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On the reddening law observed for Type Ia Supernovae

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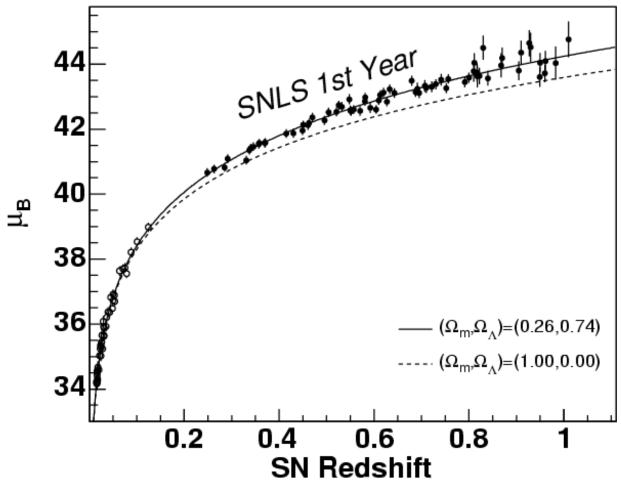
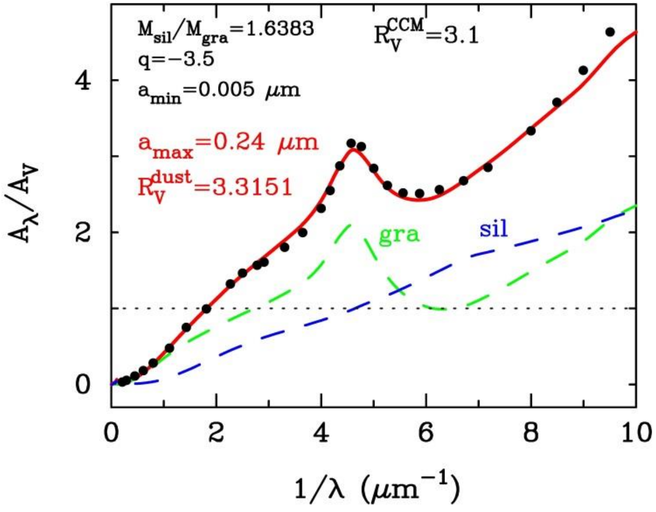




1-1. Extinction law towards Type Ia SNe

○ Type Ia supernovae (SNe Ia)

- thermonuclear explosion of a white dwarf (WD)
  - progenitor system: (WD+MS) or (WD+WD)?
- discovered in all types of galaxies
  - star-forming, elliptical, irregular, etc …
- used as cosmic standard candles

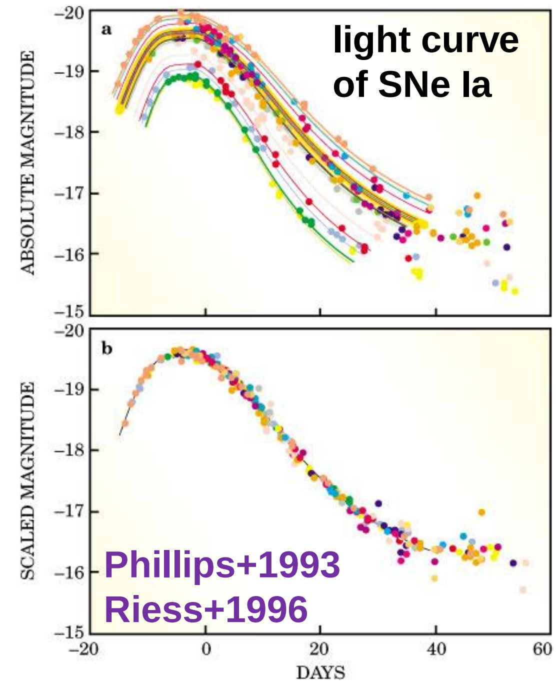
$$M_B = m_B - 5\log_{10}(D_L) - A_B - 5$$

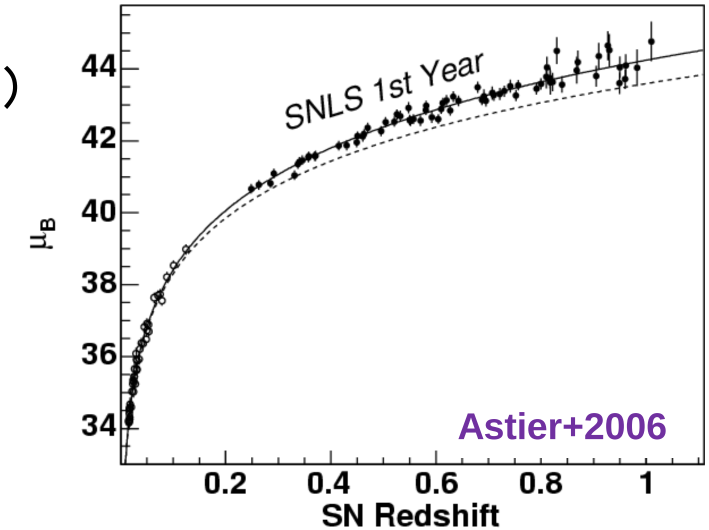
➜ $R_V = 1.0 \sim 2.5$ ($R_V = A_V/(A_B - A_V)$)

