2012/11/30

減光曲線から探る星間ダストの多様性
(Variation of interstellar dust probed by extinction curves)

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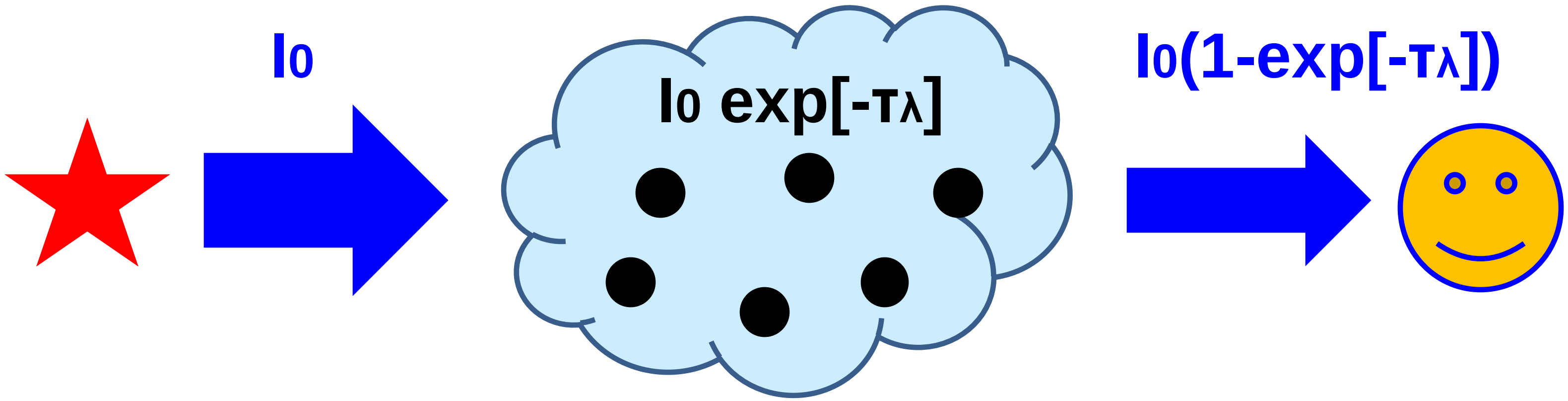
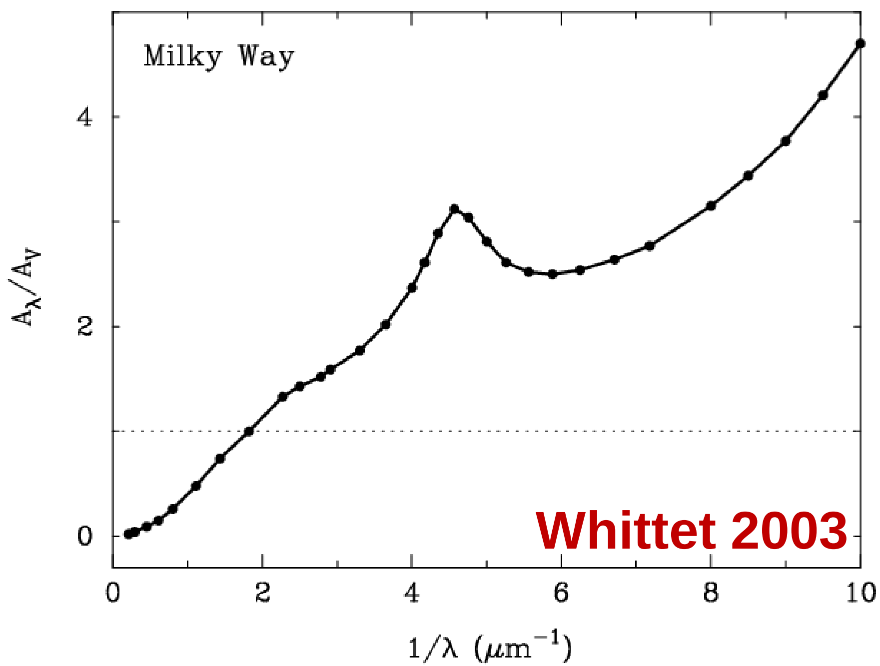
1. Extinction curve



Extinction curve: wavelength-dependence of extinction caused by interstellar dust grains

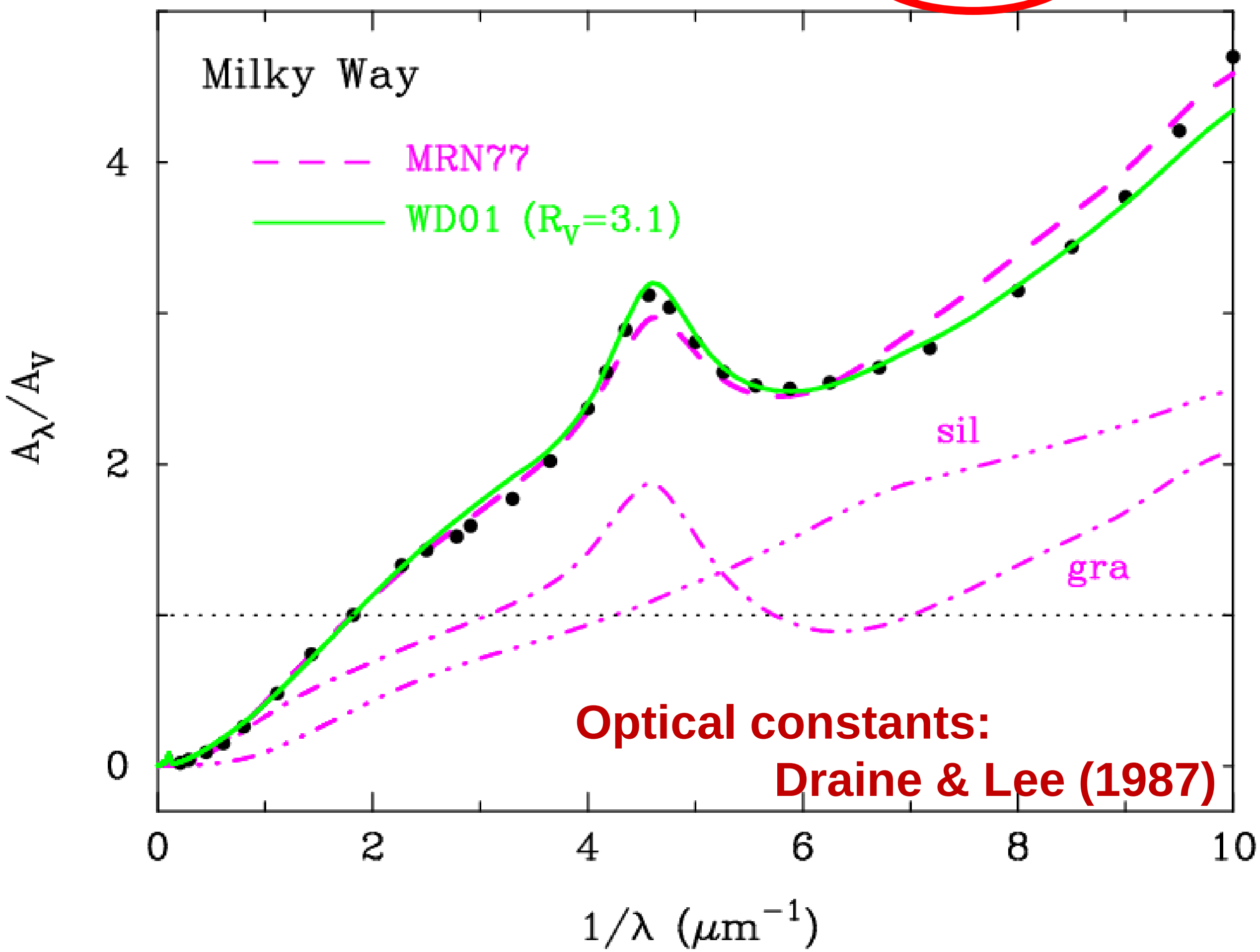


- **essential for knowing the intrinsic SEDs of galaxies**

- **depends on physical and optical properties of dust**

2. Interstellar dust models in MW

○ **MRN dust model** (Mathis, Rumpl & Nordsieck 1977)
- dust composition : graphite & silicate ($Mg_{1.1}Fe_{0.9}SiO_4$)
- size distribution : power-law distribution
  $n(a)da \propto a^{-q}da$ with $q = 3.5$, $0.005\ \mu m \leq a \leq 0.25\ \mu m$



