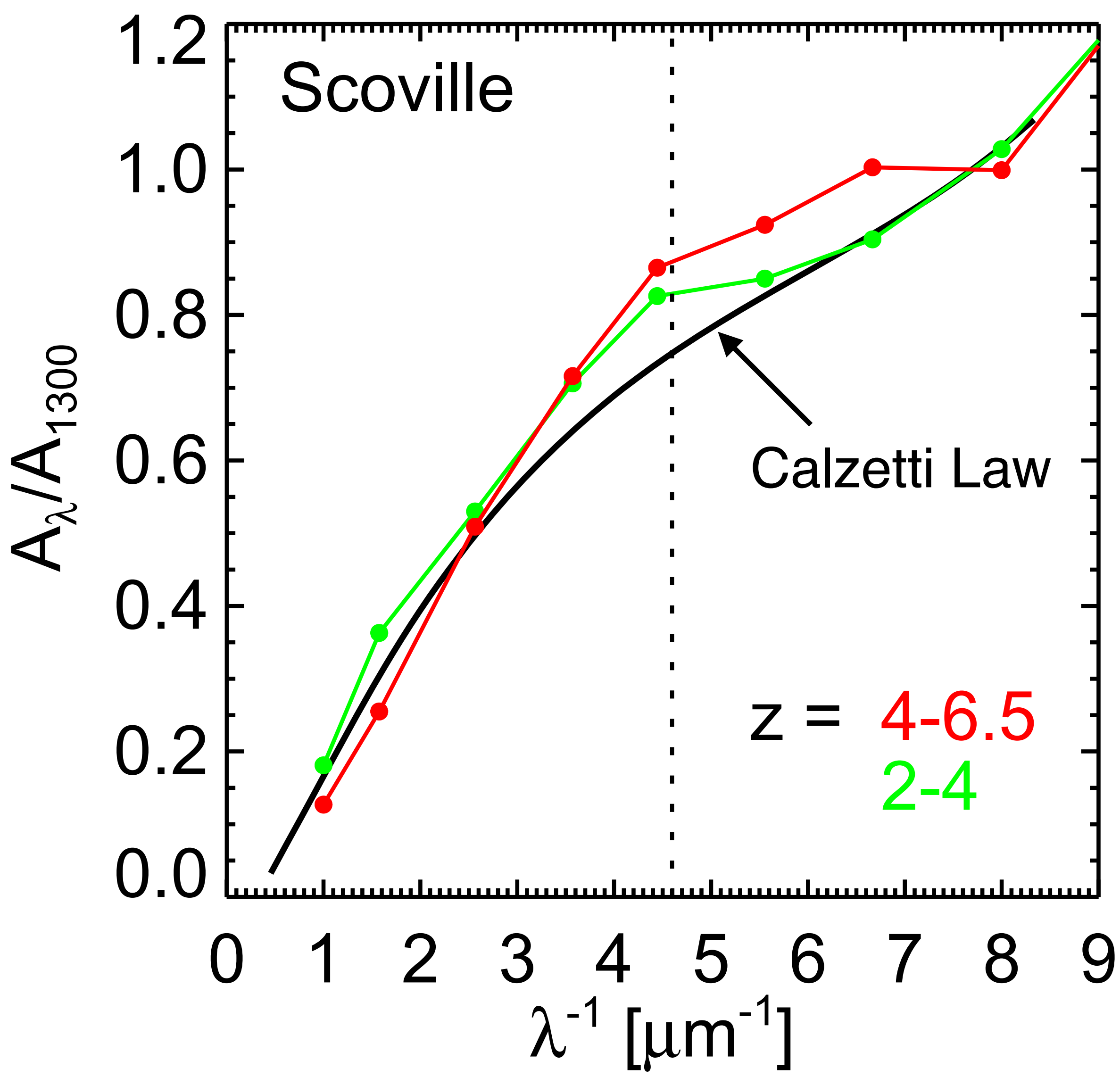
1. Why no UV bump?
2. Why shallower than the MW extinction
3. Is it universal?



- Witt & Gordon (2000) - **the SMC dust is attributed to be responsible to the Calzetti curve**, mainly because of no UV bump feature in the Calzetti curve.

“Diamonds in the Sky”

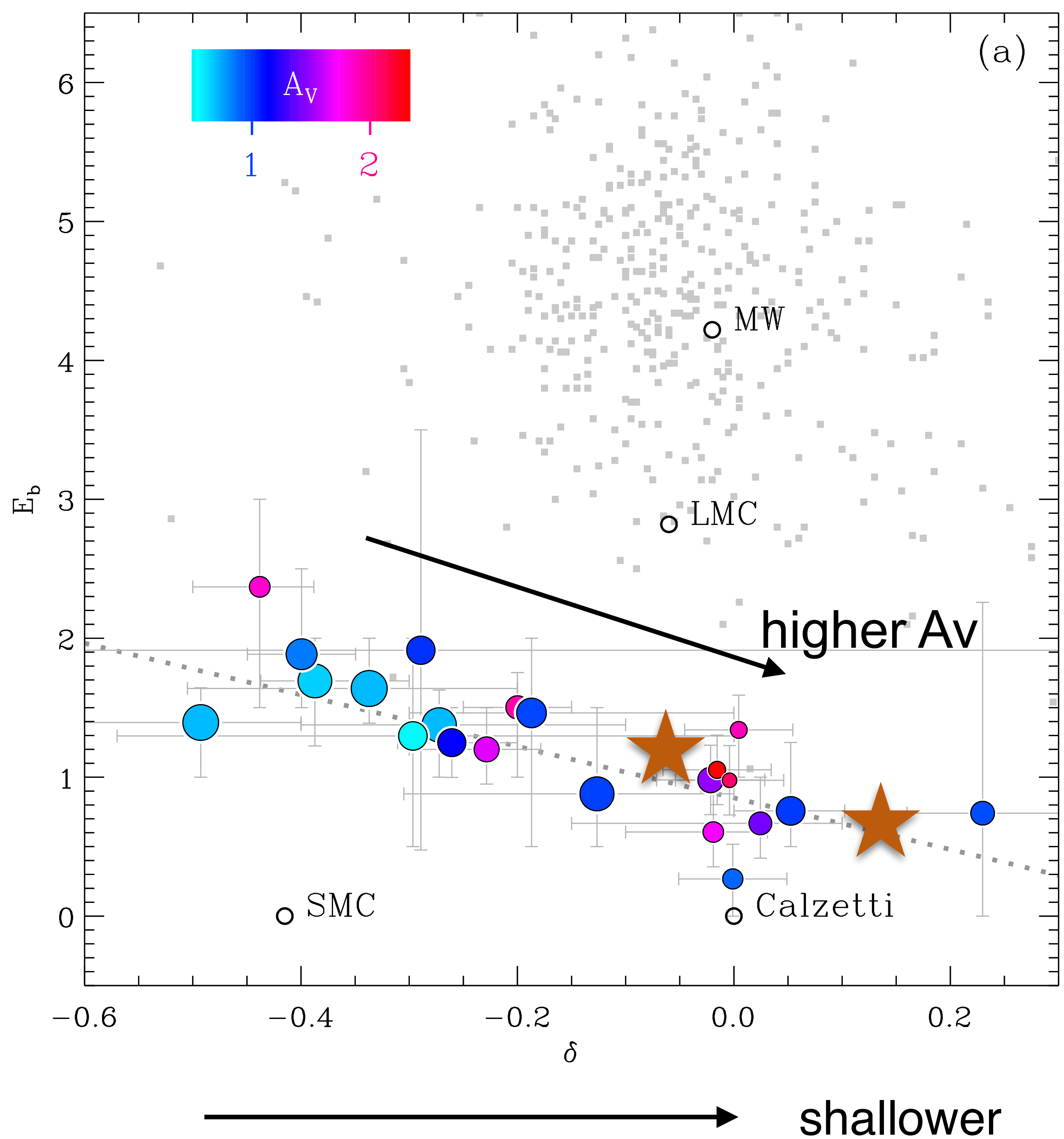
- Scoville et al. (2015) derived dust attenuation curves from a galaxy sample with z = 2-6.5 and found the 2175A bump feature.



Correlation between slope and UV bump strength

- **Kriek & Conroy (2013)**
  galaxies with 0.5 < z < 2.0

$$E_b = 0.85 - 1.9\delta$$



- **Modified Calzetti Curve**
  (Noll et al. 2009)

slope

$$A_\lambda = \frac{A_V}{k(V)}\left[k(\lambda)+D(\lambda)\right]\left(\frac{\lambda}{\lambda_V}\right)^{\delta},$$