to minimize the dispersion of Hubble diagram

(e.g., Tripp+1998; Conley+2007; Phillips+2013)

cf. $R_V = 3.1$ for the average extinction curvei n the Milky-Way (MW)



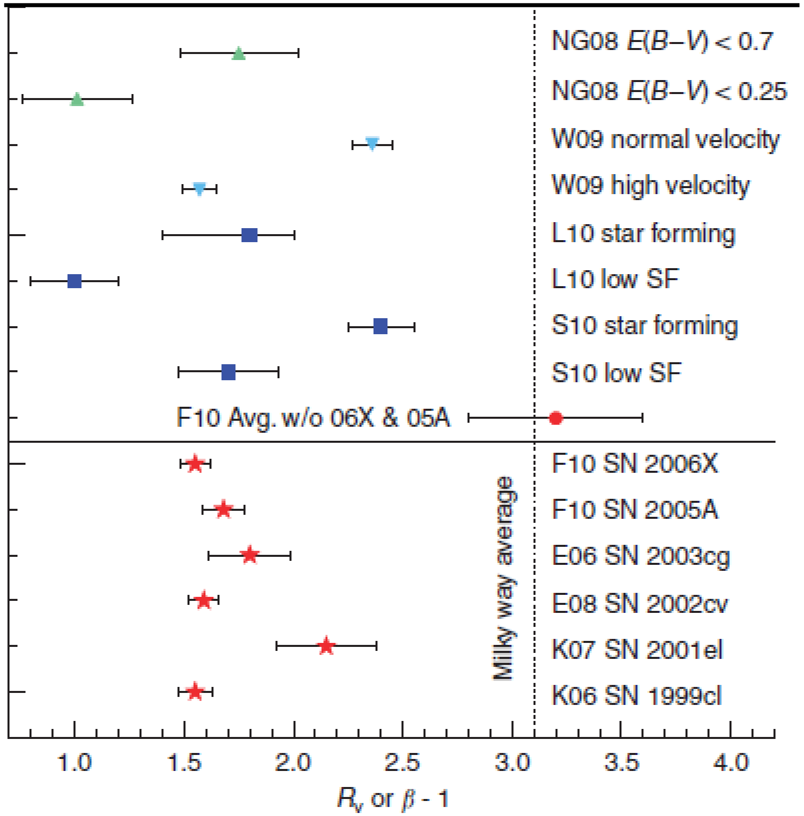


1-2. Other examples of reddening for SNe Ia

○ Other examples of Rv for SNe Ia

- average of ensembles of SNe Ia
  Rv = 1.0-2.3

- from obtained colors of SNe Ia in near-UV to near-infrared (NIR)
  Rv ~ 3.2 (Folatelli+2010)
  Rv = 1.5-2.2
  (e.g., Elisa-Rosa+2008; Kriscinuas+2007)



Howell+2011

○ Extinction in nearby galaxies

- M 31 (Andromeda Galaxy)
  Rv = 2.1-3.1 (e.g., Melchior+2000; Dong+2014)

- elliptical galaxies
  Rv = 2.0-3.5 (Patil+2007)