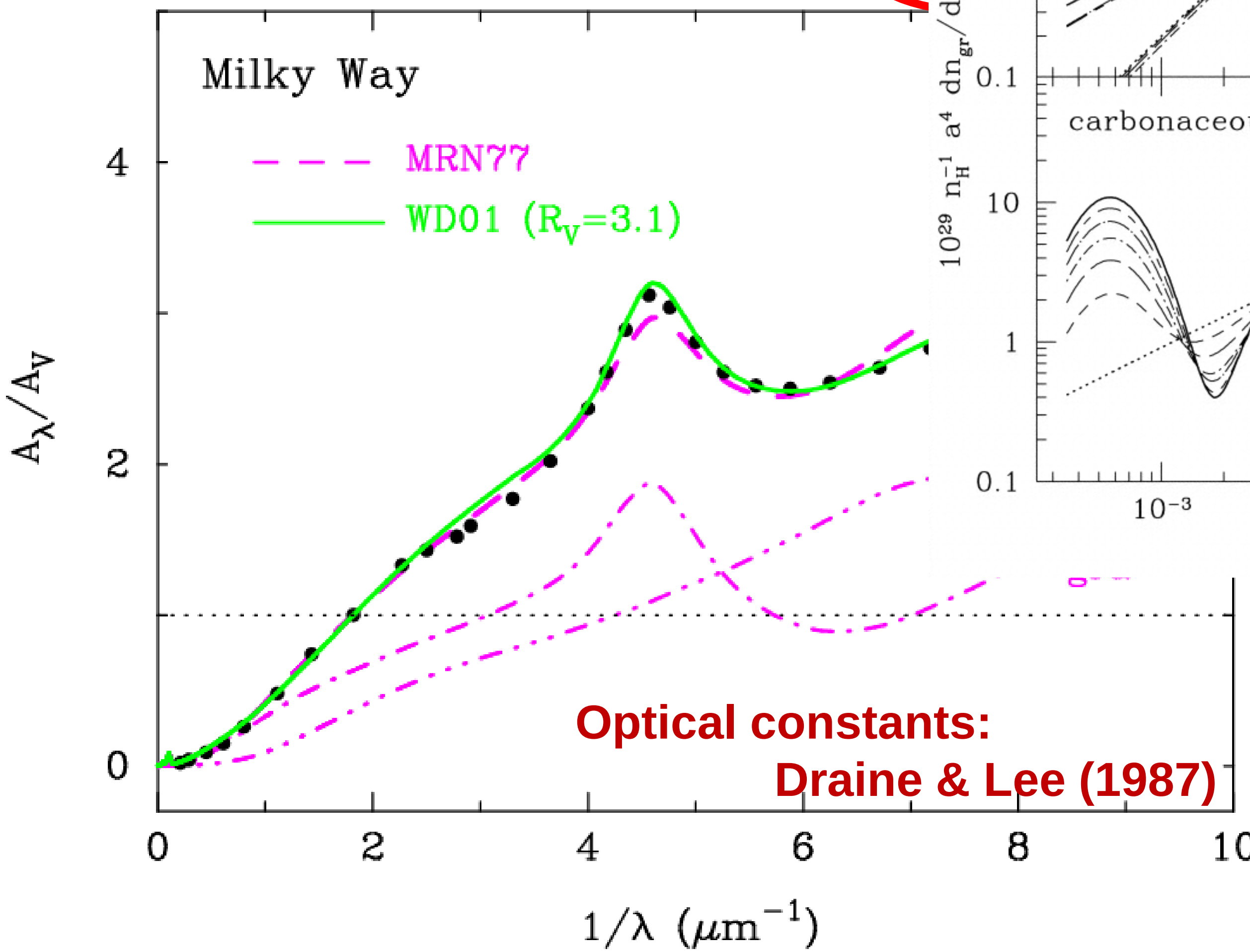
○ **WD01 model**
(Weingartner & Draine 2001)
- dust composition : silicate + graphite + PAHs
- size distribution : power-law with exponential decay + lognormal
  $0.3\ nm \leq a \leq 1\ \mu m$

2. Interstellar dust models in MW

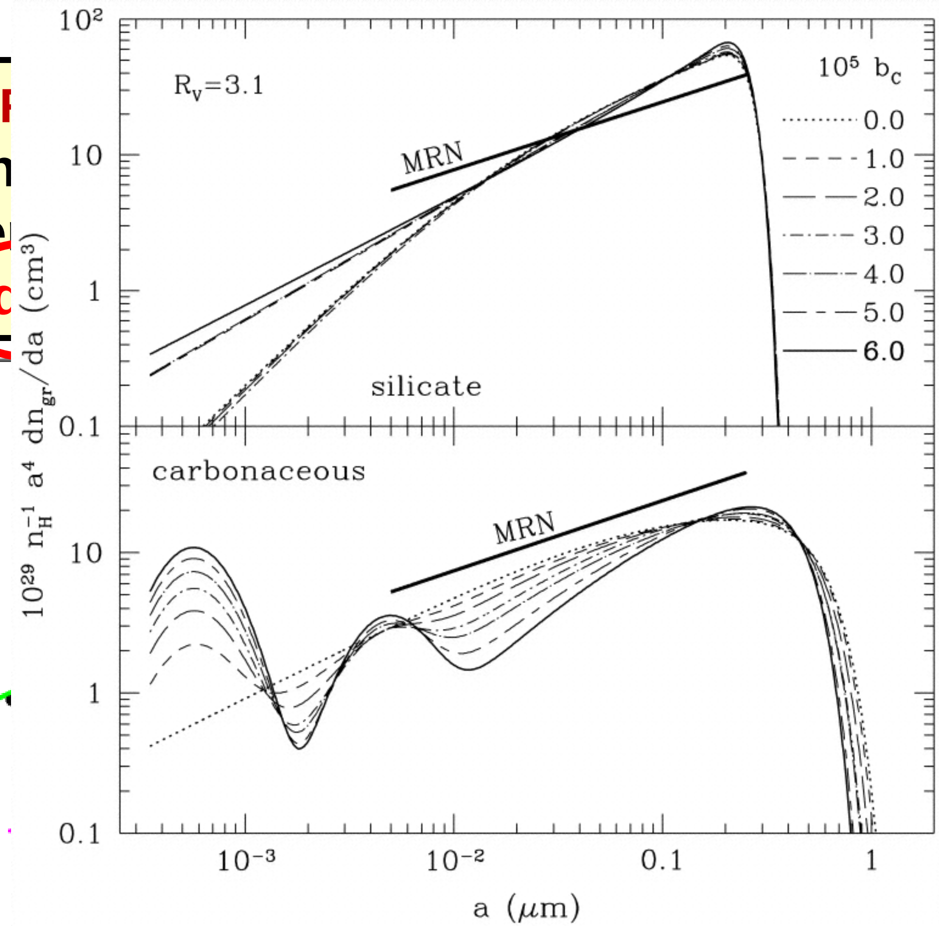
○ MRN dust model (Mathis, R

- dust composition : graph
- size distribution : powe

  n(a)da ∝ a^{-q}da with q



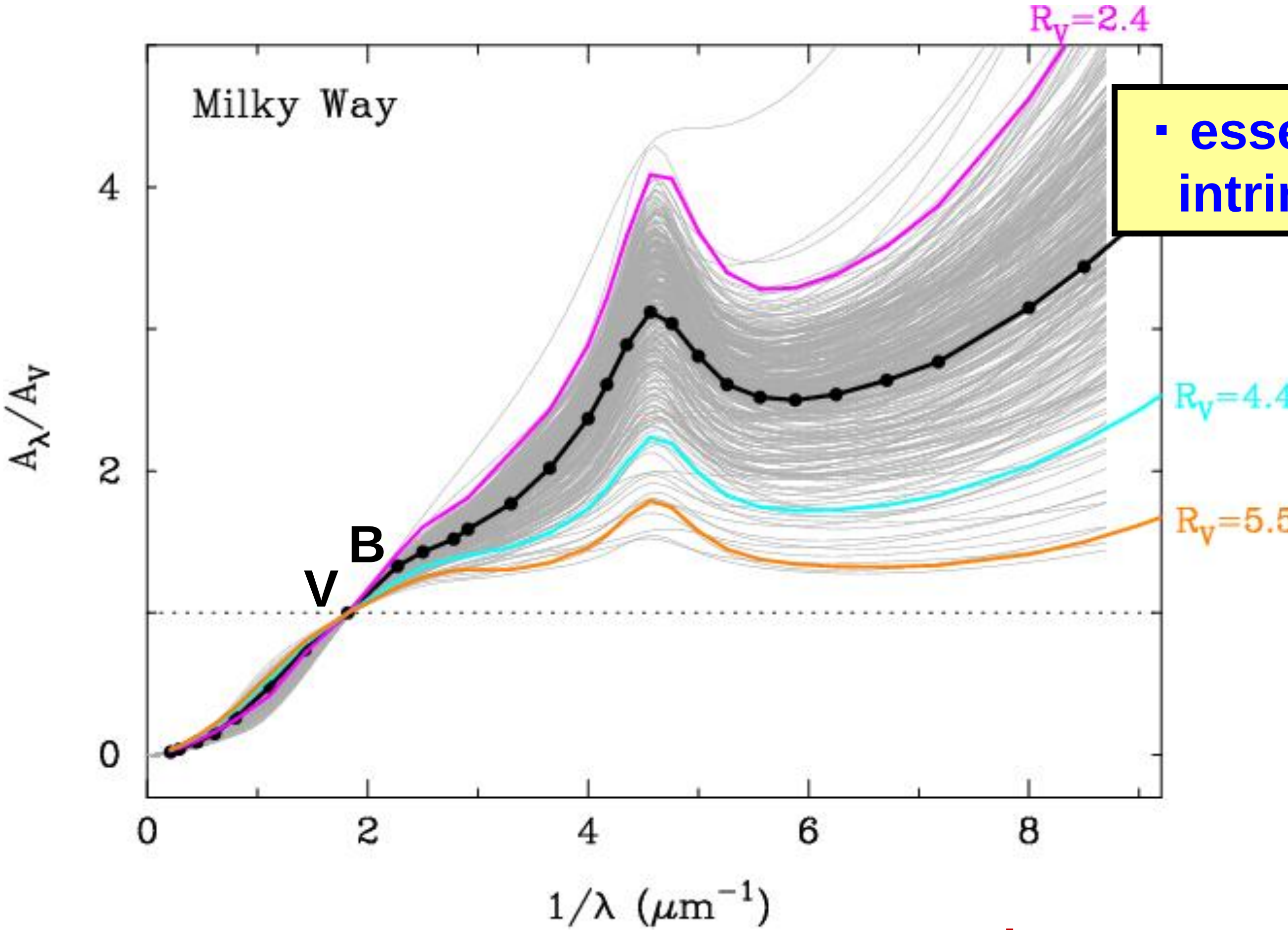
Optical constants:
Draine & Lee (1987)