Calzetti Curve

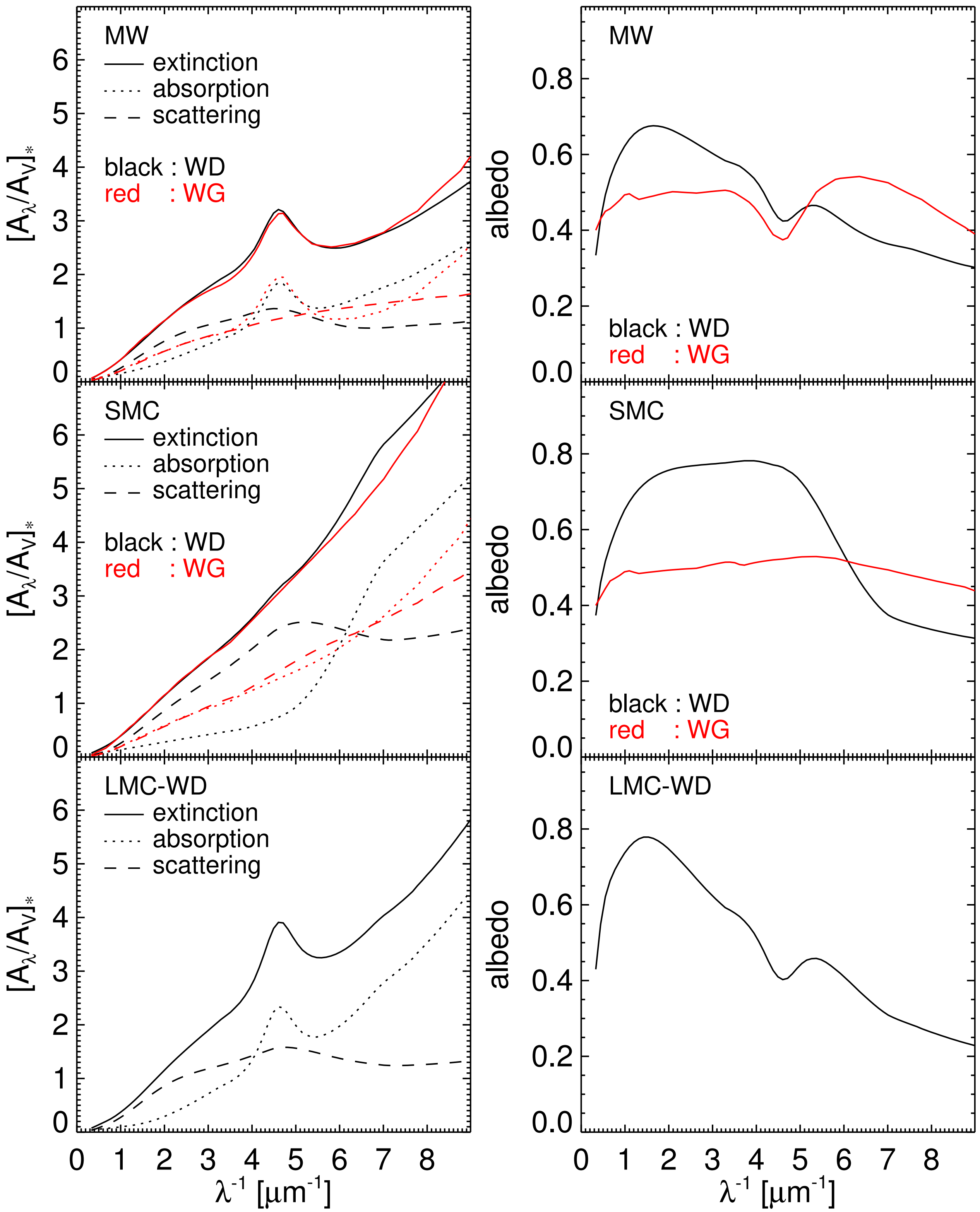
UV bump: Drude profile

bump strength

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

★ = Scoville et al. (2015)

Model - (1) Dust



Five extinction curves **are considered.**

1. WD : Weingartner & Draine (2001)

Theoretically derived, silicate-carbonaceous dust

Milky Way (MW)
Small Magellanic Cloud (SMC)
Large Magellanic Cloud (LMC)

2. WG : Witt & Gordon (2000)

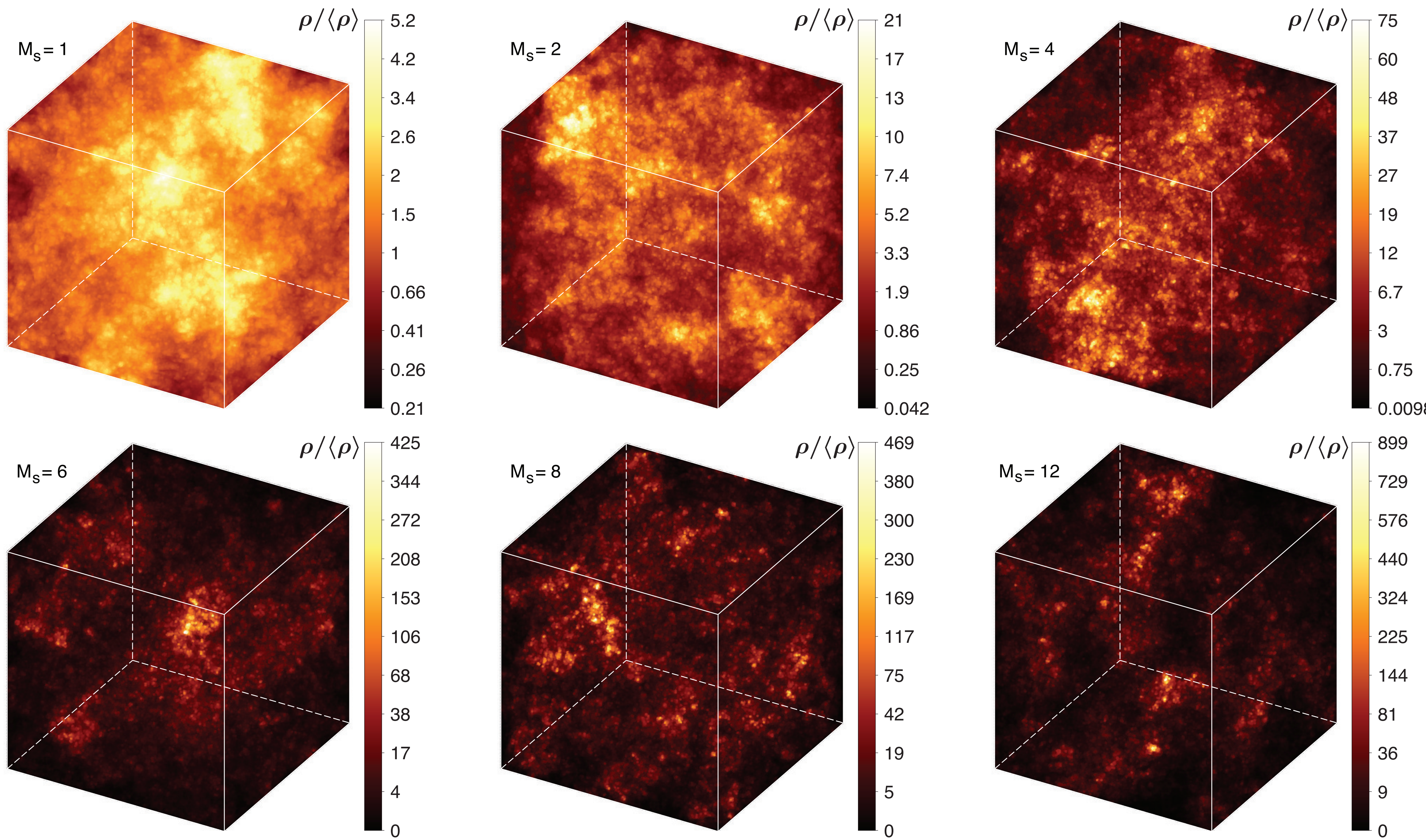
Empirically derived albedo from reflection nebulae

Milky Way (MW)
Small Magellanic Cloud (SMC)

albedo = scattering/extinction
= scattering/(scattering + absorption)