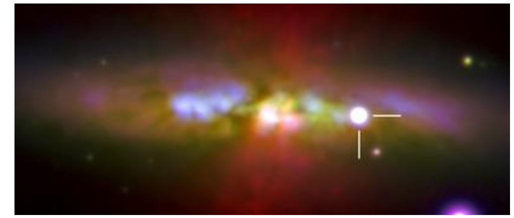
➜ **Rv is moderately low or normal**

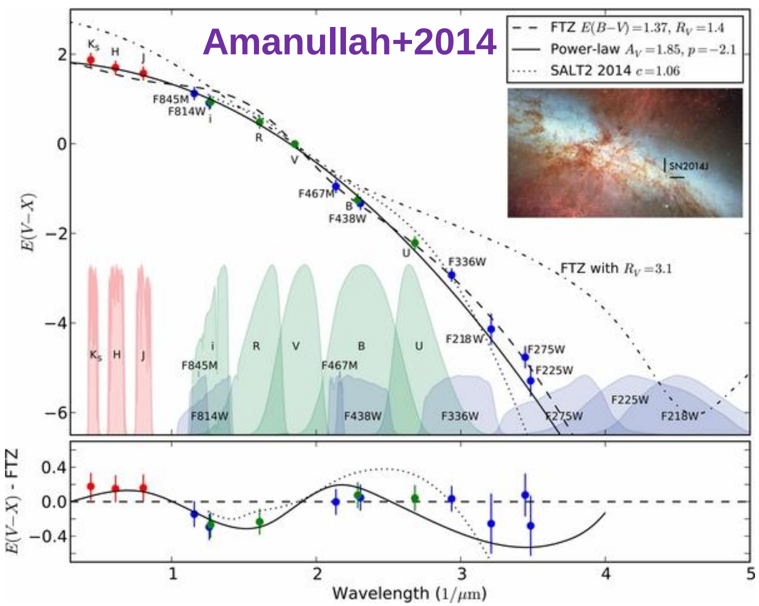
1-3. Peculiar extinction towards SN 2014J

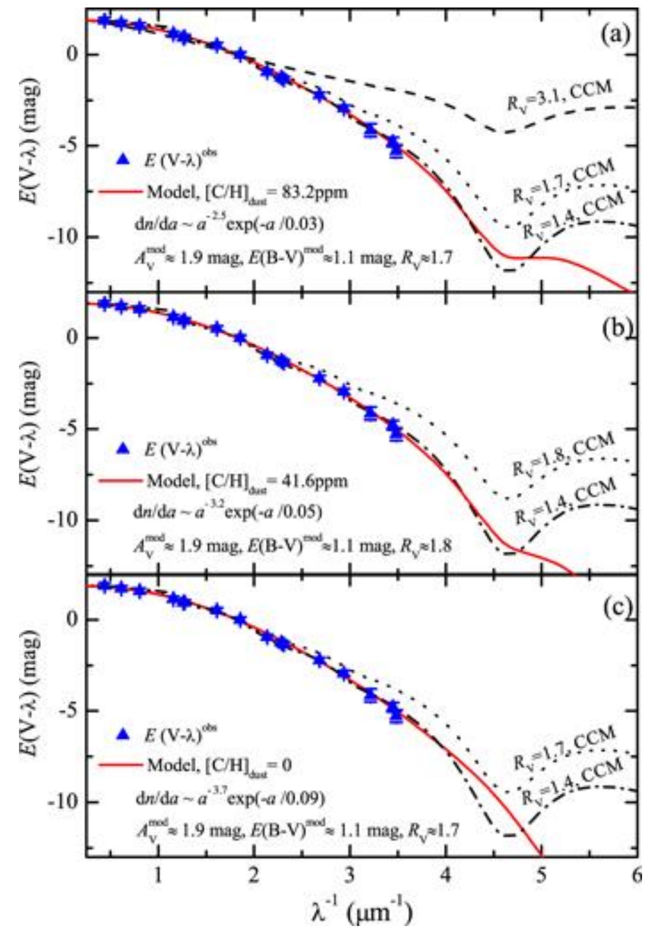
○ Type Ia SN 2014J

- discovered in M 82 (D ~ 3.5±0.3 Mpc)
  - closest SN Ia in the last thirty years
  - highly reddened (Av ~ 2.0 mag)
- reddening law is reproduced by CCM relation with **Rv ~ 1.5**

(Ammanullah+2014; Foley+2014; Gao+2015)