- size distribution : power-law with exponential decay + lognormal

  0.3 nm ≤ a ≤ 1 μm

3. CCM relationship and R_V



- **essential for knowing the intrinsic SEDs of galaxies**

…ends on physical and …al properties of dust

…assa (2007)

○ **CCM relation** (Cardelli, Clayton, & Mathis 1989)

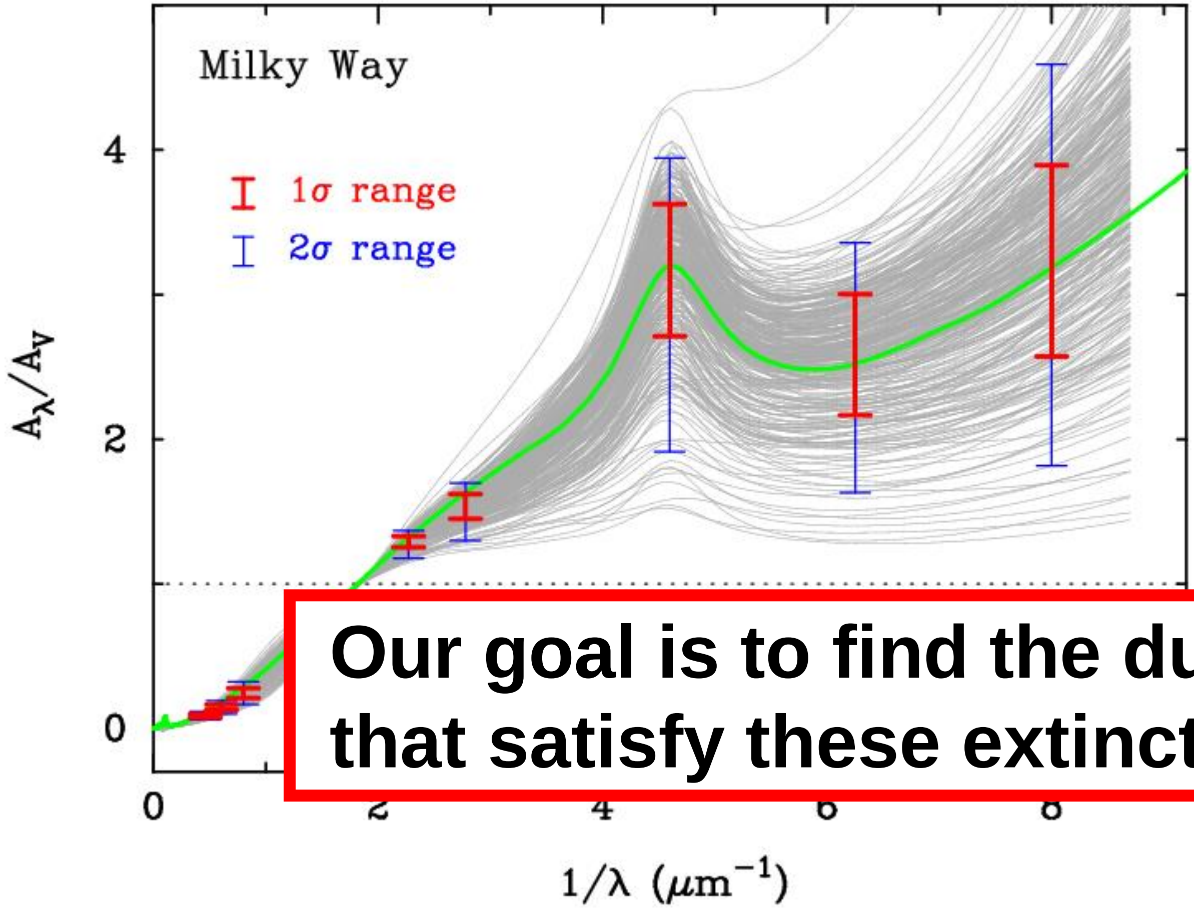
- $A_\lambda / A_V = a(x) + b(x) / R_V$, where $x = 1 / \lambda$
- R_V : ratio of total-to-selective extinction

  $R_V = A_V / (A_B - A_V) = 1 / (A_B/A_V - 1)$ cf. $R_{V,ave} = 3.05–3.10$

4. Variety of interstellar extinction curves

- There are a large variety of interstellar extinction curves

- **How much can the properties of dust grains be changed?**



gray curves:
328 extinction curves derived by **Fitzpatrick & Massa (2007, FM07)**

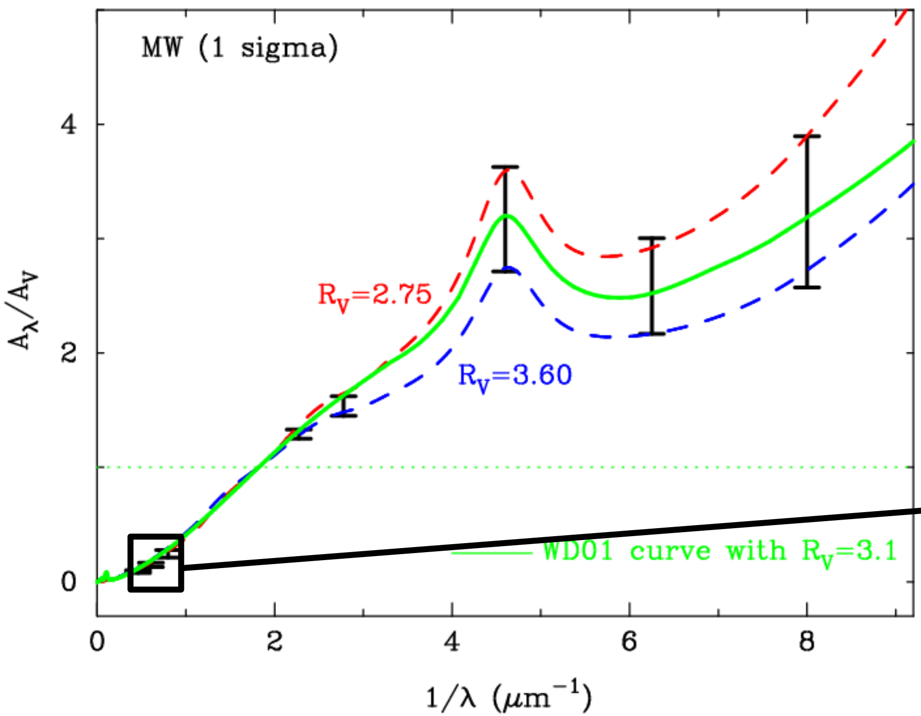
red bars:
1σ ranges including 224 data

ling
312 data

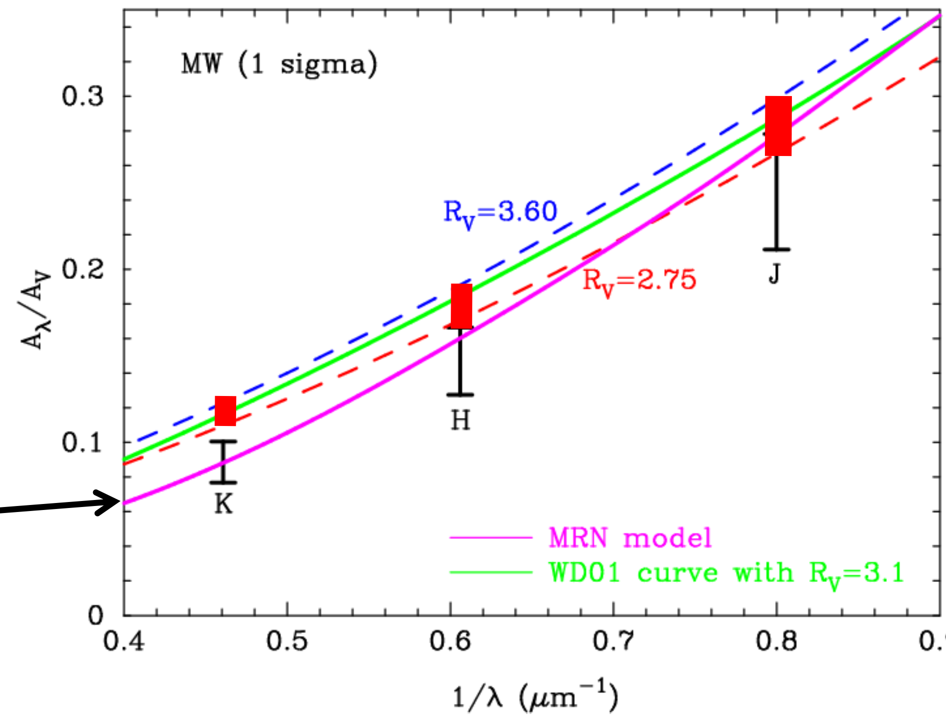
Our goal is to find the dust properties that satisfy these extinction ranges

5. Comparison between FM07 and CCM89

UV-through-IR extinction curves



Close-up of IR extinction curves



black: 1σ range of the FM07 data
red: CCM curve with Rv = 2.75
blue: CCM curve with Rv = 3.60
green: extinction curve for the case of Rv=3.1 by WD01
fully consistent in UV region

Results from CCM formula with Rv = 2.75-3.60 are 0.02-0.06 mag higher than the 1σ range in JHK
WD01 model is based on result by Fitzpatrick (1999), which is similar to CCM curve w/ Rv=3.1

