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)

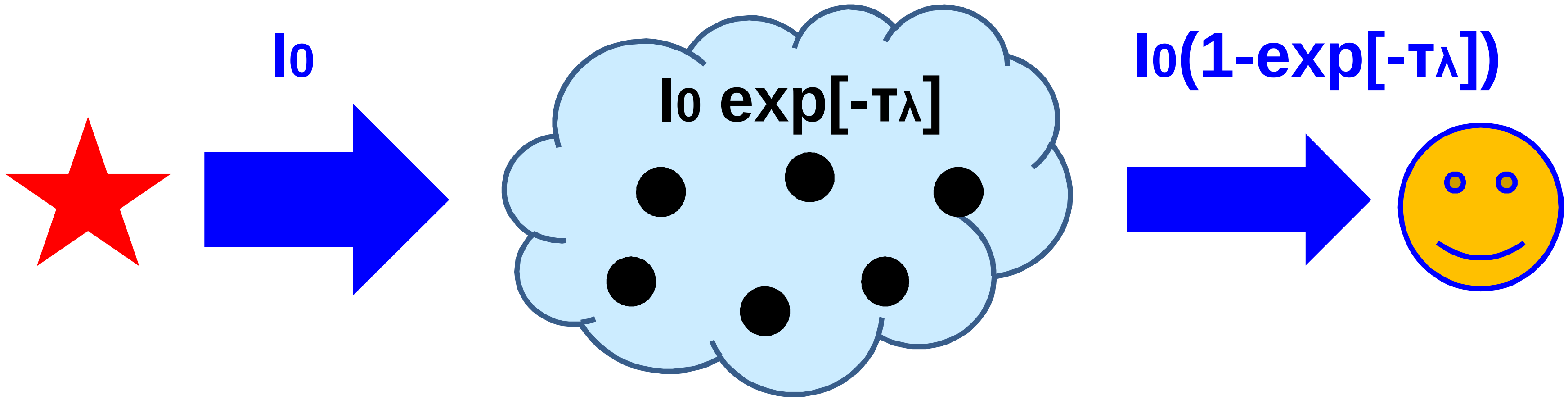
野沢 貴也　(Takaya Nozawa)

&　福来 正孝 (Masataka Fukugita)

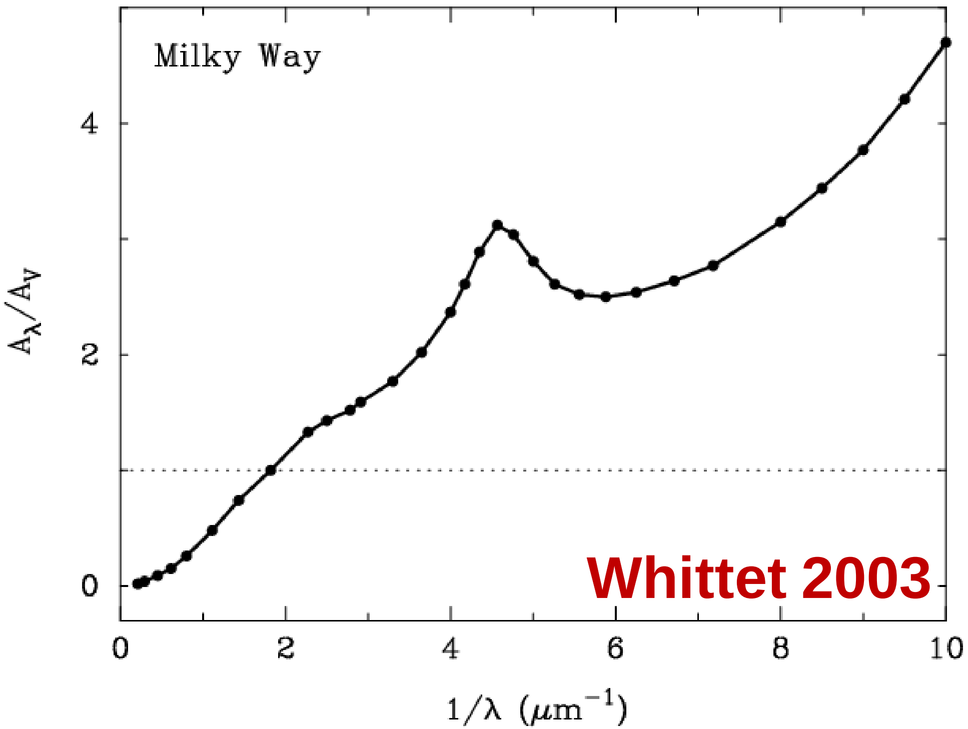
(Kavli IPMU, University of Tokyo)