Model - (2) 3D Density Field

Log-normal distribution
10 realizations for each Mach number
box size = 128^3



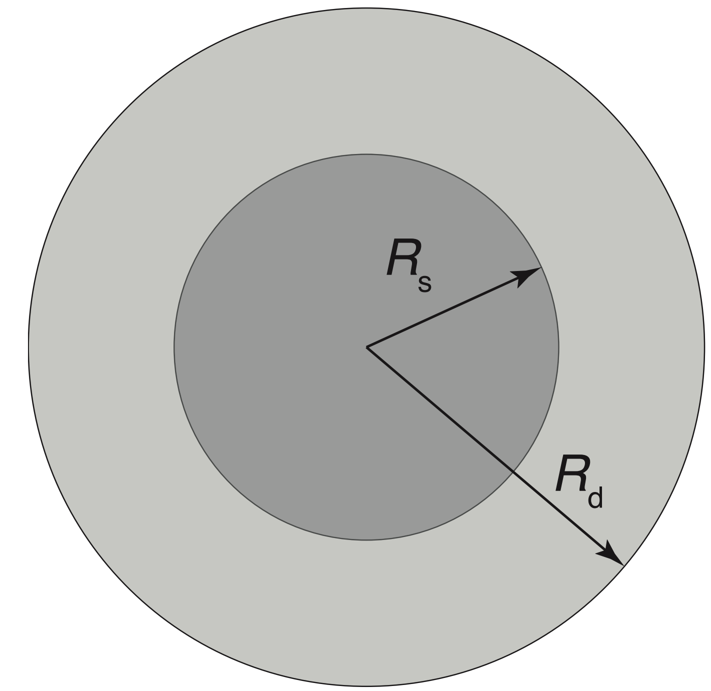
Model - (3) Geometry

- **Geometry**

  R_s: photon source size,

  R_d: dust cloud size

  R_s/R_d = 0.0, 0.2, 0.4, 0.6, 0.7, 0.8, 0.9, 1.0

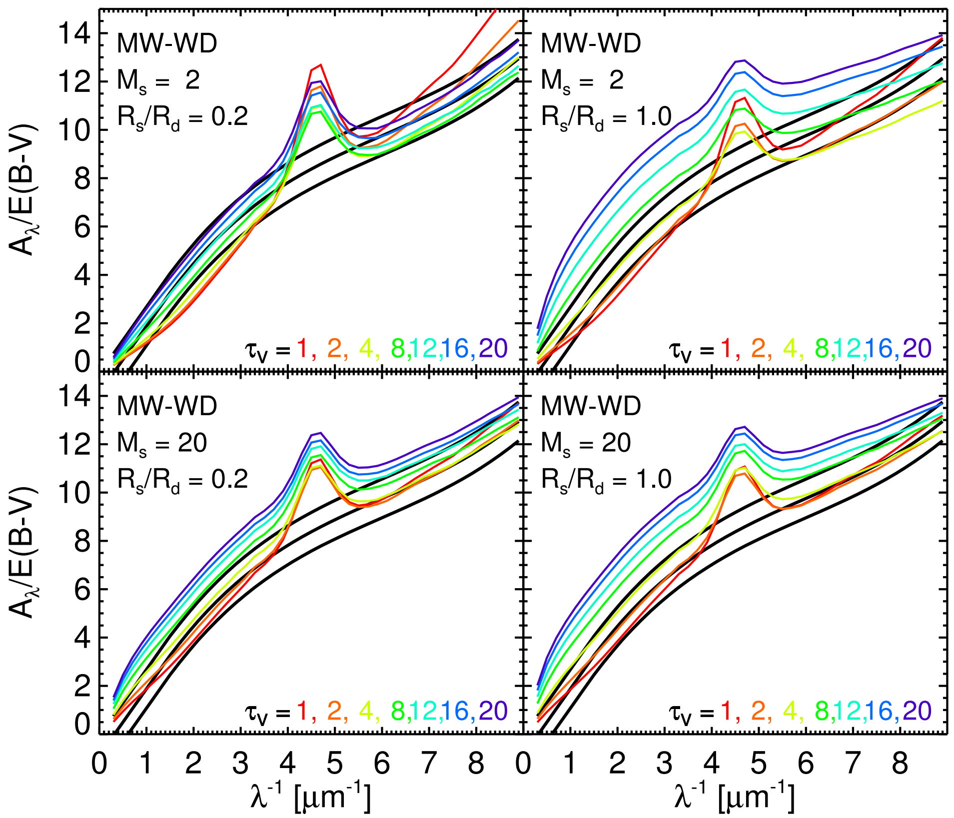


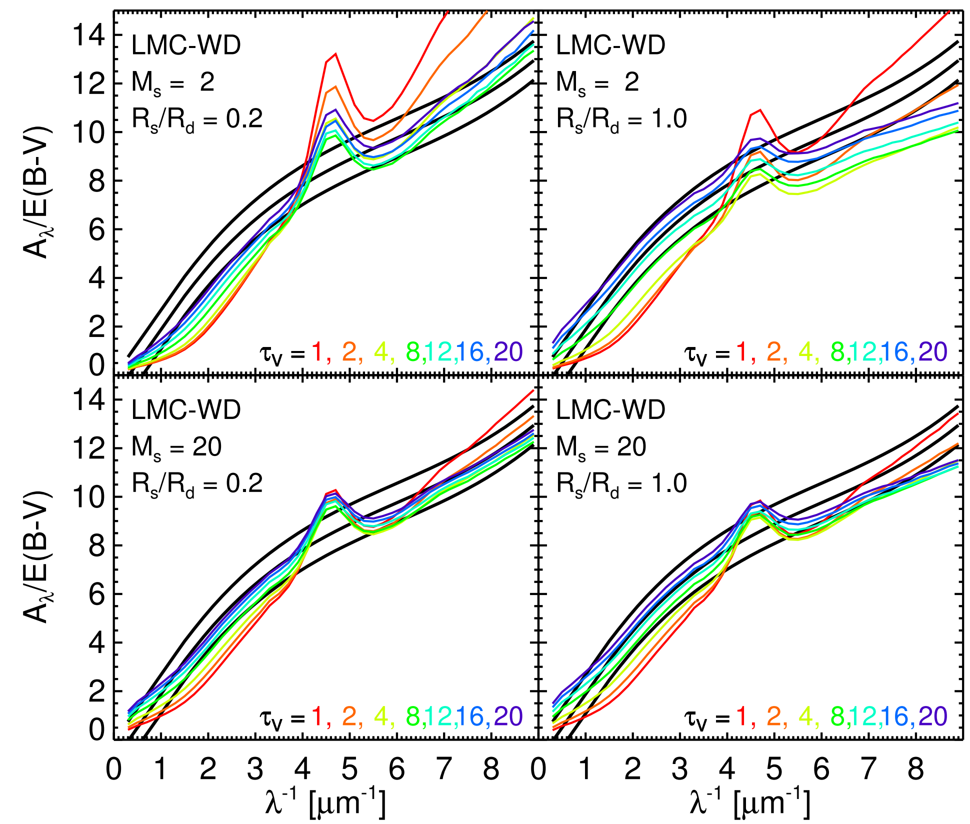
- **Optical depth** at V-band = 0.1, 0.5, 1.0, 2.0, 3.0, 4.0, …, 20.0

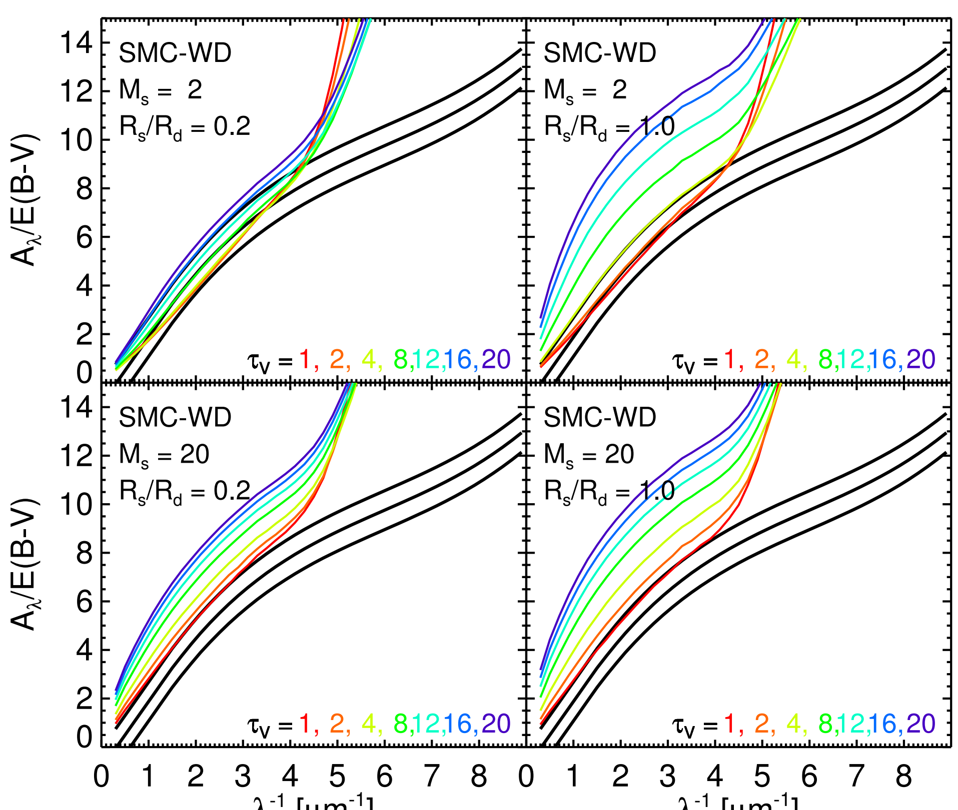
  (Homogeneous optical depth = center-to-edge optical depth of a cloud with a constant density, but with the same dust mass as the lognormal density cloud)

- **Mach number** = 1, 2, 4, 6, 8, 10, 12, 20

Results for the Weingartner-Draine dust types





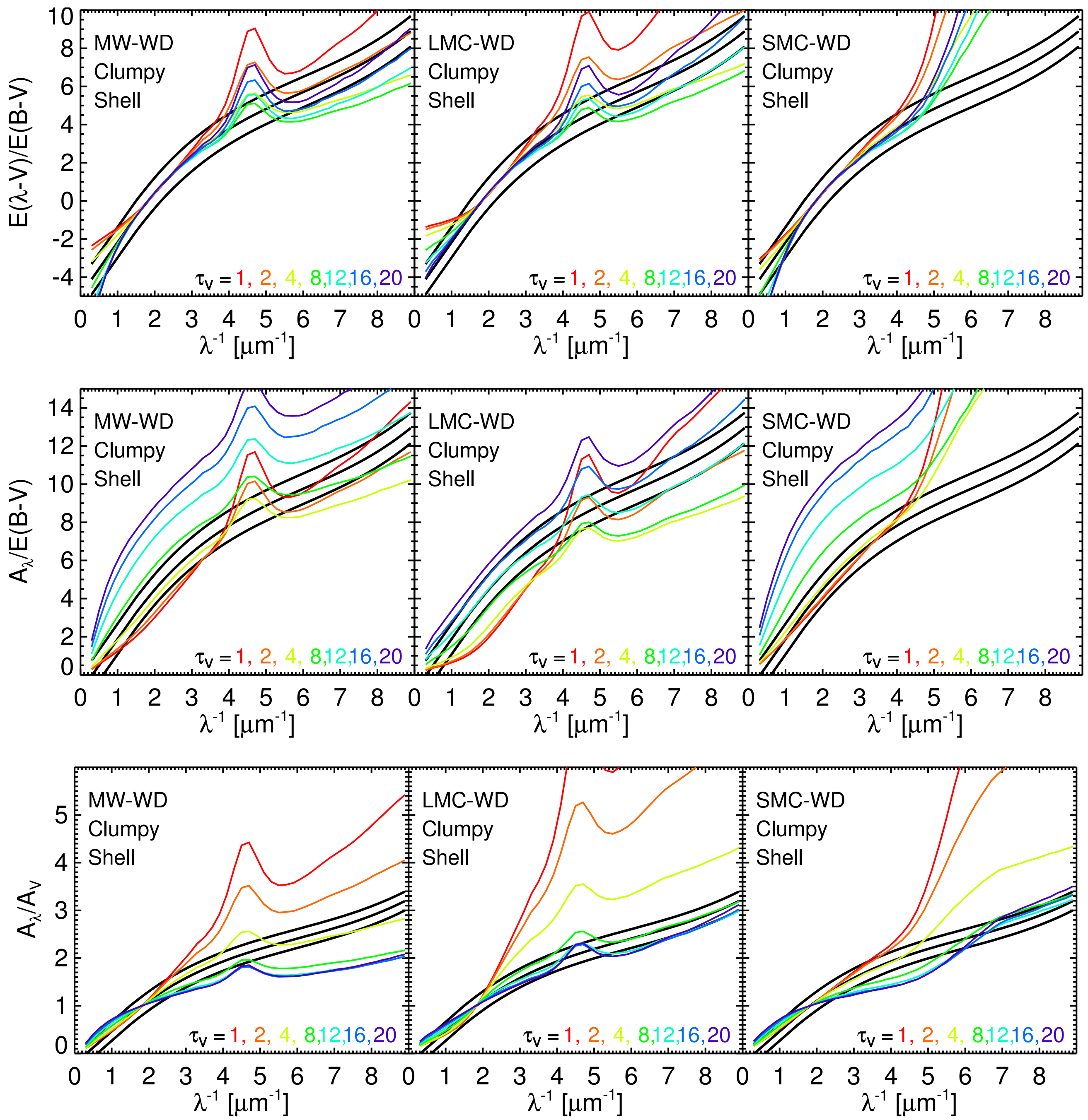


- The MW dust reproduces the overall shape of the Calzetti curves. But, the UV bump strength is too strong.