6. Dust model

$$A_\lambda = 1.086 \sum_j \int dl \int_{a_{\min,j}}^{a_{\max,j}} \pi a^2 Q_{\lambda,j}^{\rm ext}(a) n_j(a) da,$$

(spherical grain)

- **power-law size distribution ($a_{min} < a < a_{max}$)**

$$n_j(a) = n_{\rm H} K_j a^{-q_j},$$

$$K_j = \frac{f_{i,j}}{V_j} \left(\frac{A_i w_j m_{\rm H}}{\nu_{i,j} \delta_j} \right),$$

a_{min} = 0.005 um (fixed)

q and a_{max} : parameters (same for all grain species)

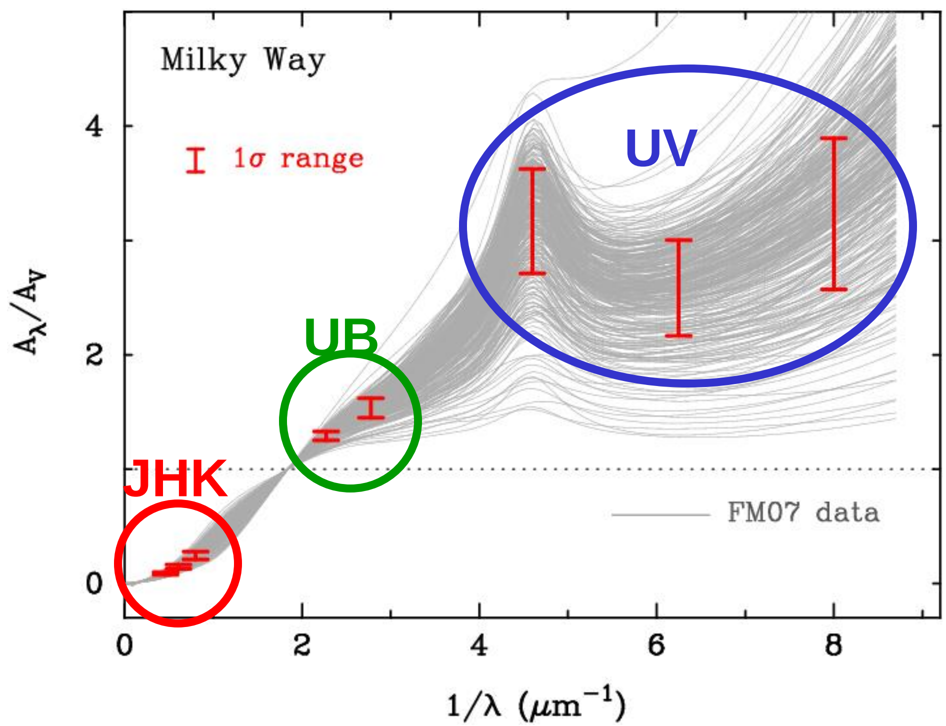
$f_{i,j}$ ➔ a fraction of an element *i* locked up in a grain *j*

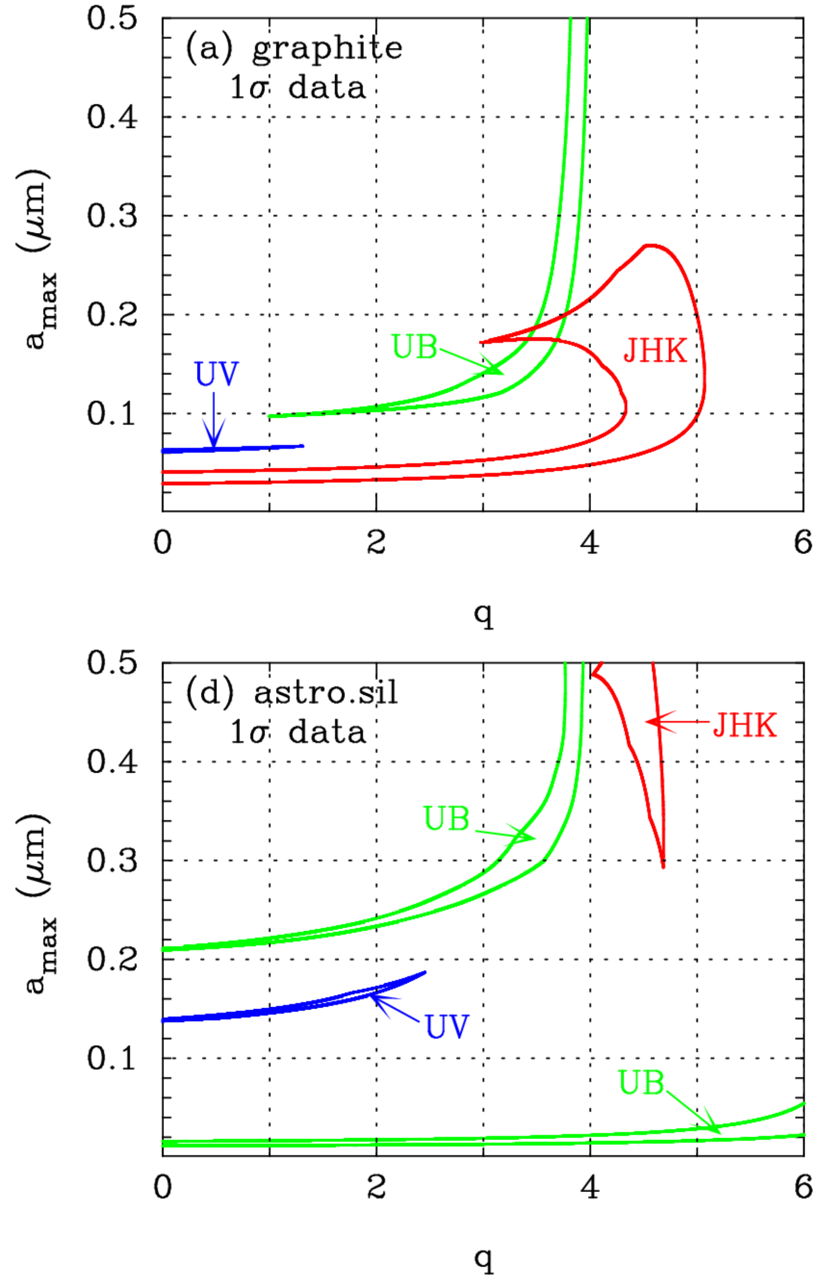
Solar abundance: Grevesse & Sauval (1998)
all of Fe (and Mg and Si) are locked in dust grains

- **grain species considered in this paper**
  - **graphite, glassy carbon, amorphous carbon, SiC**
  - **astronomical silicate ($MgFeSiO_4$), Mg_2SiO_4**
  - **Fe, Fe_3O_4, FeS**

7. Illustration of contour plots

1σ range of FM07 data





The 1σ ranges from FM07 data are classified into three groups

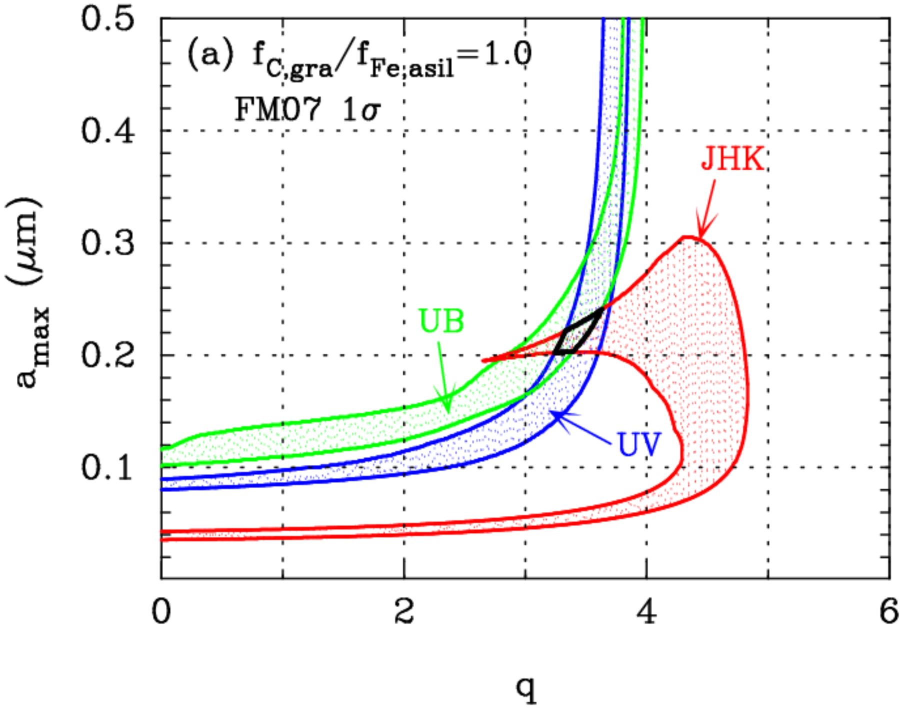
UV: UV bump (0.22 μm), FUV dip (0.16 μm), FUV rise (0.125 μm)