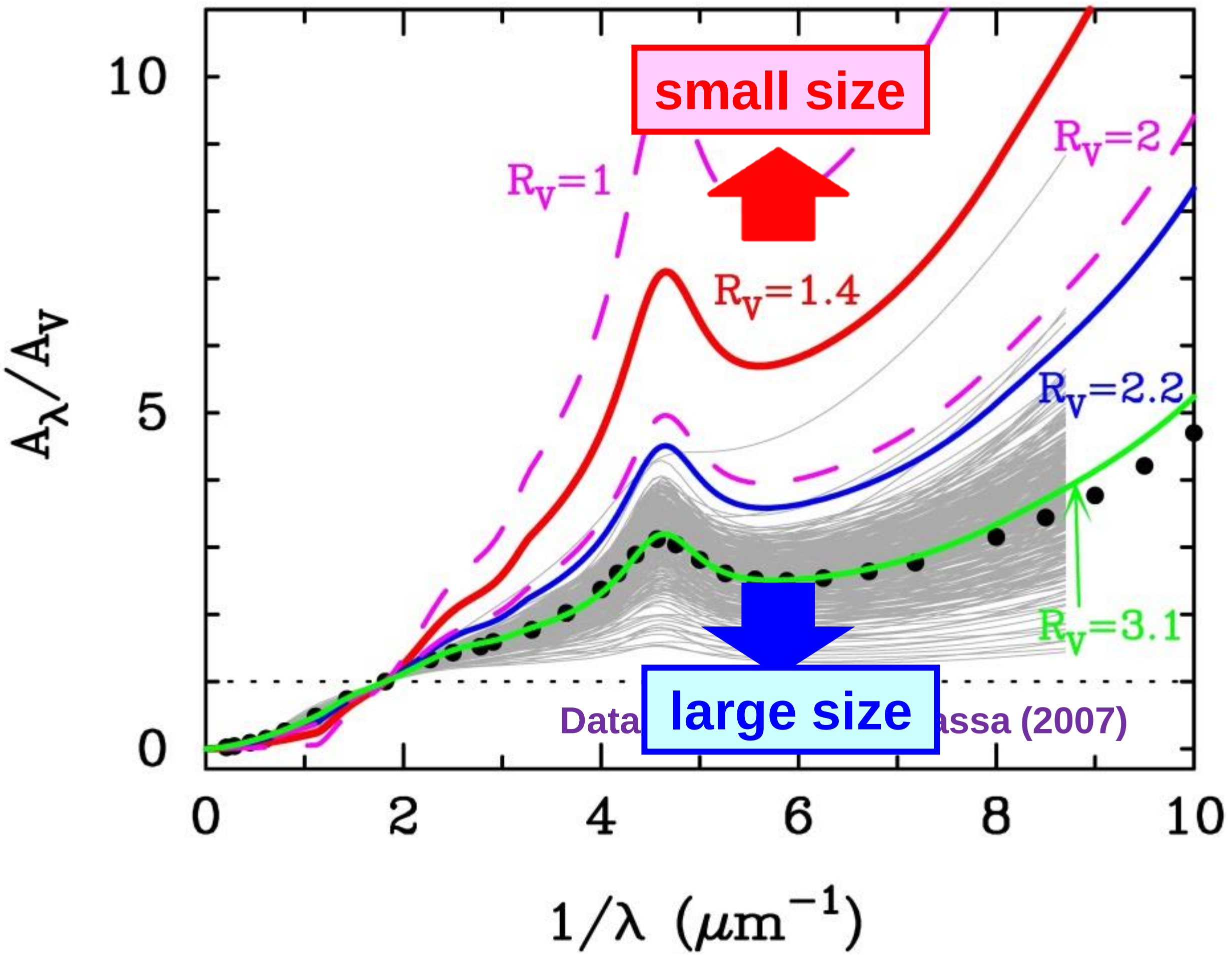






Gao+2015, Li's talk

1-4. How peculiar is SNe Ia extinction curves?



○ CCM relation

(Cardelli, Clayton, Mathis 1989)

Rv : ratio of total-to-selective extinction

$R_V = A_V / E(B - V)$
$= A_V / (A_B - A_V)$

$A_\lambda/A_V = a(x) + b(x) / R_V$
where $x = 1 / \lambda$

in our Galaxy
R_V = 2.2-5.5
$R_{V,ave}$ ~ 3.1

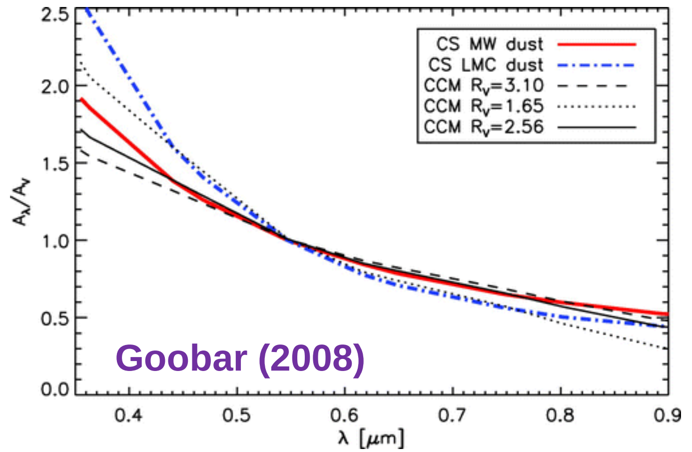
- **steeper** extinction curve (**lower** Rv) ➜ **smaller** grains
- **flatter** extinction curve (**higher** Rv) ➜ **larger** grains

2-1. Low Rv: interstellar or circumstellar origin?