- The LMC dust results in steeper curves.
- The SMC dust give completely different shapes.

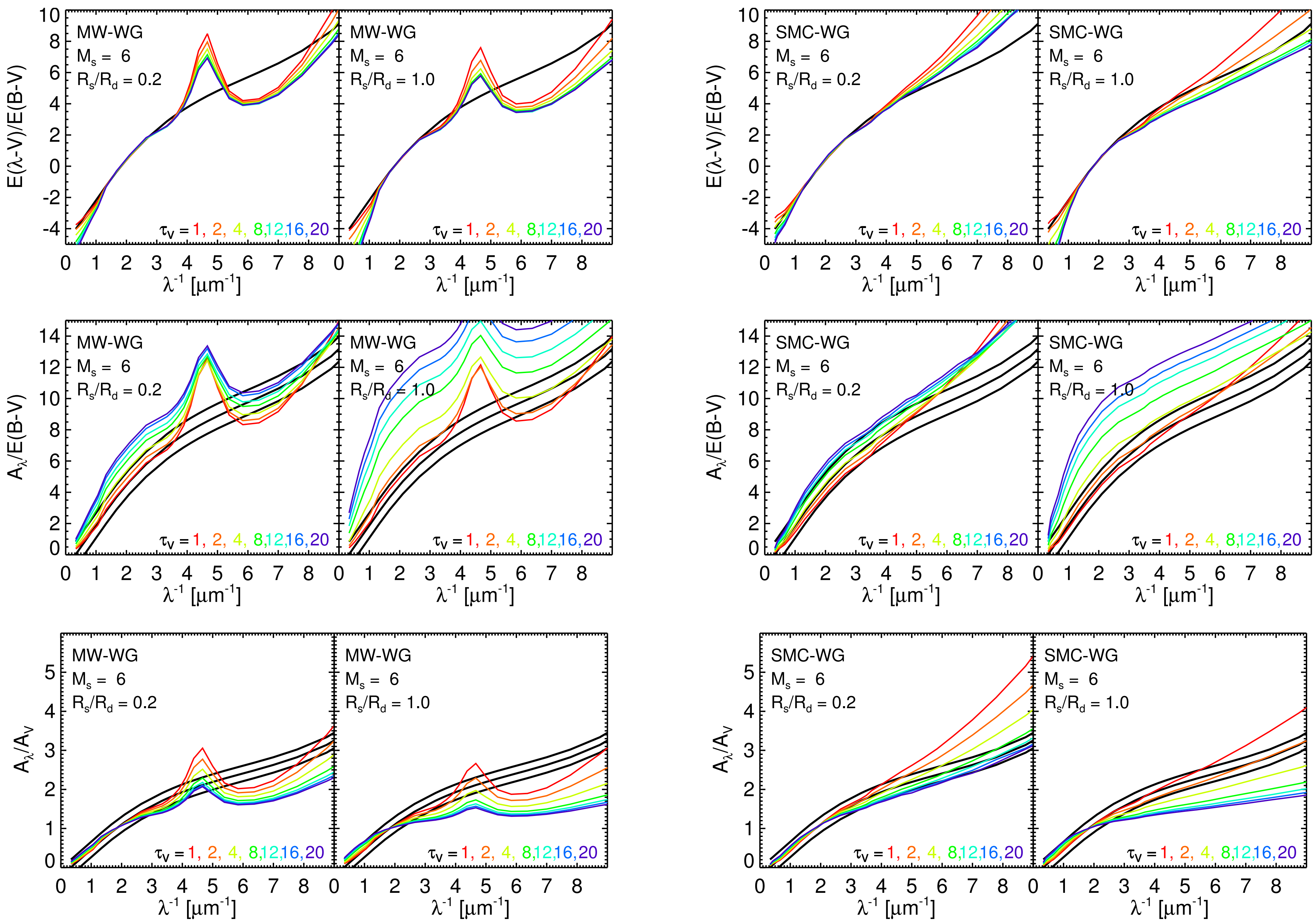
Discrepancy with the results of Witt & Gordon

- This results disagree with the result of Witt & Gordon (2000).
- Witt & Gordon assumed (1) two-phase clumpy medium and shell geometry and adopted (2) dust albedo which were empirically derived.



- **First test**: geometry of Witt & Gordon (2000) + Draine's dust type.
- The Draine's MW dust reproduces the overall shape of the Calzetti curve.

- **Second test**: Our geometry + Witt & Gordon dust type.
- The Witt's SMC dust well reproduces the Calzetti curve.
- The discrepancy is not caused by geometry.



What Determines the Shape of Attenuation Curve?

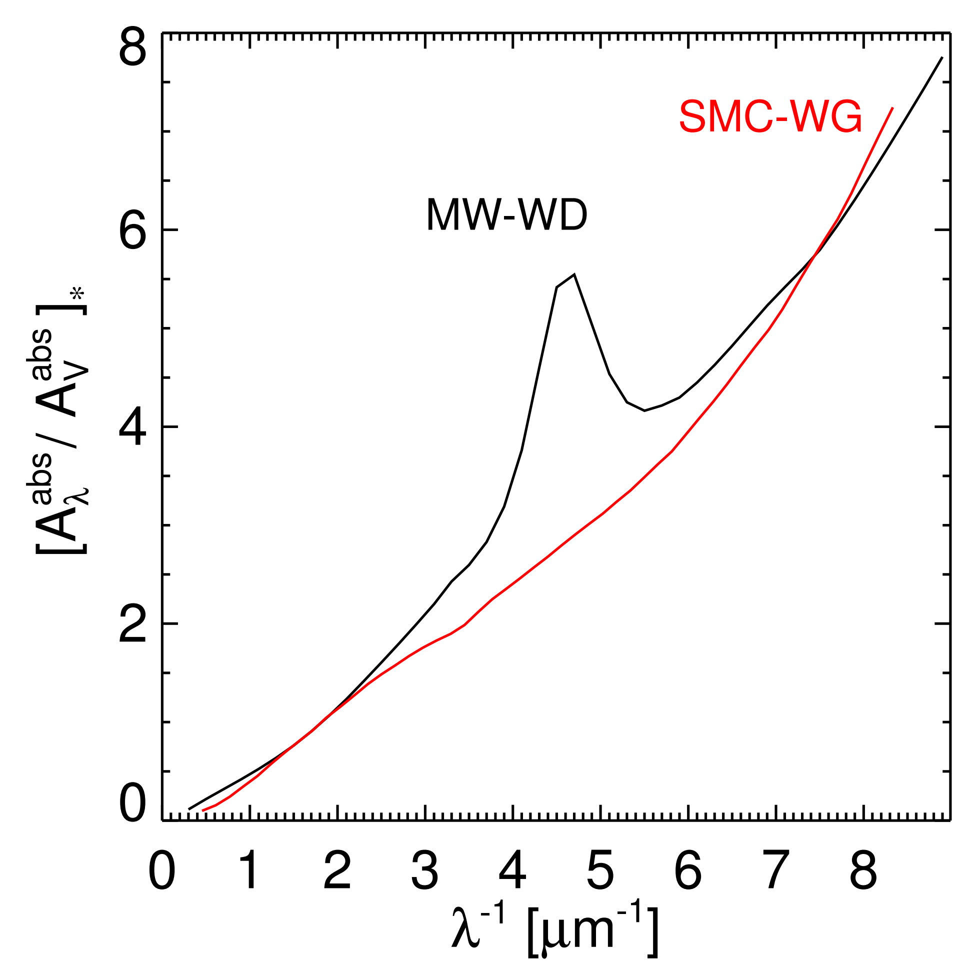
- The discrepancy is mainly due to difference in the adopted albedo curve.

- Attenuation curves are primarily determined by the absorption curve rather than by the extinction (absorption+scattering) curve, because the scattering is strongly forward-directed at optical and UV wavelengths.

$$I_\lambda = I_\lambda^0 \exp(-\tau_{\rm abs})$$

for the case of perfect forward scattering

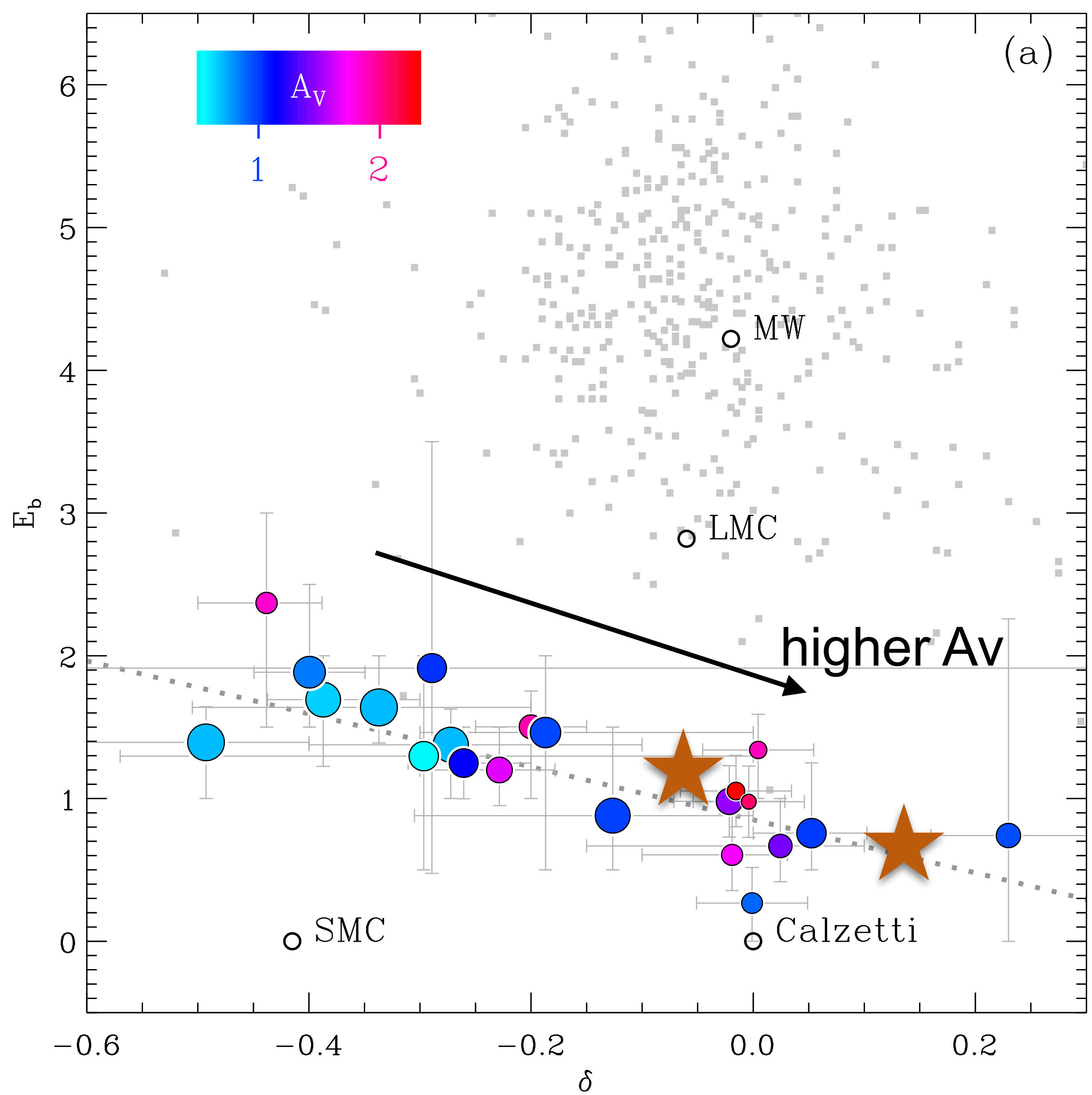
- **The absorption curves of the MW-WD and SMC-WG dust are very similar**, except the presence of the UV bump feature in the MW-WD dust.