UB: U band and B band

JHK: J band, H band, K band

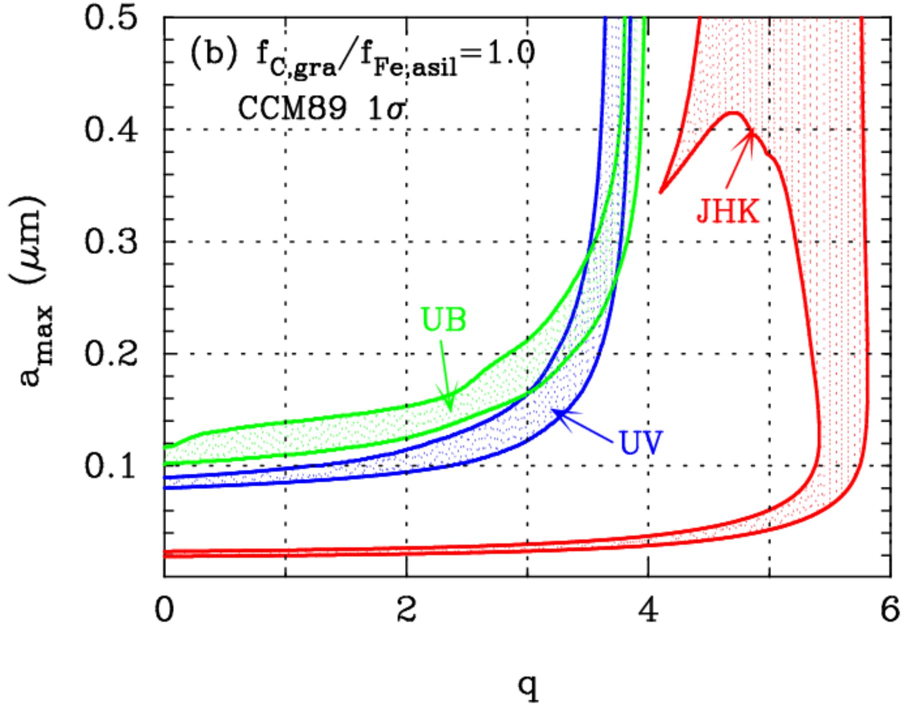
7-1. Contour plots for f_{gra}/f_{sil} = 1.0

Case of 1σ data, f_{gra}/f_{sil} = 1.0



contour plots of a_{max} and q that fulfill the 1σ range of FM07 data for f_{gra}/f_{sil} = 1.0 (M_{gra}/M_{sil} = 0.78)
blue: constraint from UV/FUV
green: constraint from UB band
red: constraint from JHK band

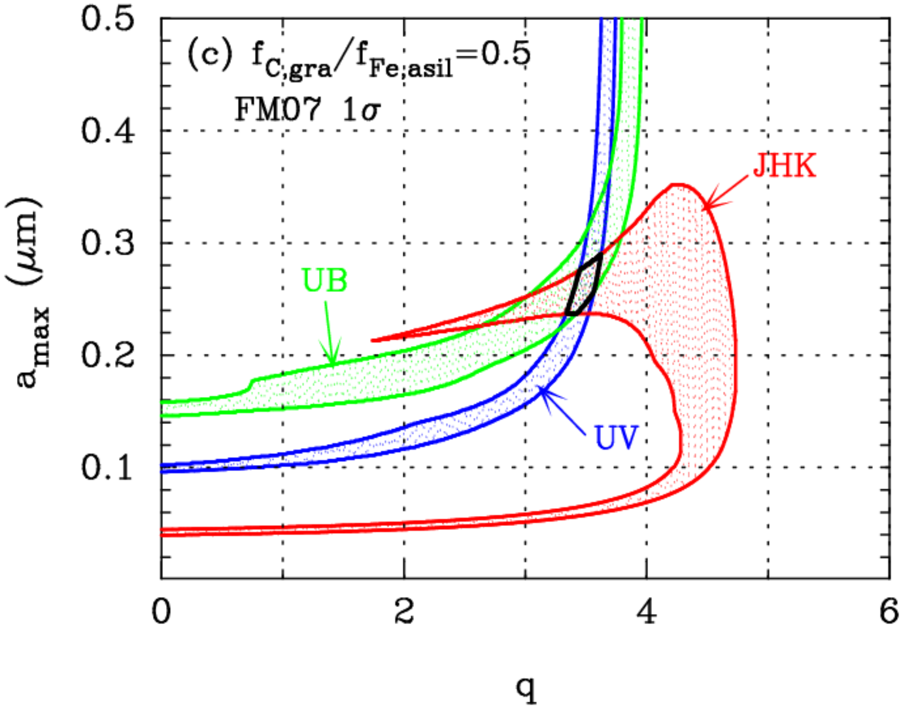
Case of 1σ data, f_{gra}/f_{sil} = 1.0



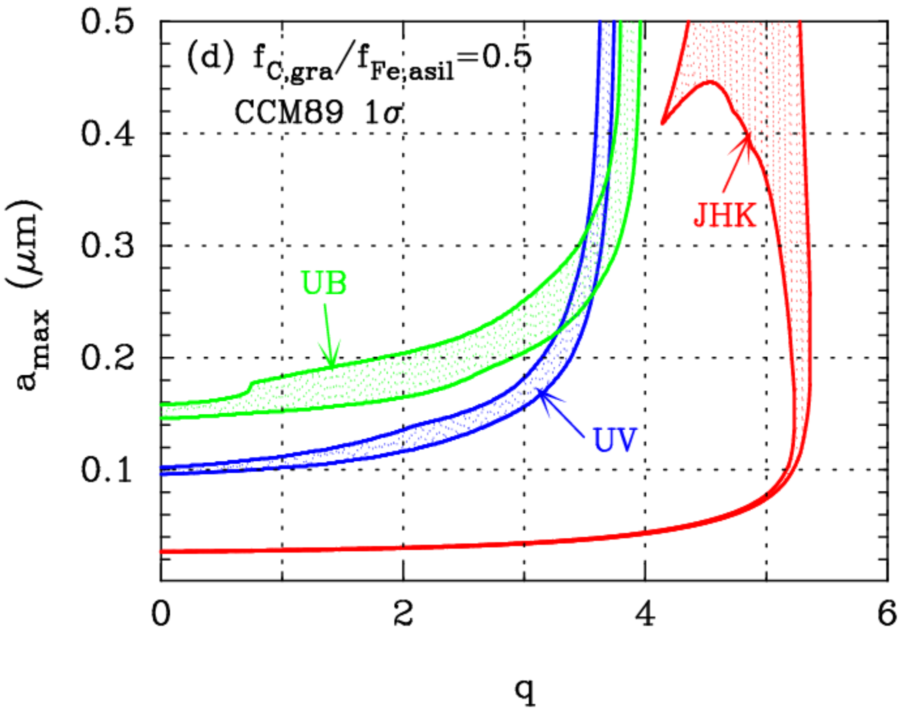
contour plots of a_{max} and q that fulfill the 1σ range of CCM result for f_{gra}/f_{sil} = 1.0 (M_{gra}/M_{sil} = 0.78)
blue: constraint from UV/FUV
green: constraint from UB band
red: constraint from JHK band

7-2. Contour plots for f_{gra}/f_{sil} = 0.5

Case of 1σ data, f_{gra}/f_{sil} = 0.5



Case of 1σ data, f_{gra}/f_{sil} = 0.5

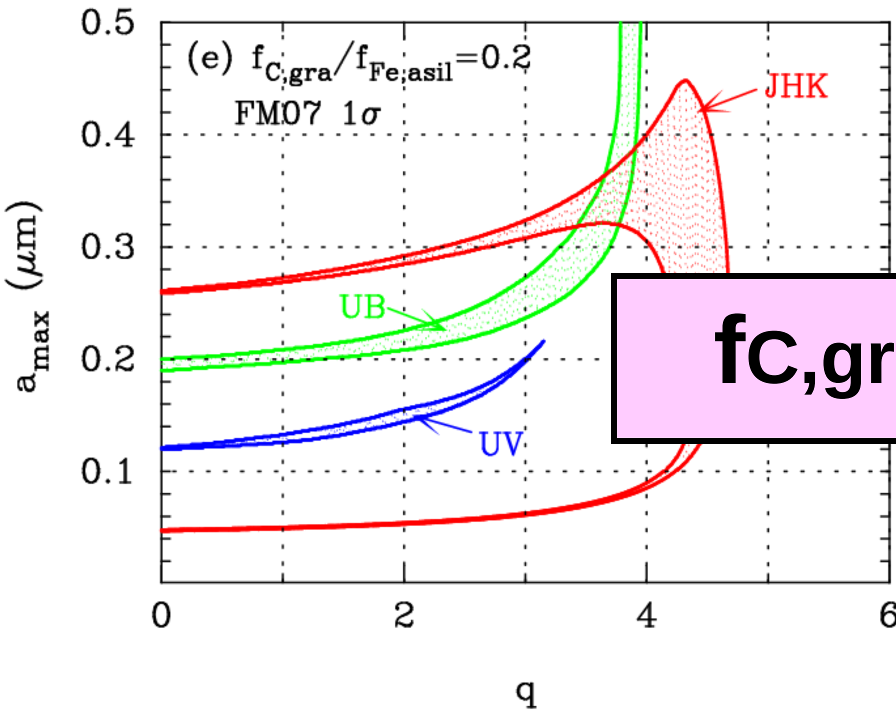


contour plots of a_{max} and q that fulfill the 1σ range of FM07 data for f_{gra}/f_{sil} = 0.5 (M_{gra}/M_{sil} = 0.39)
blue: constraint from UV/FUV
green: constraint from UB band
red: constraint from JHK band

contour plots of a_{max} and q that fulfill the 1σ range of CCM result for f_{gra}/f_{sil} = 0.5 (M_{gra}/M_{sil} = 0.39)
blue: constraint from UV/FUV
green: constraint from UB band
red: constraint from JHK band