○ Origin of low Rv observed for SNe Ia

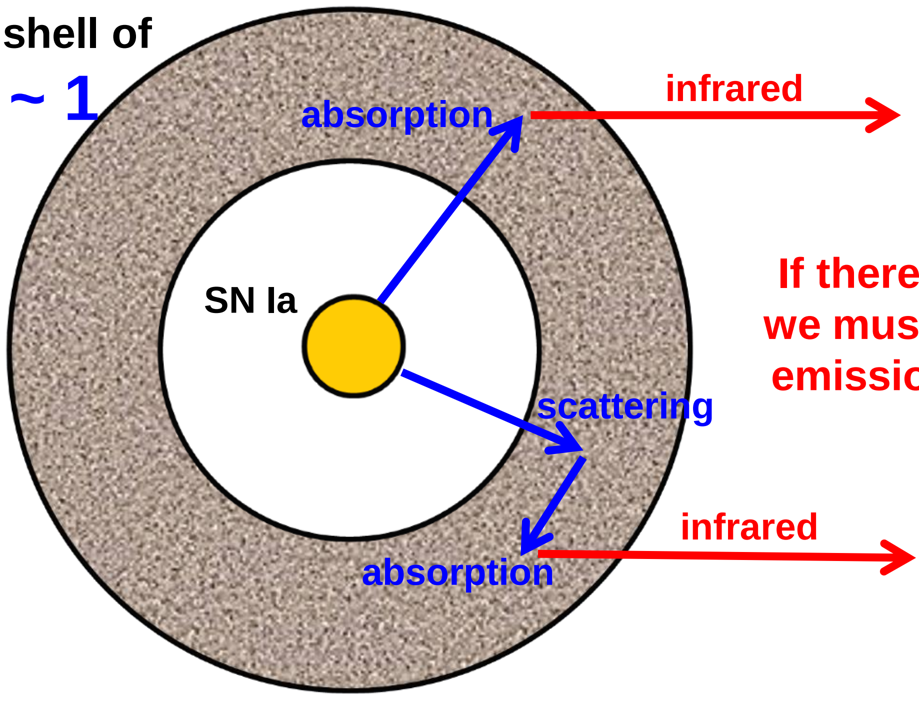
- odd properties of interstellar dust
  (e.g., Kawabata+2014; Foley+2014)

- multiple scattering by circumstellar dust
  (Wang 2005; Goobar 2008; Amanullah & Goobar 2011)



circumstellar dust shell of

$\tau_V \sim 1$



If there is a thick dust shell, we must detect thermal dust emission as infrared echoes

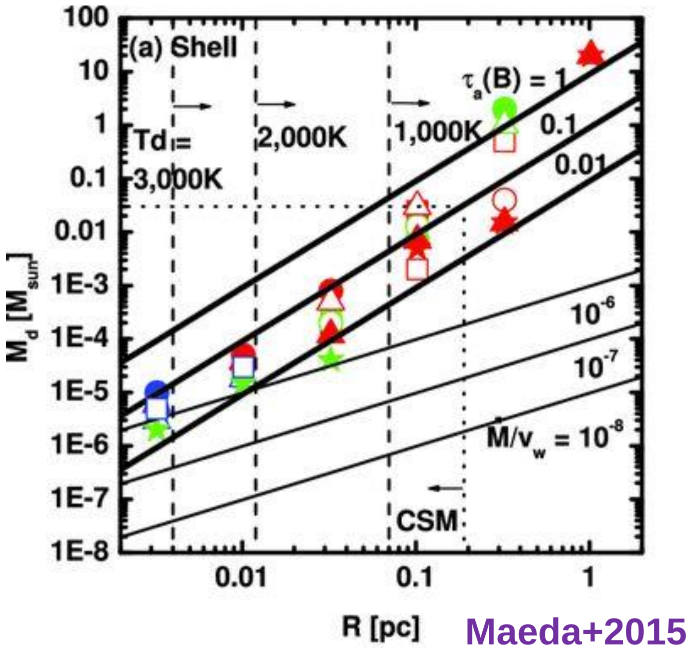
2-2. Near-infrared observations of SNe Ia

○ Near-infrared (NIR) observations

- no excess flux at *JHK* bands
- IR echo model (thin shell approximation)

  constrain the mass of dust for a given position of the dust shell (Maeda, TN+2015)