Correlation between slope and UV bump strength

- **Kriek & Conroy (2013)**
  galaxies with 0.5 < z < 2.0

$$E_b = 0.85 - 1.9\delta$$



shallower

- **Modified Calzetti Curve**
  (Noll et al. 2009)

slope

$$A_\lambda = \frac{A_V}{k(V)}\left[k(\lambda)+D(\lambda)\right]\left(\frac{\lambda}{\lambda_V}\right)^{\delta},$$

Calzetti Curve

UV bump: Drude profile

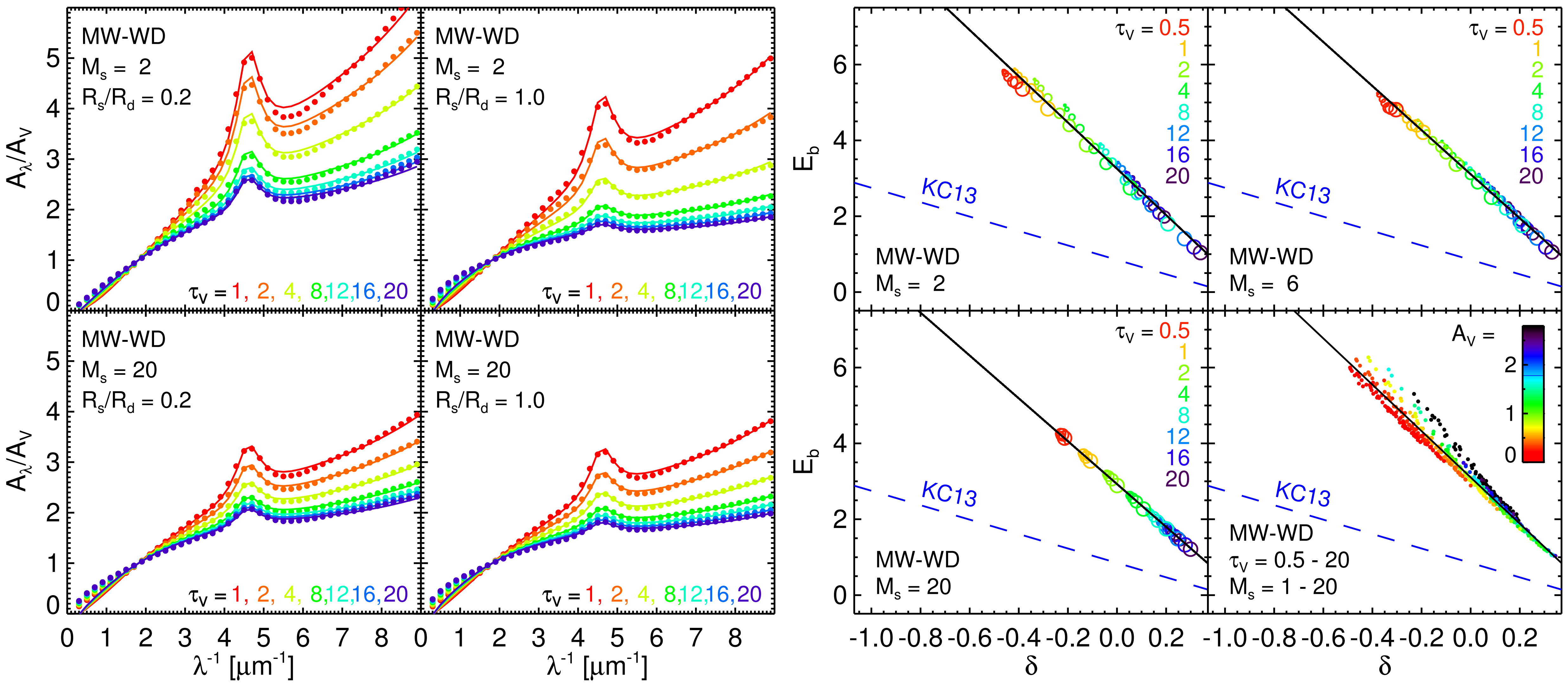
bump strength

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

 = Scoville et al. (2015)

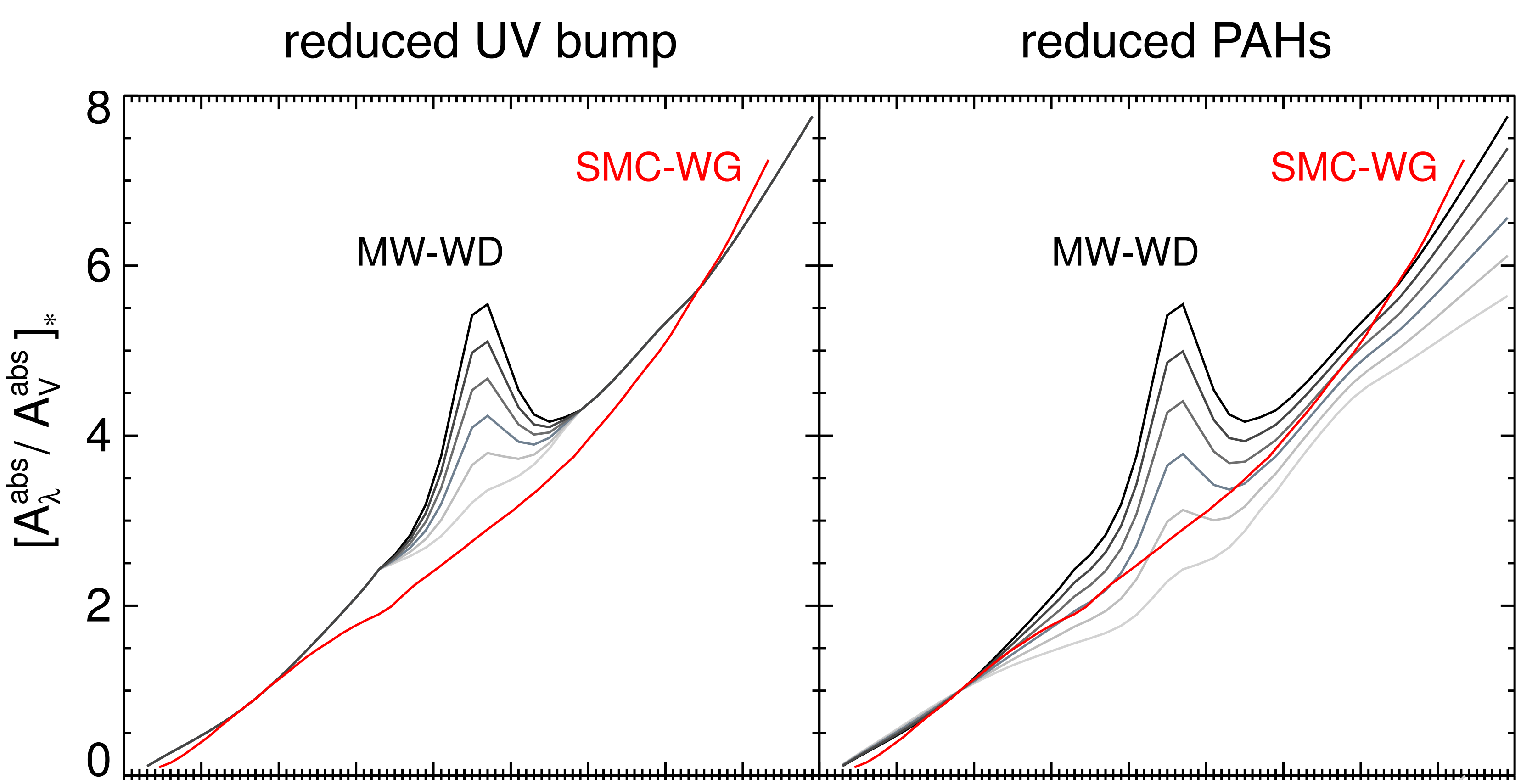
Fit of the MW-WD models to the modified Calzetti

- The slope is in general consistent with the observational results of KC13, but the UV bump appears to be too strong.