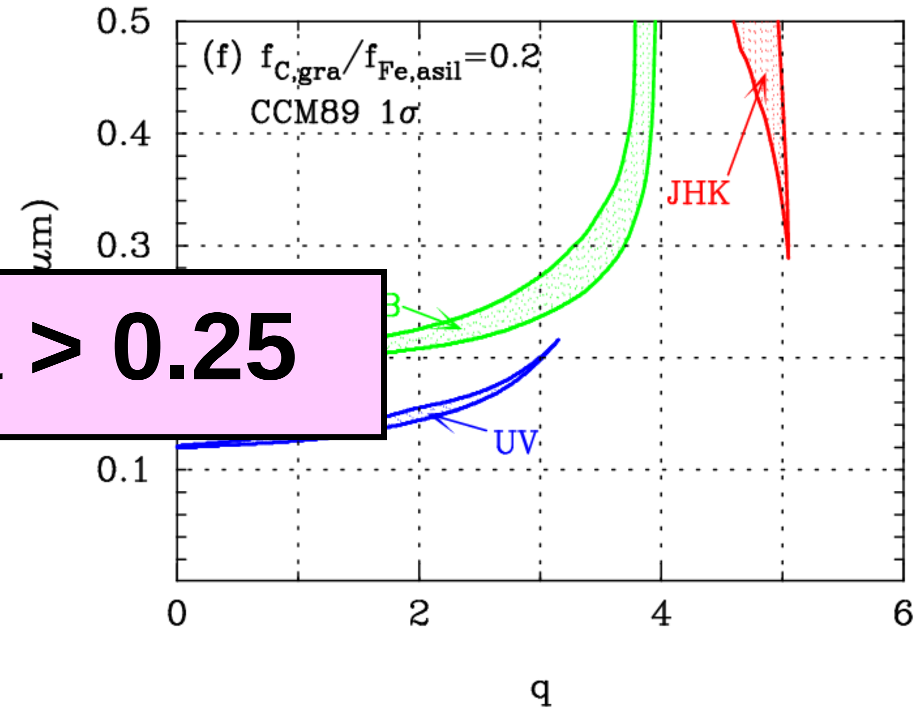
7-3. Contour plots for f_{gra}/f_{sil} = 0.2

Case of 1σ data, f_{gra}/f_{sil} = 0.2



$f_{C,gra}$ > 0.25

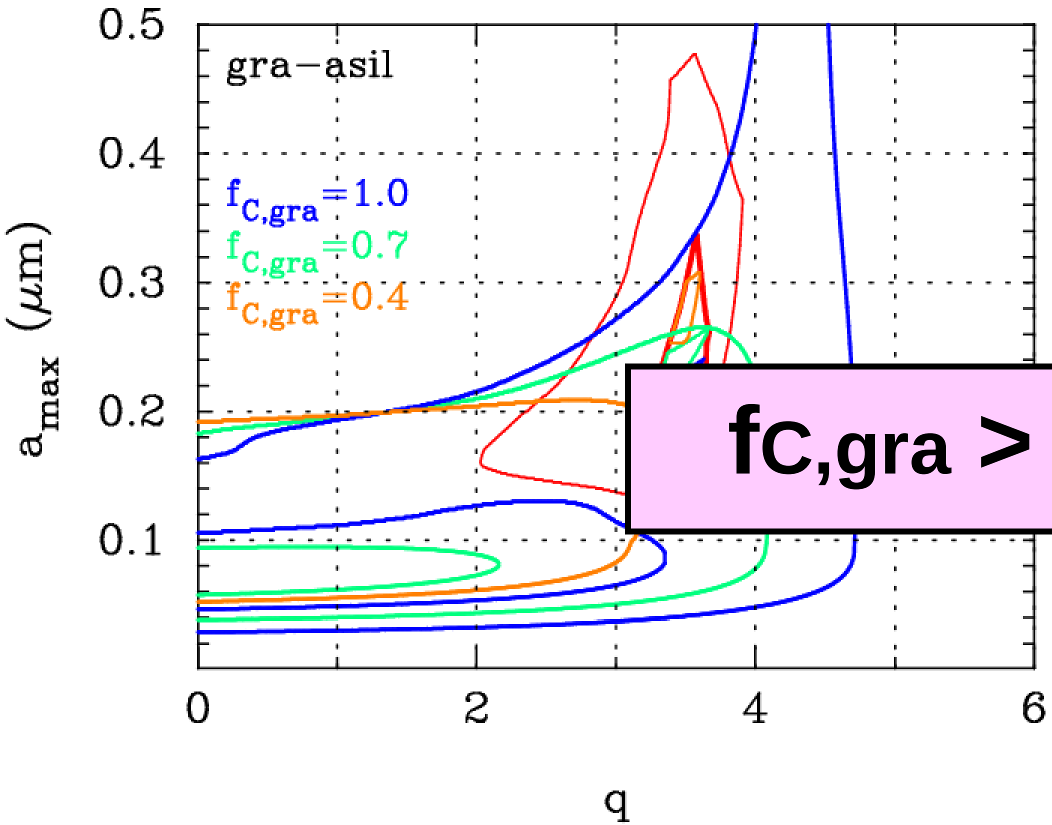
Case of 1σ data, f_{gra}/f_{sil} = 0.2



contour plots of a_{max} and q that fulfill the 1σ range of FM07 data for f_{gra}/f_{sil} = 0.2 (M_{gra}/M_{sil} = 0.16)
blue: constraint from UV/FUV
green: constraint from UB band
red: constraint from JHK band

contour plots of a_{max} and q that fulfill the 1σ range of CCM result for f_{gra}/f_{sil} = 0.2 (M_{gra}/M_{sil} = 0.16)
blue: constraint from UV/FUV
green: constraint from UB band
red: constraint from JHK band

8-1. Piled-up contour for graphite-astro.sil



$f_{C,gra} > 0.56$

In this study,
$N_H/E(B-V)$ =
$(5.7\pm1.7)\times10^{21}$ cm³/mag
(Gudennavar et al. 2012)

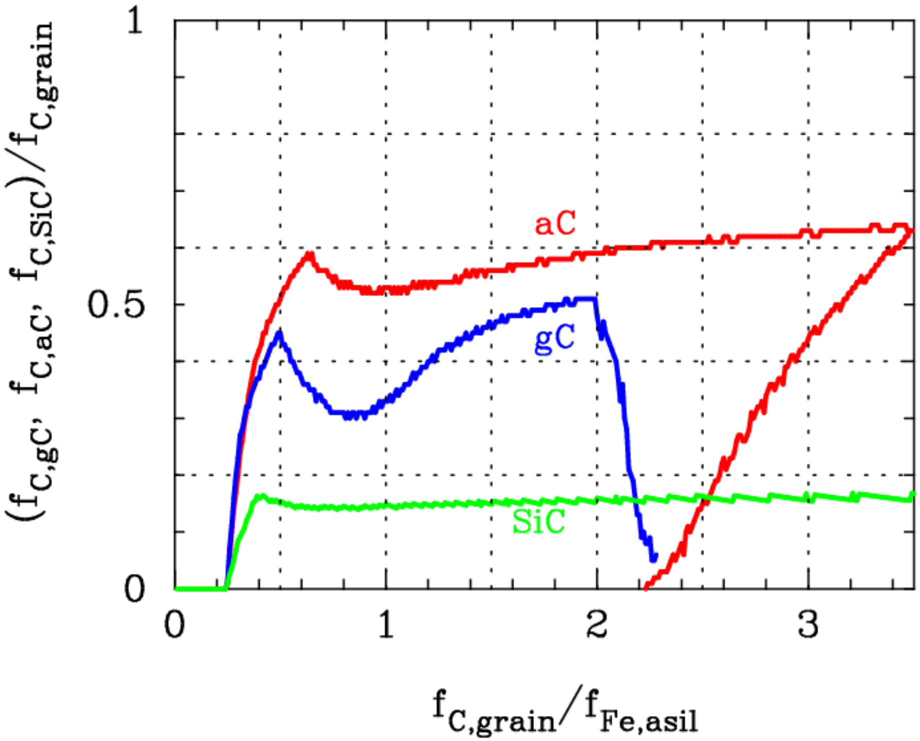
In previous studies,
$N_H/E(B-V) = N_H/(A_B-A_V)$
= 5.8×10^{21} cm³/mag
(Bohlin et al. 1978)

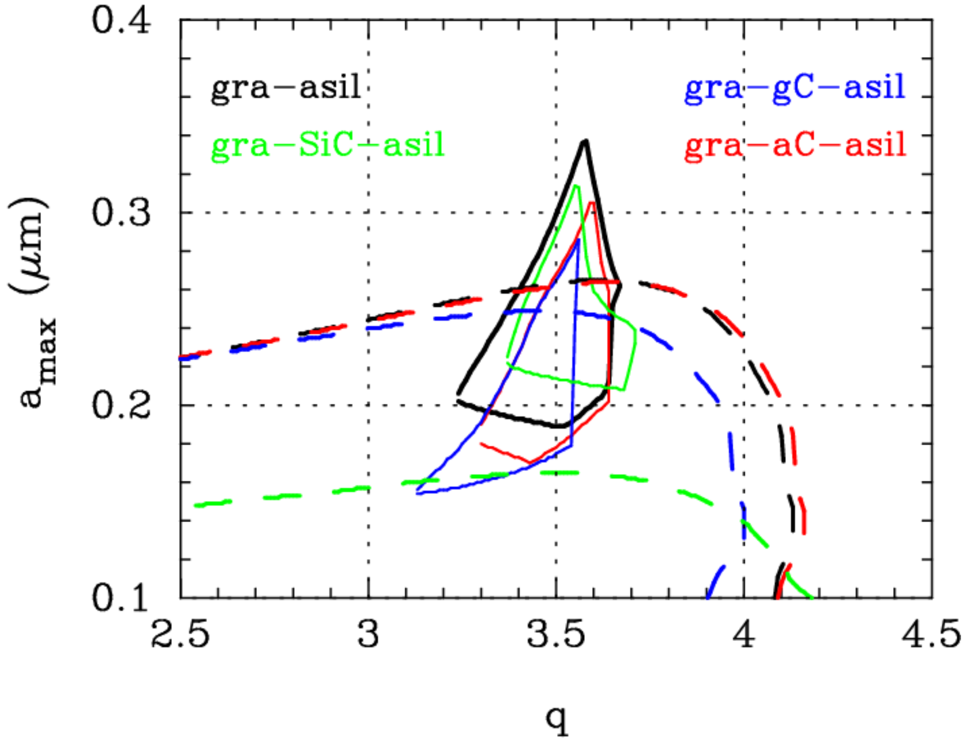
Values of q and a_{max} that meet the 1σ range of FM07 data are confined to be narrow ranges