東京大学 THE UNIVERSITY OF TOKYO　TODIAS 東京大学国際高等研究所 TODAI INSTITUTES FOR ADVANCED STUDY　wpi World Premier International Research Center Initiative　KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

1. Extinction curve



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



- essential for knowing the intrinsic SEDs of galaxies

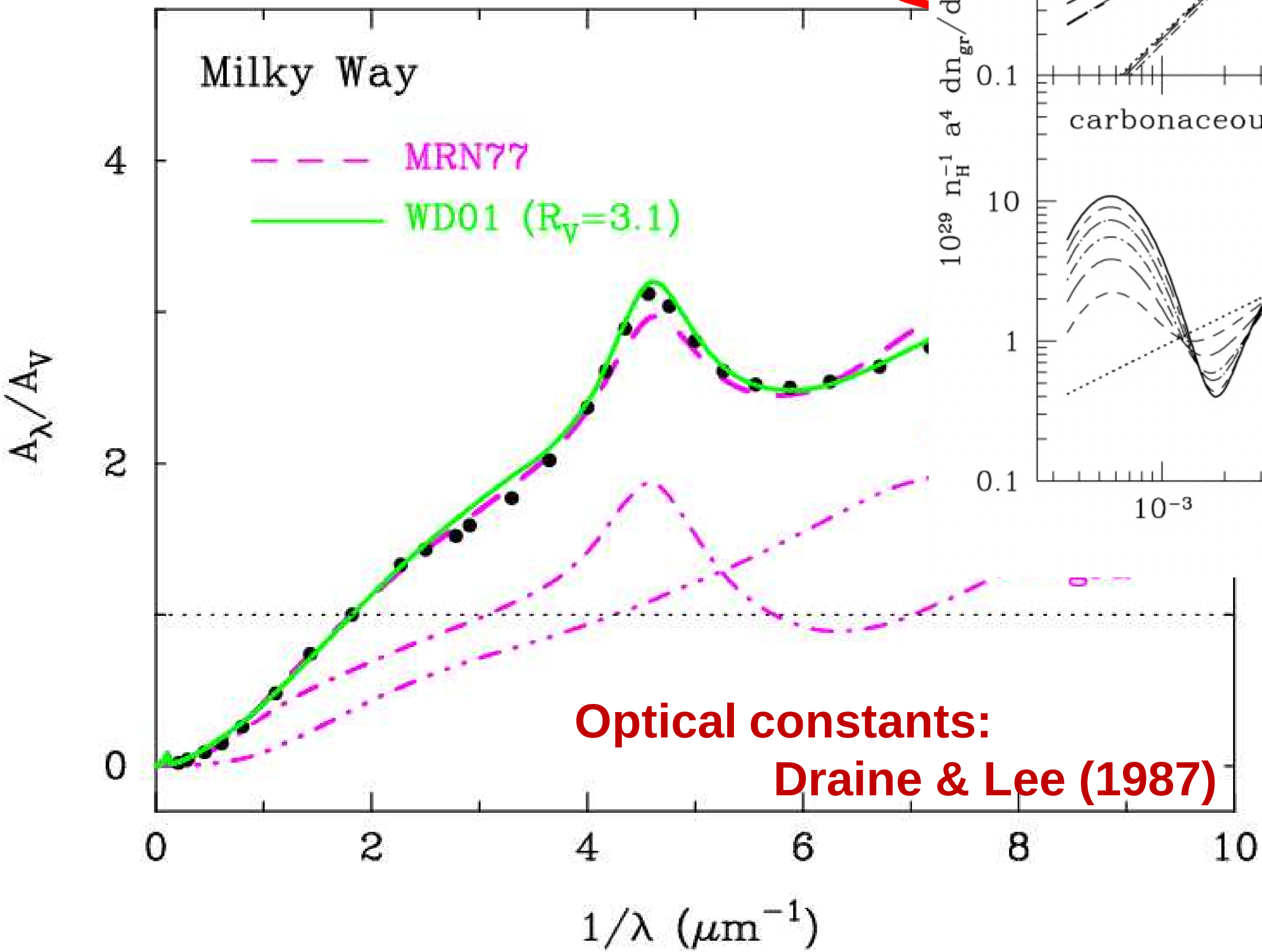
- depends on physical and optical properties of dust