  ➜ conservative upper limits of optical depths in B band is τ_B < ~0.1



Maeda+2015

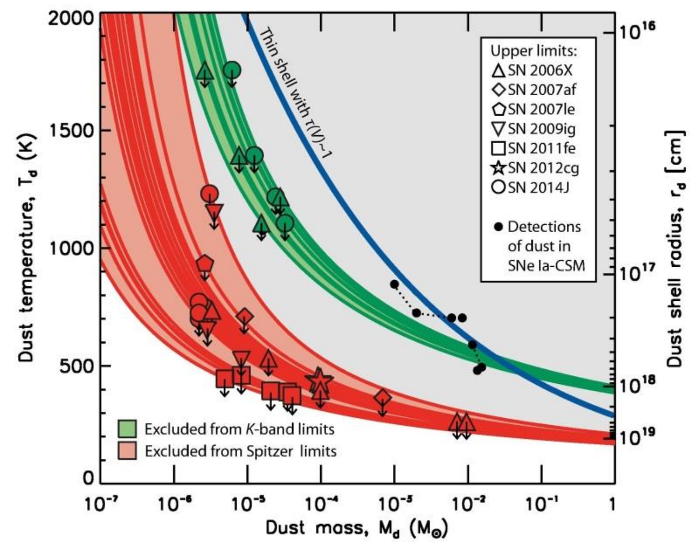
○ Spitzer observations

- no excess flux at 3.5/4.5 μm

  (Johansson+2015)

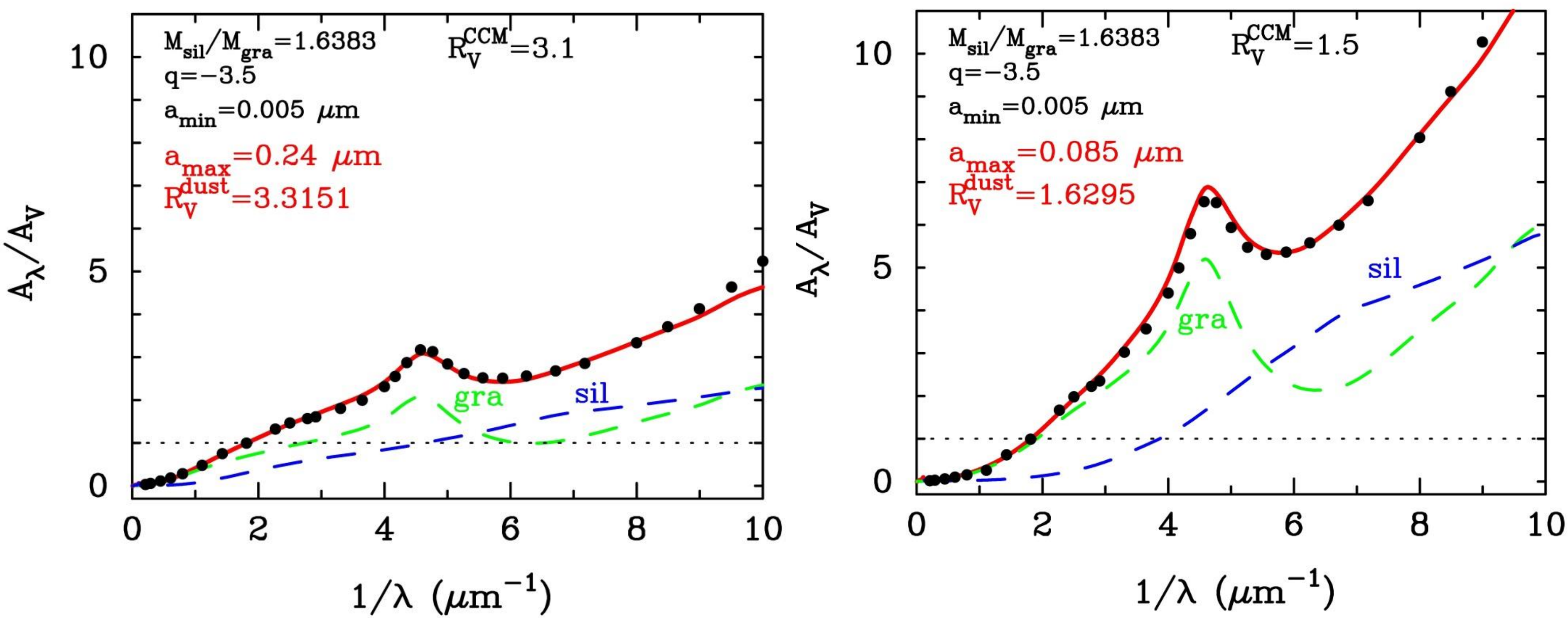
- upper limit of dust mass: ~10^{-4} Msun