Reduced UV bump/PAH abundance

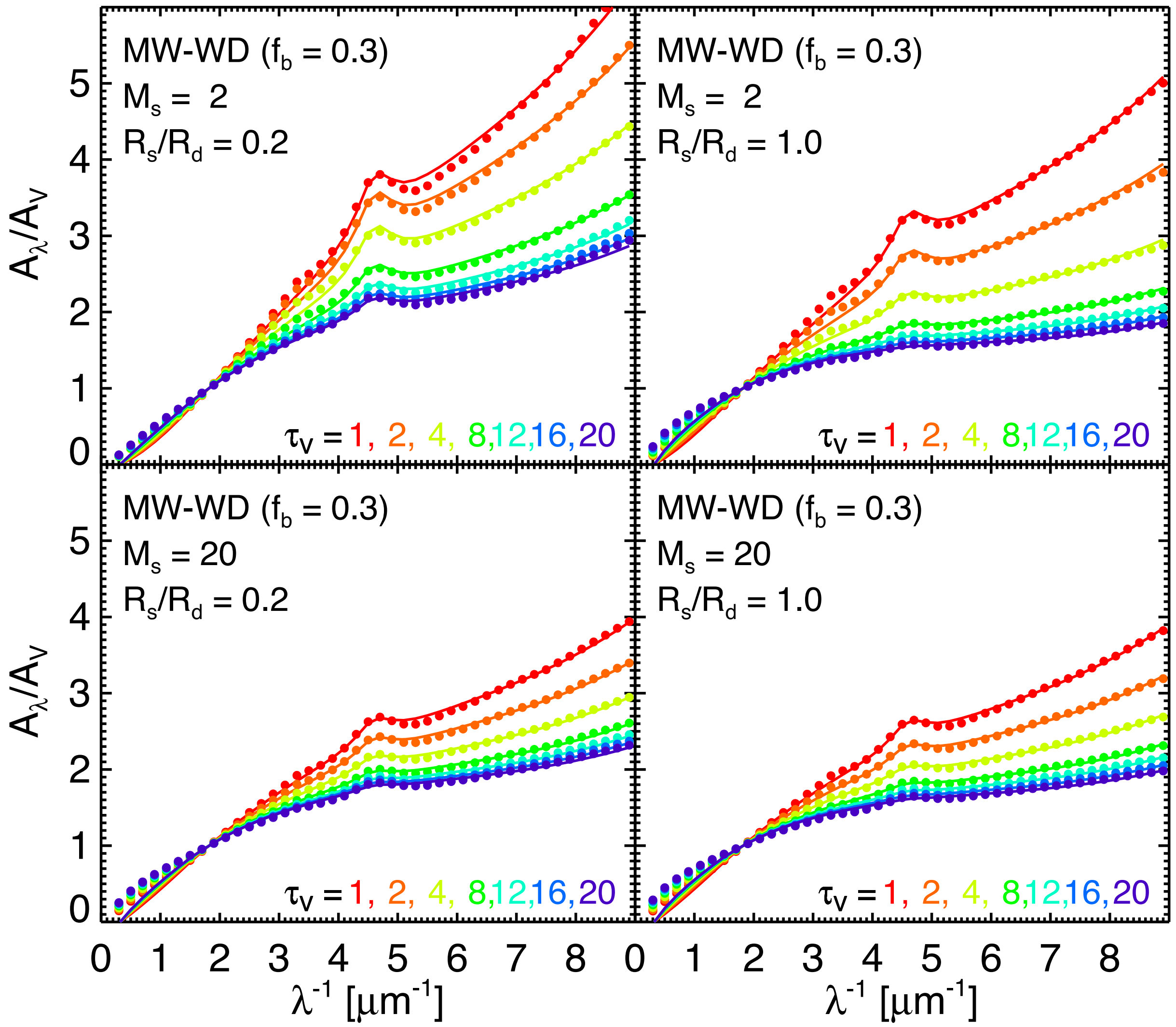
- Absorption curves with lower (left) UV bump and (right) PAH features, shown in grayscale.
- Strengths were reduced from 0.8 to 0.0 in steps of 0.2 relative to those of the MW dust.

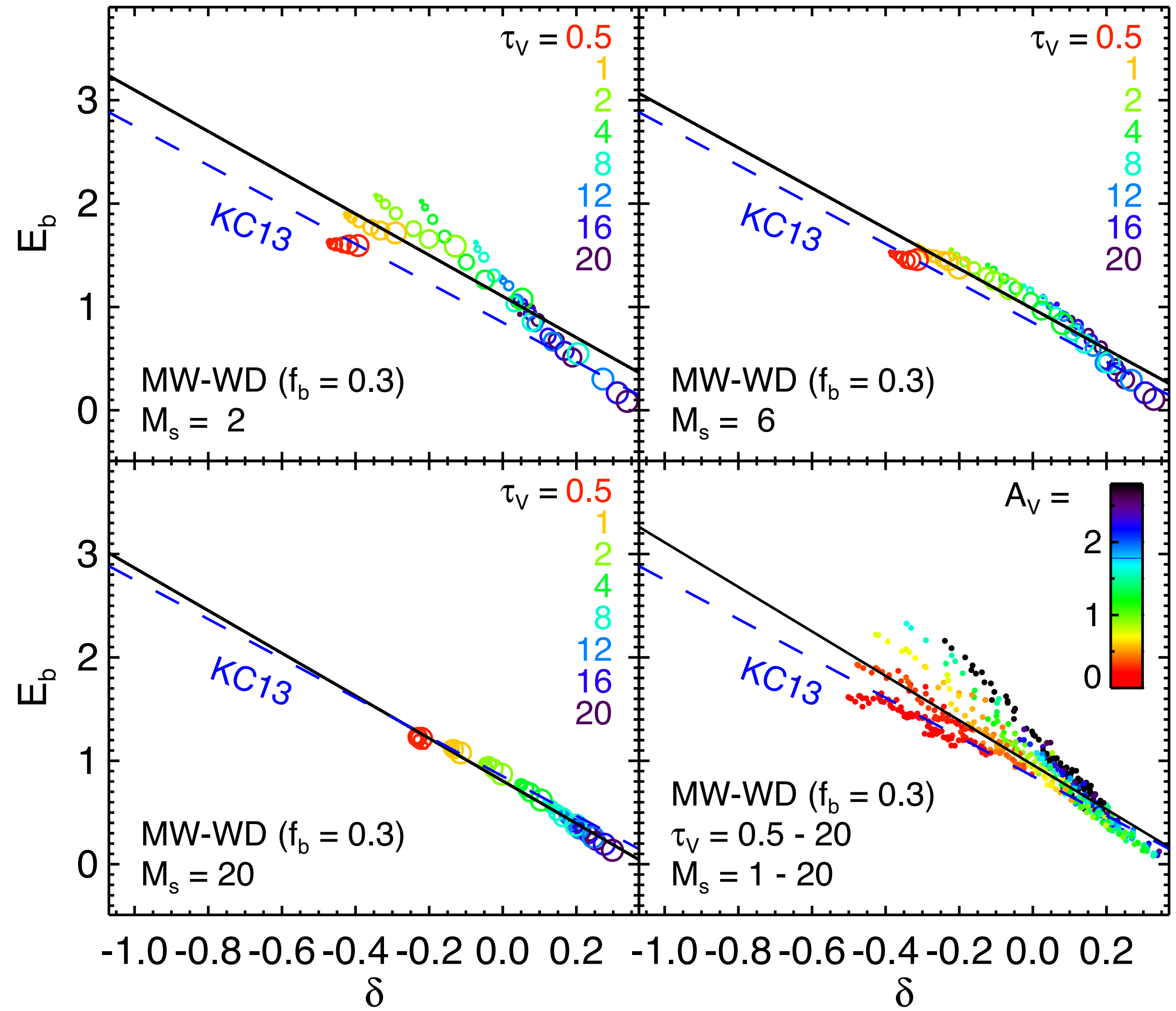


PAHs feature = UV bump + FUV extinction rise.
(PAHs = Polycyclic Aromatic Hydrocarbons)