2. Interstellar dust models in MW

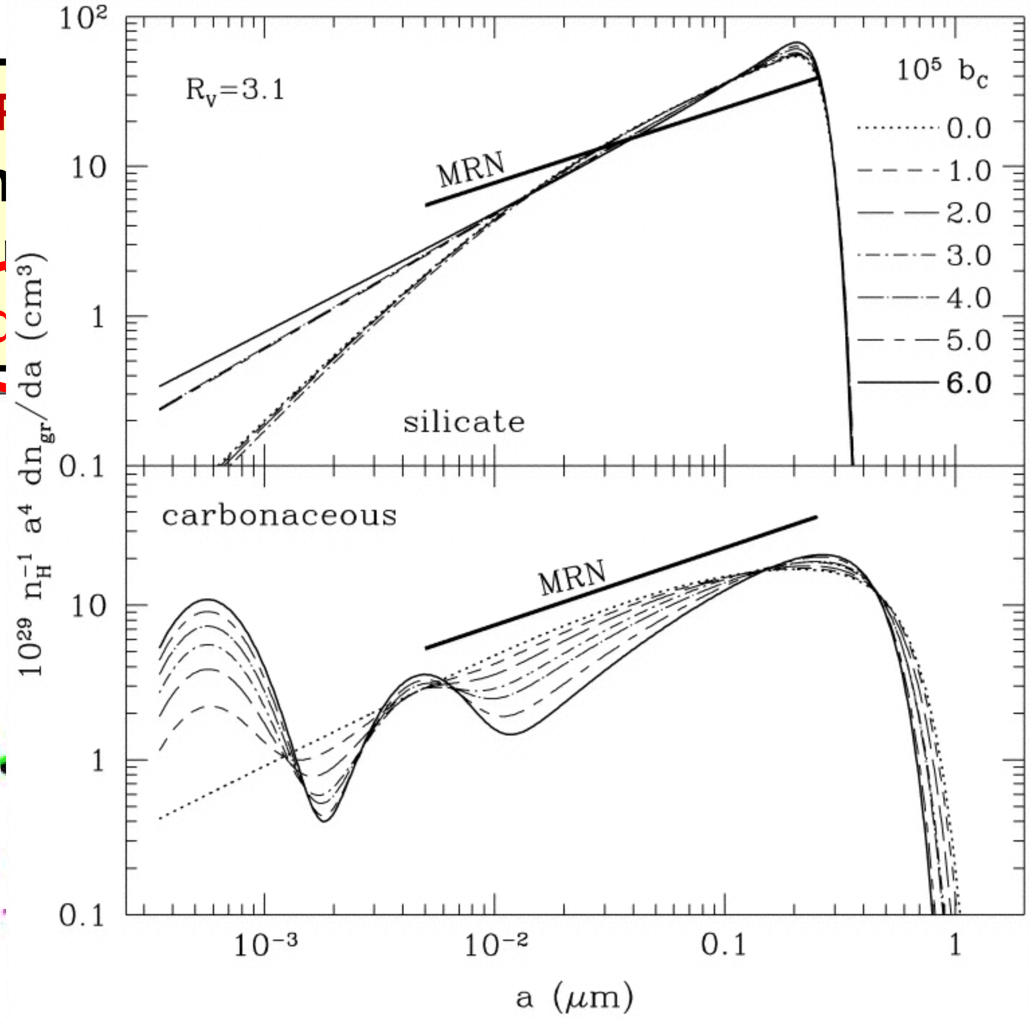
○ MRN dust model **(Mathis, R**

- dust composition : graph