$3.2 < q < 3.7$

0.19 um $< a_{max} <$ 0.34 um

8-2. Piled-up contour for carbon-astro.sil





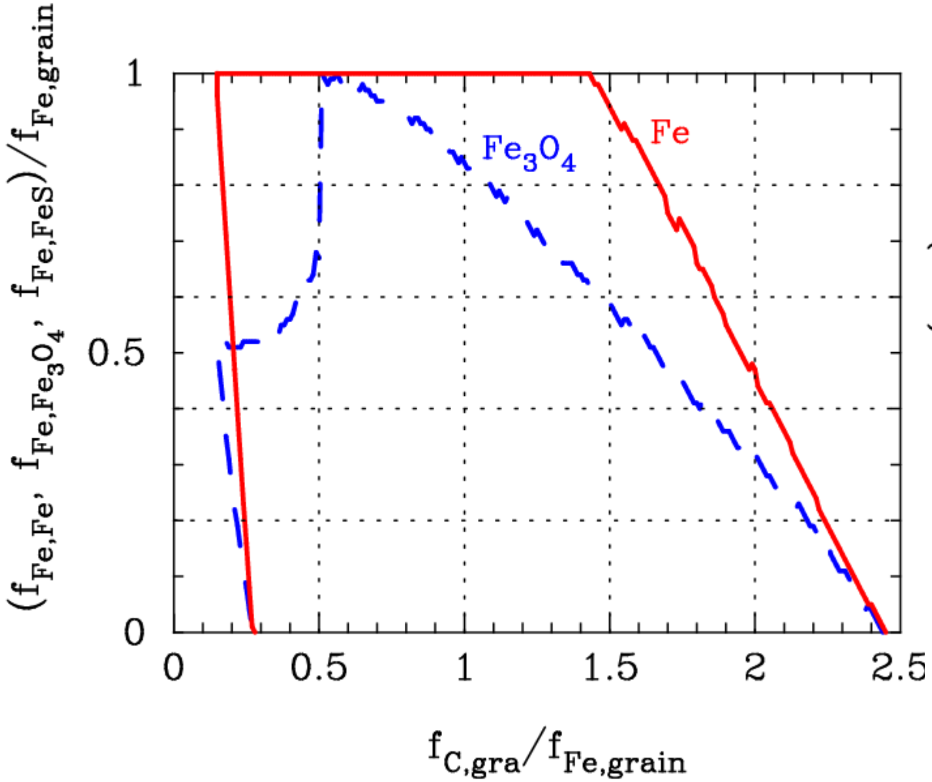
amorphous C ➔ up to ~60 %
glassy C ➔ up to ~50 %
SiC ➔ up to ~15 %

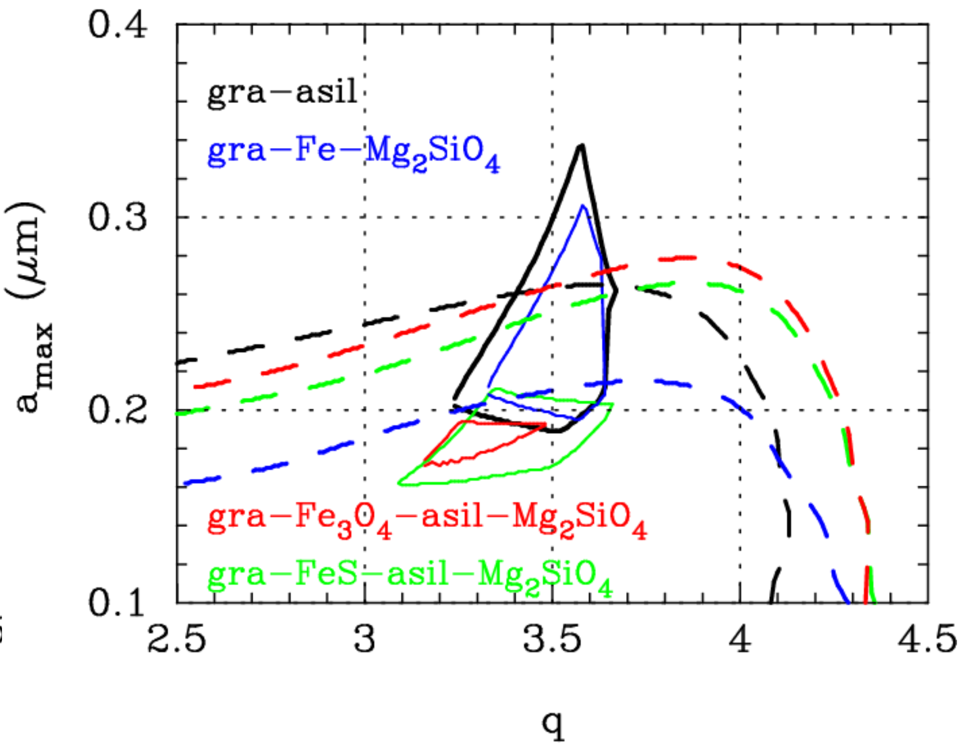
more than 40 % carbon are needed to be locked in graphite

Dashed line ($f_{C,\ grain}$ = 0.7)

- gra-asil ($f_{C,\ gra}/f_{C,\ grain}$ = 1.0)
- gra-aC-asil ($f_{C,\ aC}/f_{C,\ grain}$ = 0.3)
- gra-gC-asil ($f_{C,\ gC}/f_{C,\ grain}$ = 0.3)
- gra-SiC-asil ($f_{C,\ SiC}/f_{C,\ grain}$ = 0.1)

8-3. Piled-up contour for carbon-astro.sil





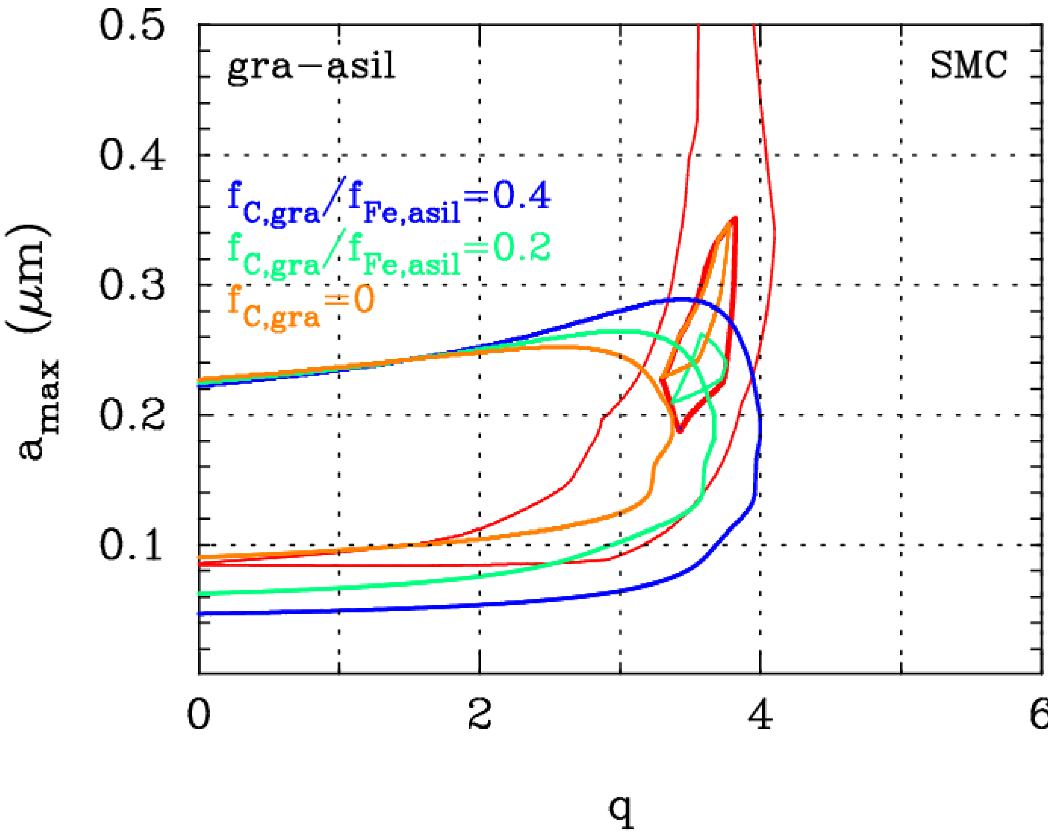
Fe ➔ up to 100 %
Fe3O4 ➔ up to ~80 %
FeS ➔ up to 100 %