Results

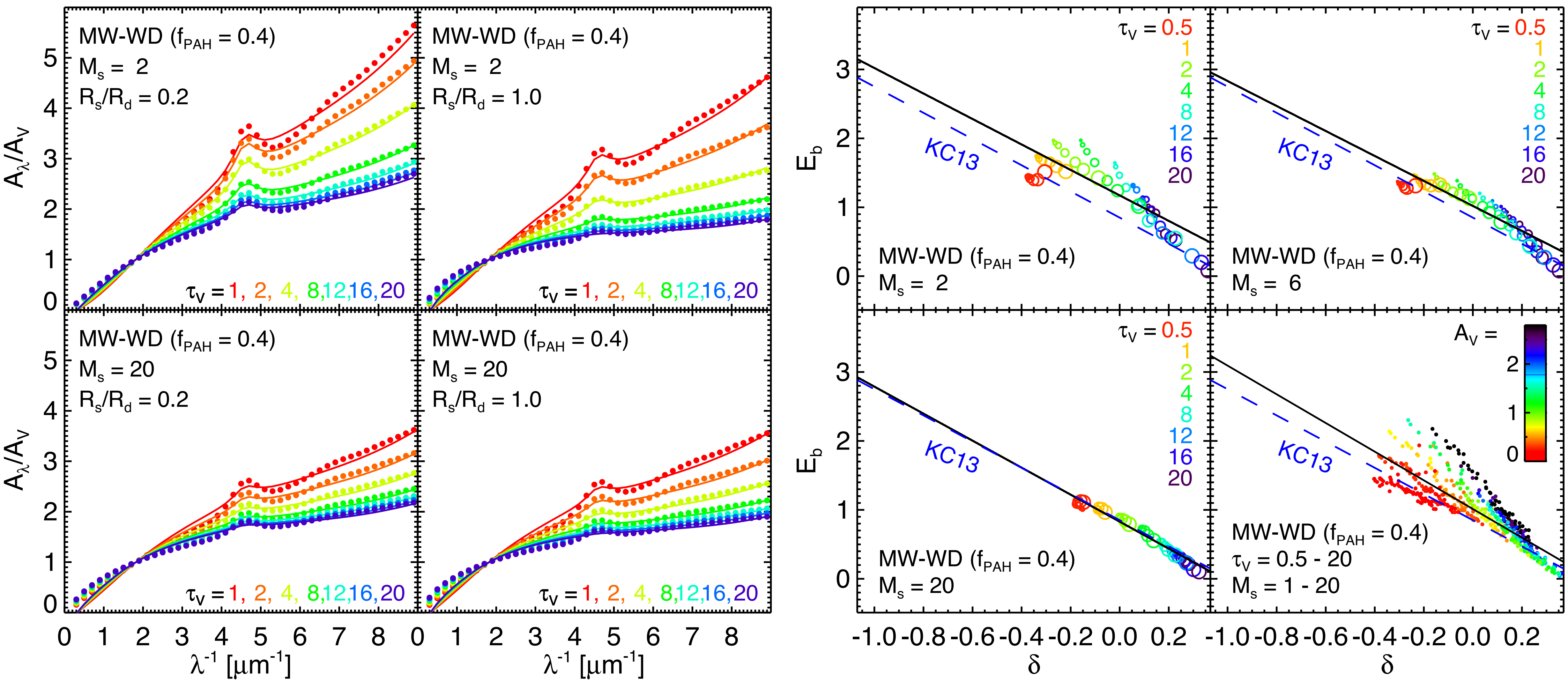
UV BUMP REDUCED BY FACTOR 0.3





Results

"UV BUMP + FUV EXTINCTION RISE" REDUCED BY FACTOR 0.4



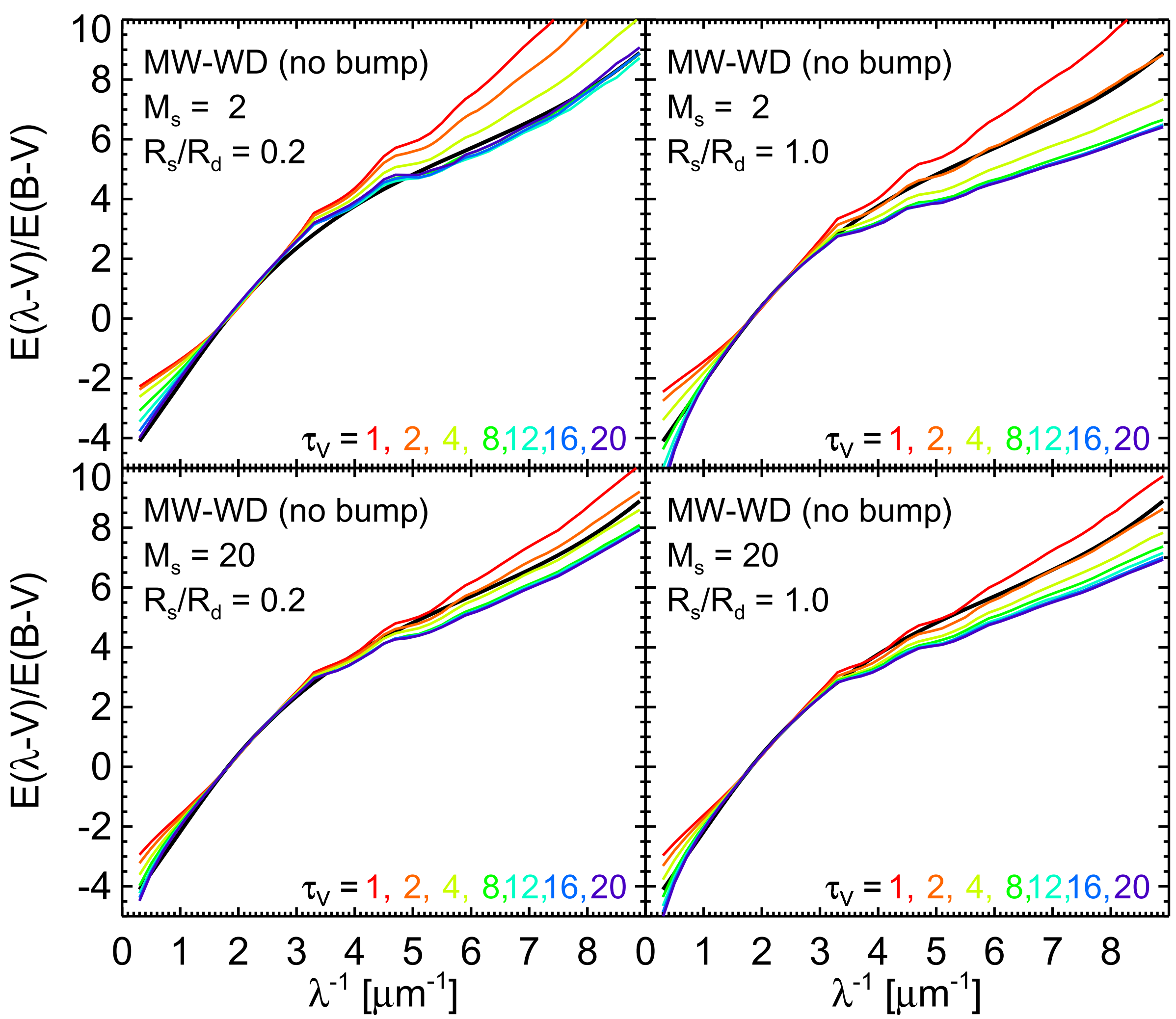
Summary

- Attenuation curves are primarily determined by the absorption curve rather than by the extinction (absorption+scattering) curve.
  - The discrepancy with Witt & Gordon (2000) is due to the difference in adopted albedos; we use the theoretically calculated albedos whereas Witt & Gordon (2000) adopted empirically derived albedos from observations of reflection nebulae.
- Attenuation curves calculated with the Draine's MW dust are well represented by the modified Calzetti curve.
- Shallower attenuation curves with weaker UV bumps are obtained when the ISM is clumpier and dustier.
- The strong correlation between the slope and UV bump strength, as found in star-forming galaxies, is well reproduced if the abundance of the UV bump carriers is 30-40% of that of the MW-dust.