- size distribution : powe

  n(a)da ∝ a^{-q}da with c



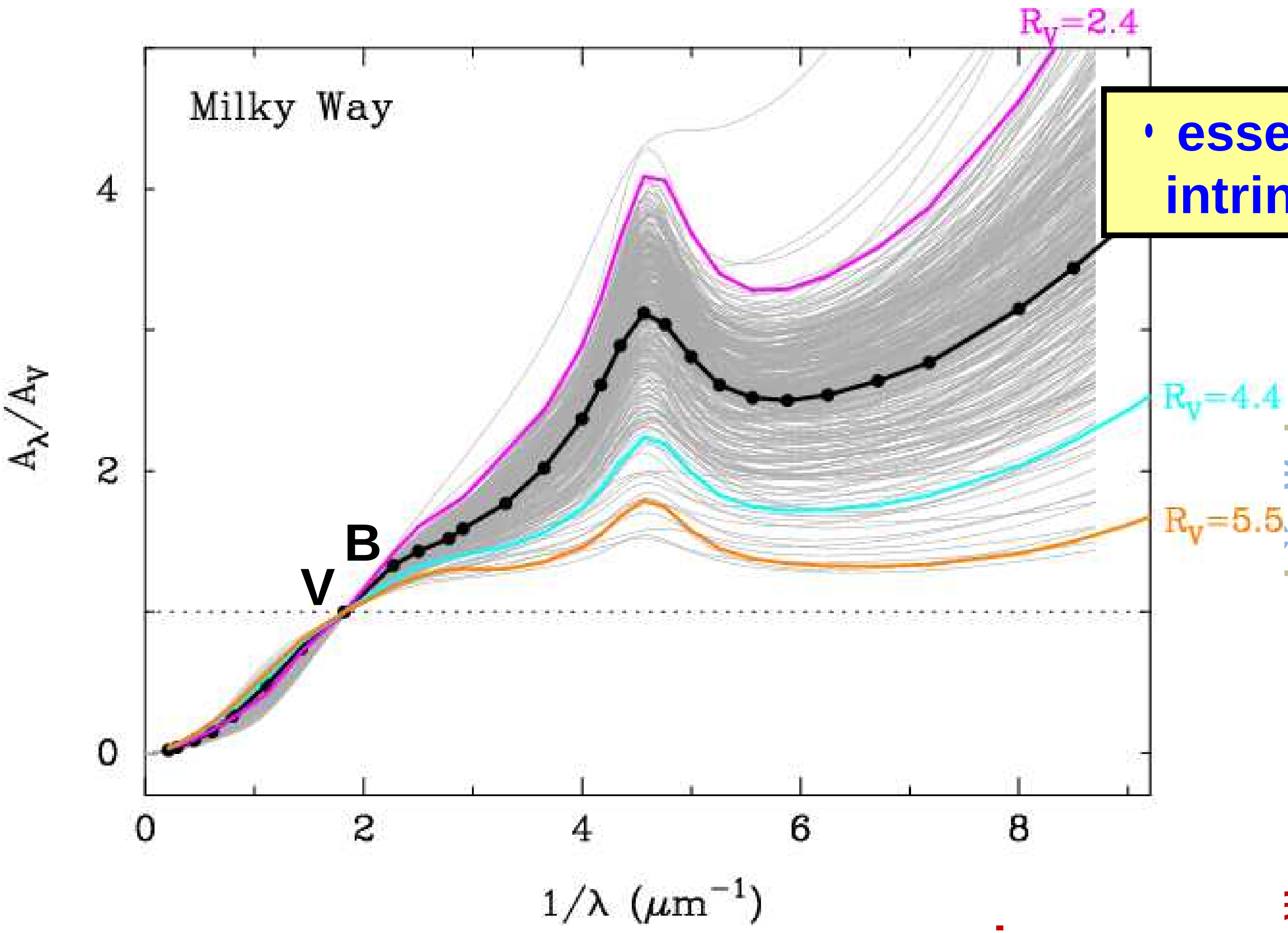
Optical constants: Draine & Lee (1987)