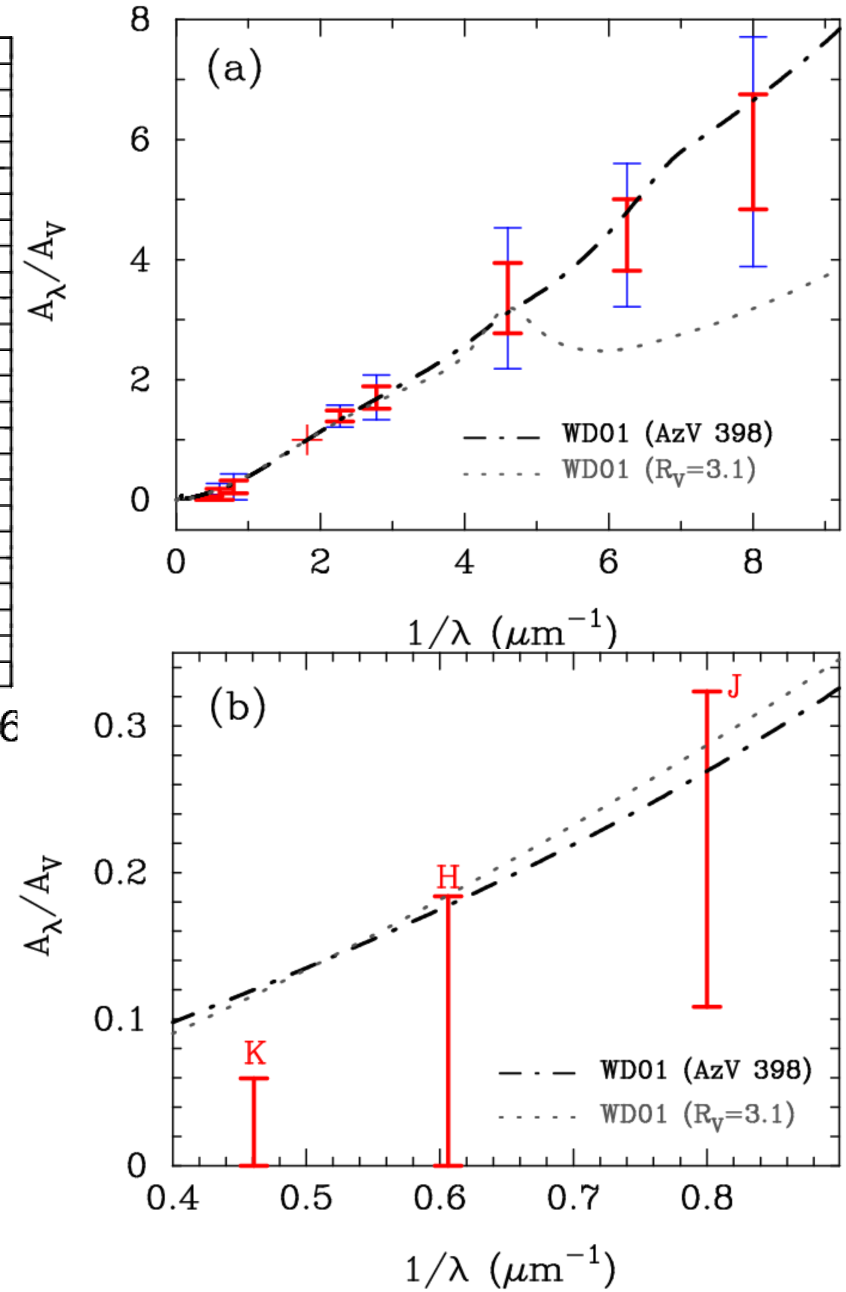
many Fe atoms are not always needed to be locked in silicate

Dashed line ($f_{C,\,gra}$ = 0.7)

- **gra-Fe-fore ($f_{Fe,\,Fe}/f_{Fe,\,grain}$ = 1.0)**
- **gra-Fe_3O_4-sil ($f_{Fe,\,Fe_3O_4}/f_{Fe,\,grain}$ = 0.8)**
- **gra-FeS-sil ($f_{S,\,FeS}$ = 1.0)**

9-1. Dust properties in SMC



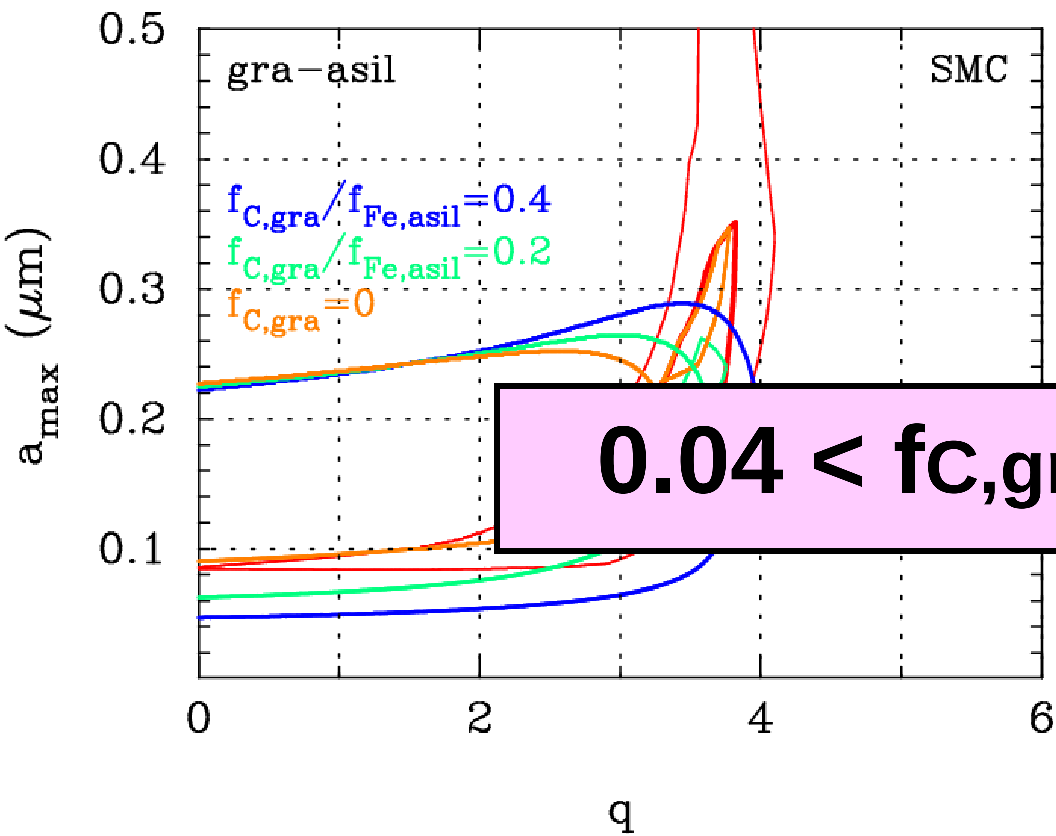


Values of q and a_{max} that meet the extinction ranges in SMC are confined to be narrow ranges

3.2 < q < 3.8

0.19 um < a_{max} < 0.35 um

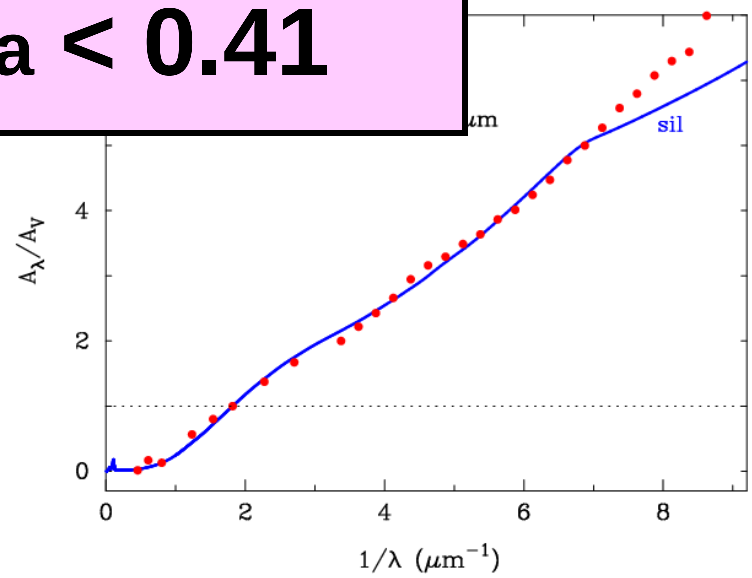
9-2. Dust properties in SMC



For SMC, $N_H/E(B-V)$ = (2.3±2.2)x10[22] cm[3]/mag (Welty et al. 2012)

For MW, $N_H/E(B-V)$ = (5.7±1.7)x10[21] cm[3]/mag

0.04 < $f_{C,gra}$ < 0.41



Values of q and a_{max} that meet the extinction ranges in SMC are confined to be narrow ranges

3.2 < q < 3.8

0.19 um < a_{max} < 0.35 um

SMC extinction curve can be explained by the MRN model without graphite (Pei 1992)

10. Summary

- **The observed ranges of NIR extinction from FM07 do not match with the results from the CCM formula**
  ➔ There is no combination of q and a_{max} that satisfy the observed ranges when CCM results are adopted

- **For graphite-silicate model, the values of q and a_{max} that satisfy the 1σ extinction ranges are, respectively,**
  - **$3.2 < q < 3.7$ and 0.19 um $< a_{max} < 0.34$ um**
    $0.56 < f_{C,gra} < 1.0$ for MW
  - **$3.2 < q < 3.8$ and 0.19 um $< a_{max} < 0.35$ um**
    $0.04 < f_{C,gra} < 0.41$ for SMC

- **~30 % of graphite can be replaced with amorphous carbon and glassy carbon**

- **Most of Fe atoms can be locked in Fe, Fe_3O_4, and FeS**