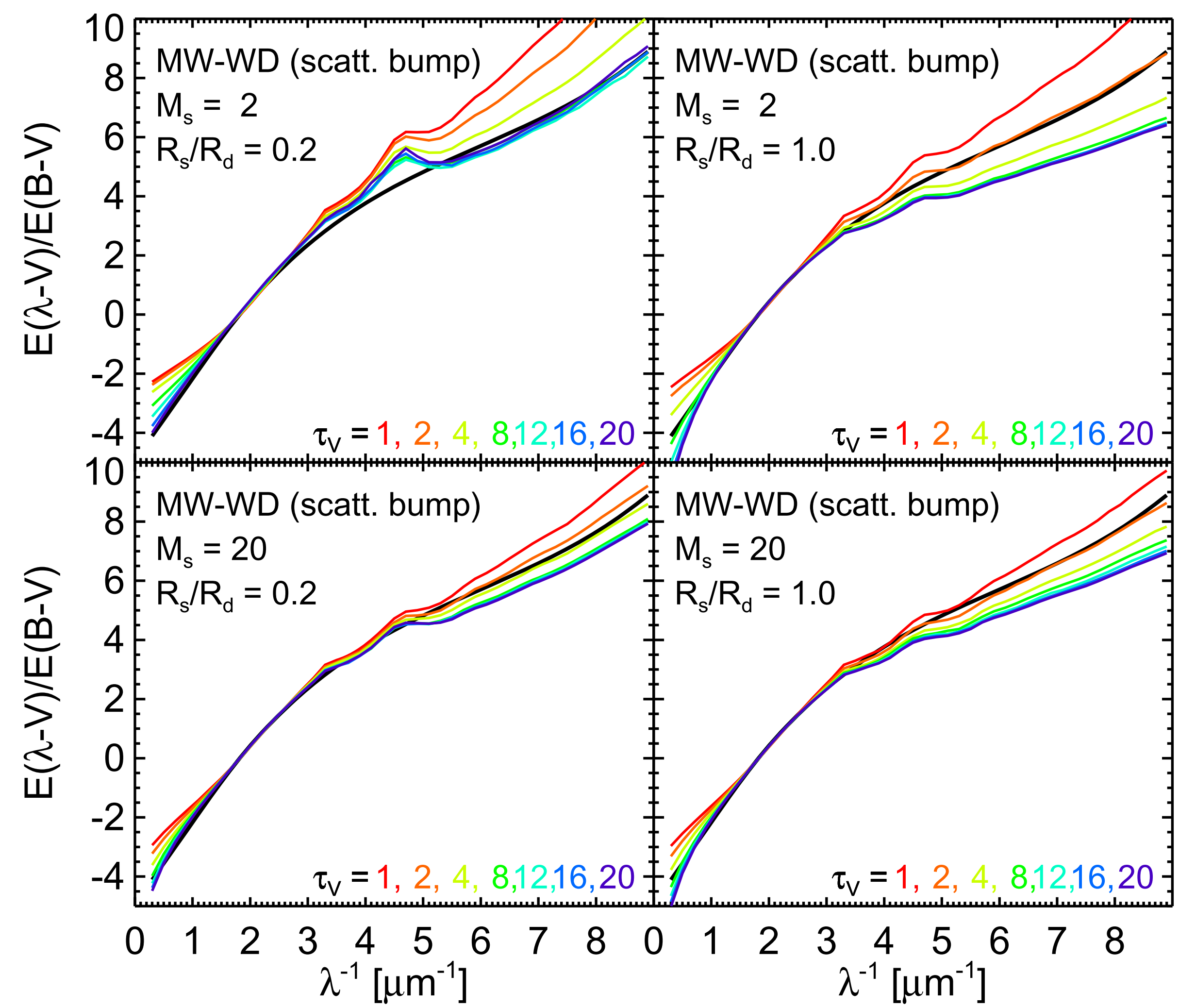
Extra slides

Two hypothetical dust types

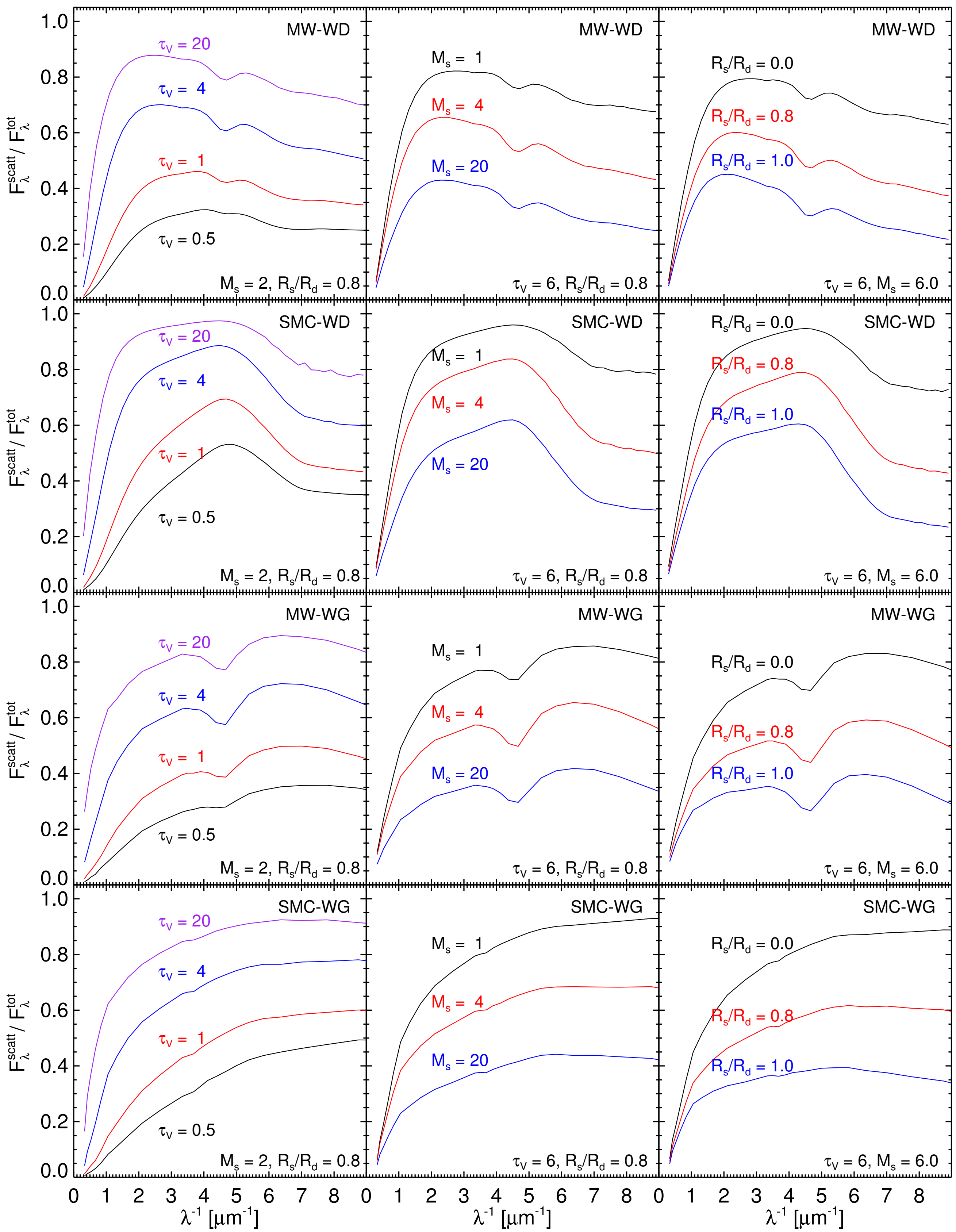
(1) The UV bump is removed.



(2) The bump is assumed to be due to scattering.



Reddening or Blueing of Scattered Light



(1) At visible wavelengths, blueing effect are always found.

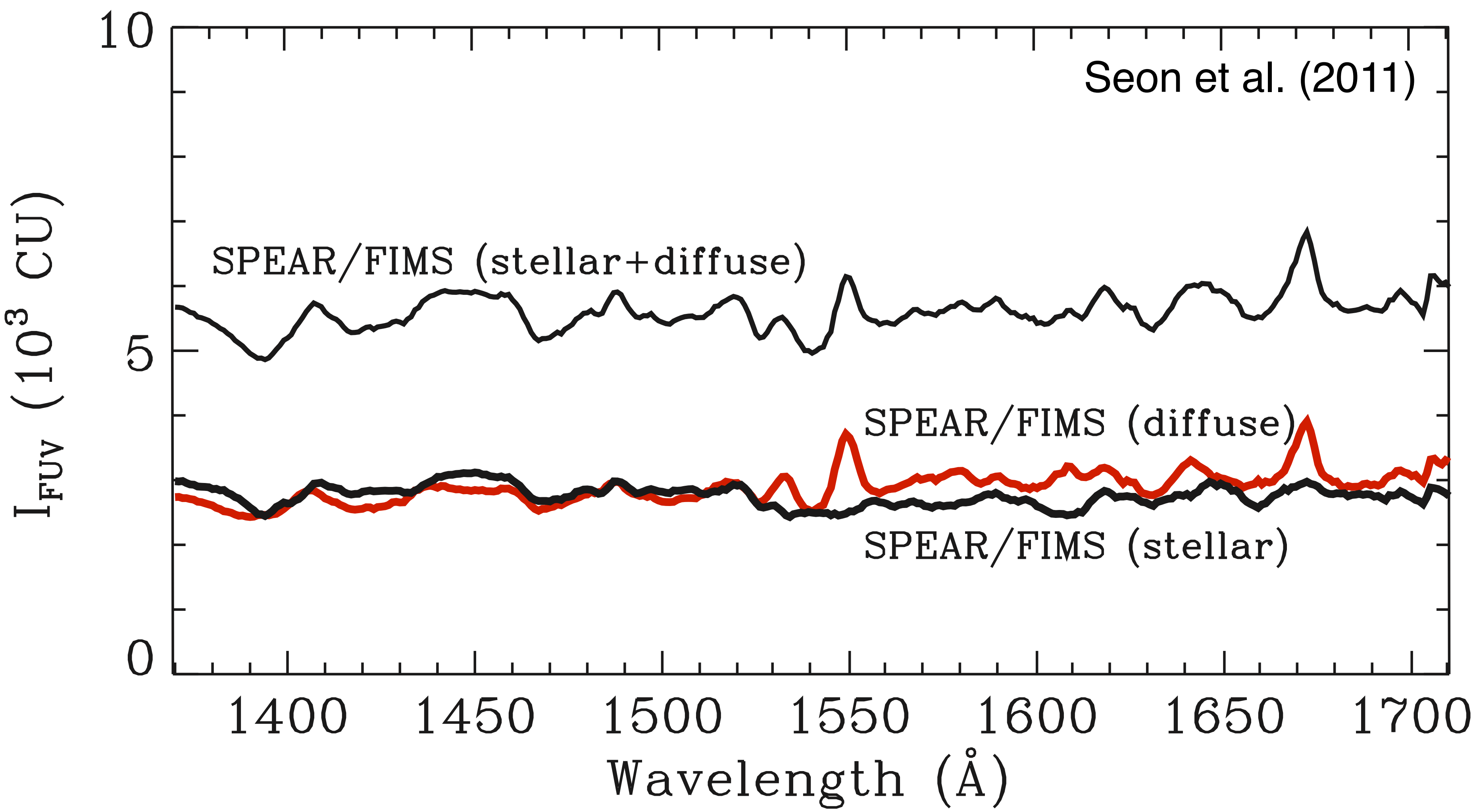
(2) At UV wavelengths,

Reddening effect of the scattered light in the MW-WD dust model,

but Blueing effect in the MW-WG dust model.

Reddening or Blueing depends on the albedo.

Is there observational estimates of albedo?

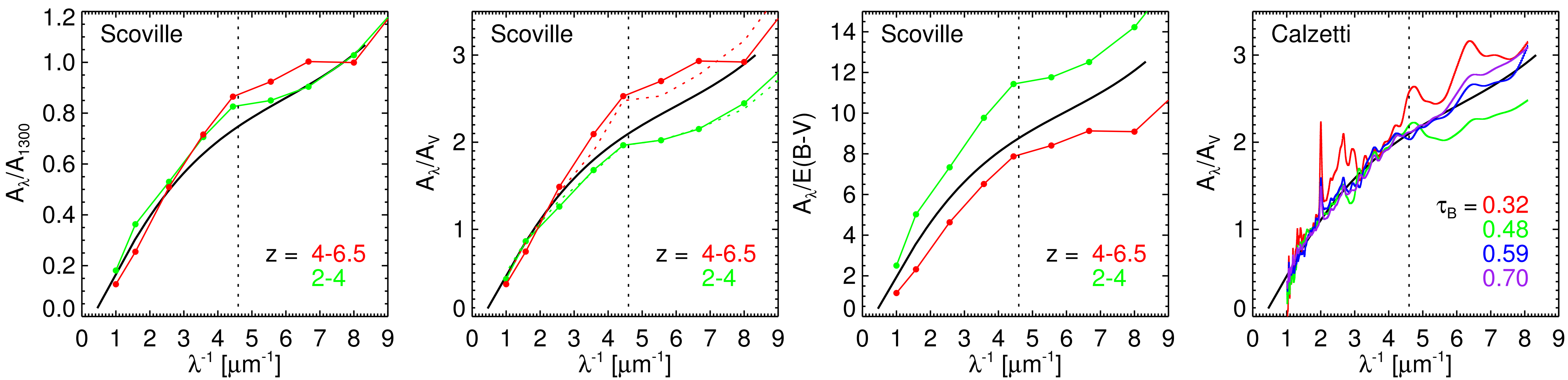


- SPEAR/FIMS observation of the diffuse FUV continuum background shows the relative redness of the scattered light.
- This result favors the Draine's MW dust (MW-WD).

“Diamonds in the Sky”

- Scoville et al. (2015) derived dust attenuation curves from a galaxy samples with z = 2-6.5 and found the 2175A bump feature.

- Their attenuation curves are quite similar to the reddening curves obtained from the Calzetti template spectra for Balmer decrement bins.



Dashed lines in the second panel are for the modified Calzetti curve.

$$(\delta, E_b) = (0.13, 0.73) \text{ for } z = 2-4$$
$$= (-0.06, 1.4) \text{ for } z = 4-6.5$$

These parameters are consistent with the KC13.