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

  0.3 nm ≤ a ≤ 1 μm

3. CCM relationship and Rv



- 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

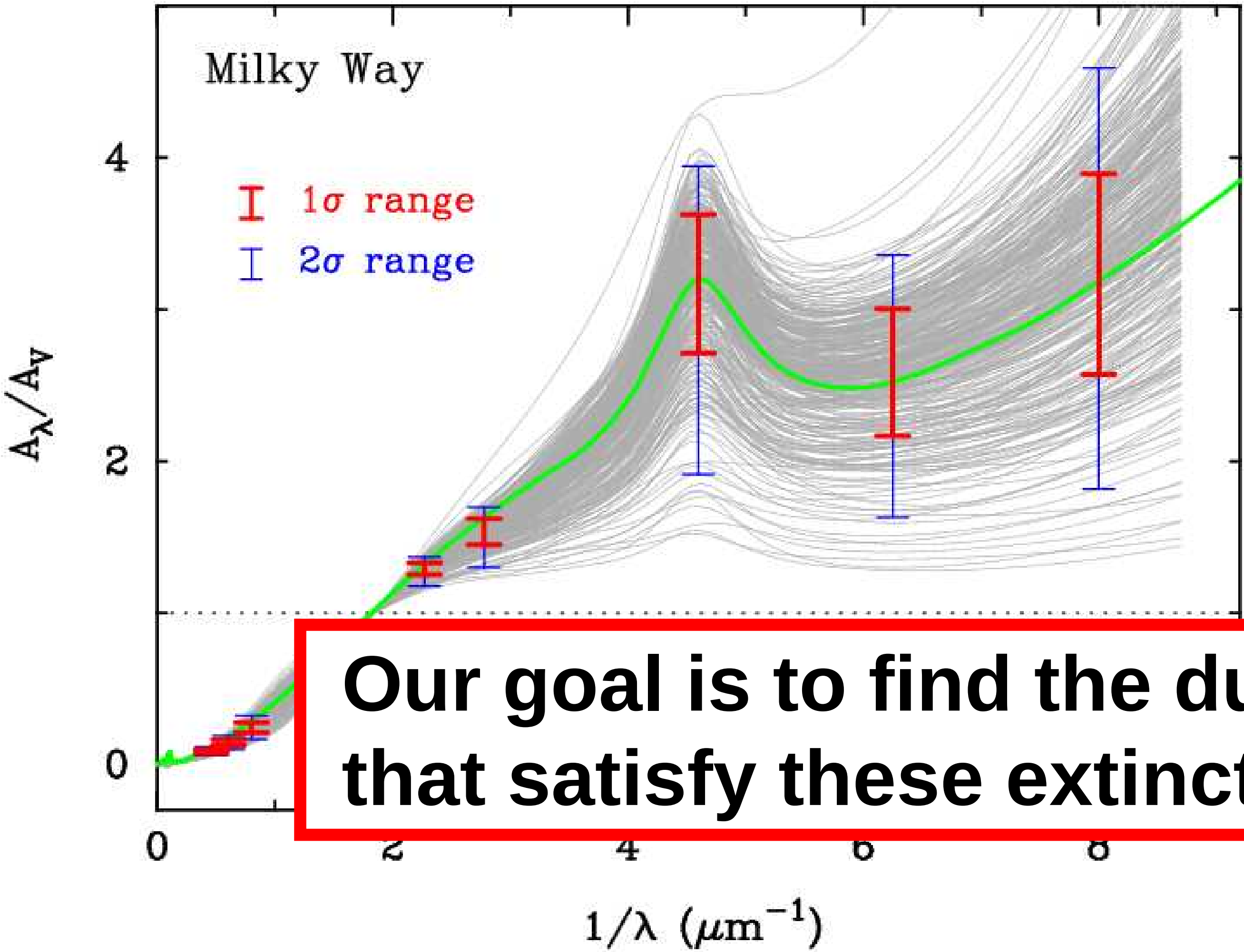
  $R_V = A_V / (A_B - A_V) = 1 / (A_B/A_V - 1)$ cf. $R_{V,ave}$ = 3.05–3.10