  ➜ optical depth τ << 1



Johansson+2015

3-1. Dust model for Rv = 1.5 CCM curve



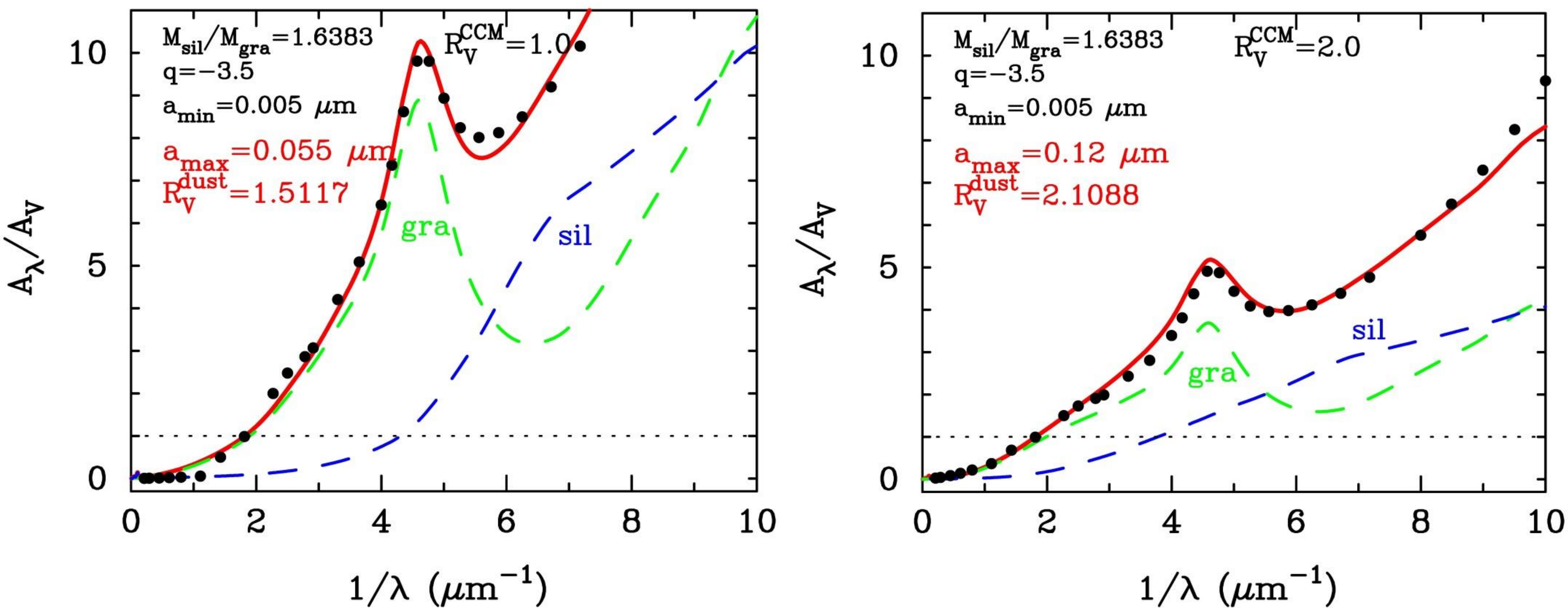
○ MRN dust model (Mathis, Rumpl, & Nordsieck 1977)

- dust composition : silicate ($MgFeSiO_4$) & graphite (C)
- size distribution : power-law distribution

  $n(a) \propto a^{-q}$ with q=3.5, a_{max} = 0.25 μm, a_{min} = 0.005 μm

Rv = 1.5 curve ➜ a_{max} = 0.085 μm, a_{min} = 0.005 μm

3-2. Dust models for Rv = 1.0 and 2.0 curve



Rv = 1.0 curve ➜ a_{max} = 0.055 μm, a_{min} = 0.005 μm

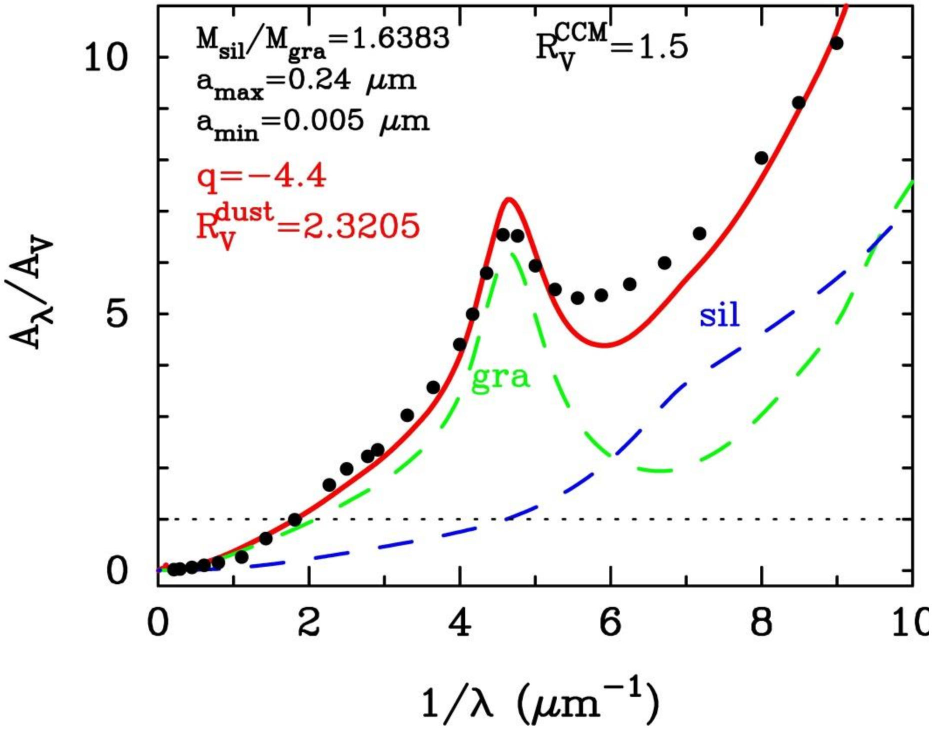
Rv = 2.0 curve ➜ a_{max} = 0.12 μm, a_{min} = 0.005 μm

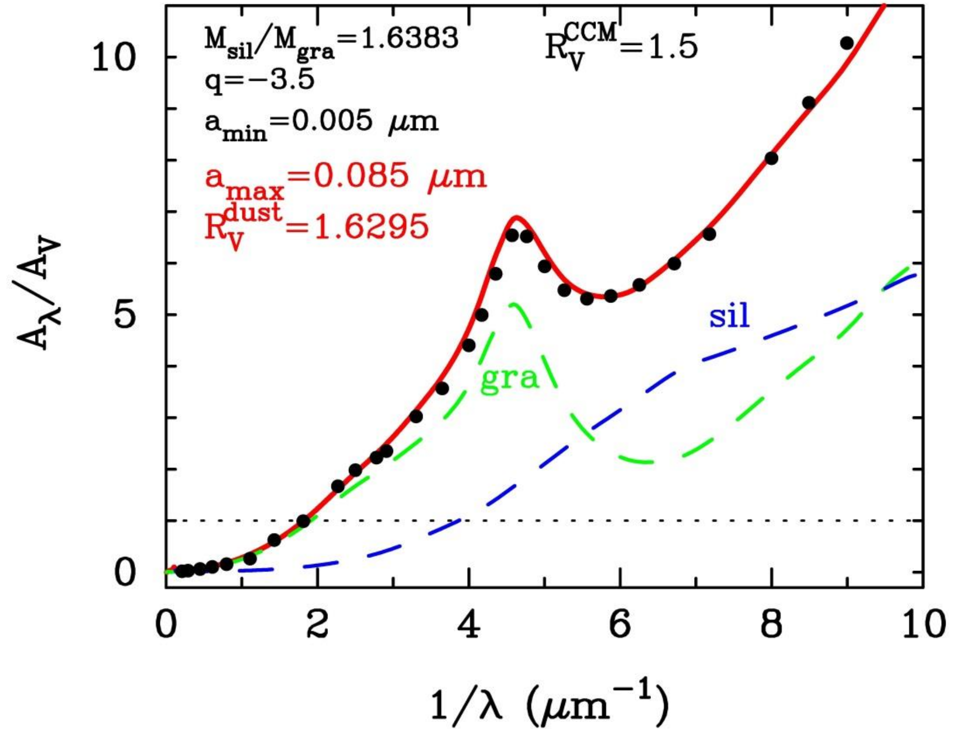
But, the values of Rv obtained from the MRN dust model are higher than Rv used for the CCM relation

$R_{V,CCM}$ = 1.0 curve ➜ $R_{V,\,dust}$ = 1.5

$R_{V,CCM}$ = 2.0 curve ➜ $R_{V,\,dust}$ = 2.1

3-4. Dependence on the power-law index





- Decreasing the power-law index (steeper size distribution) does not fit the CCM curve with a low Rv very well

  ➜ leading to a remarkable 2175A-bump and UV-dip

  ➜ quite high Rv values obtained from the MRN dust model, compared to the Rv used for the CCM relation

5. Summary of this talk

1) Many studies (mainly SNe Ia cosmology) suggest that the Rv values towards SNe Ia are very low (Rv ~ 1-2.5), compared with Rv = 3.1 in our Galaxy

2) Non-detection of IR echoes towards SNe Ia indicates that the low Rv is not due to the circumstellar dust but due to the interstellar dust in the host galaxies

3) The CCM curves with Rv = 1-2 can be reasonably fitted by the MRN dust model (graphite/astronomical silicate) with a_{max} = 0.05-0.15 μm (instead of a_{max} = 0.24 μm for Rv = 3.1)