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)**

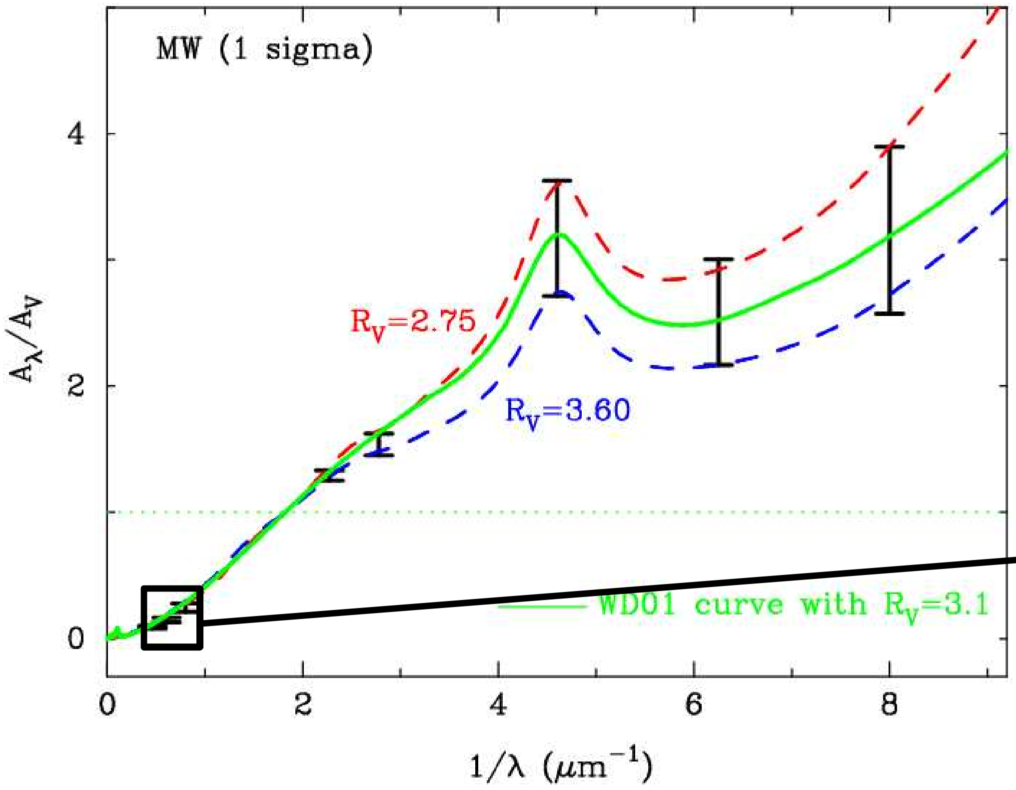
red bars:
1σ ranges including 224 data

...ing
312 data

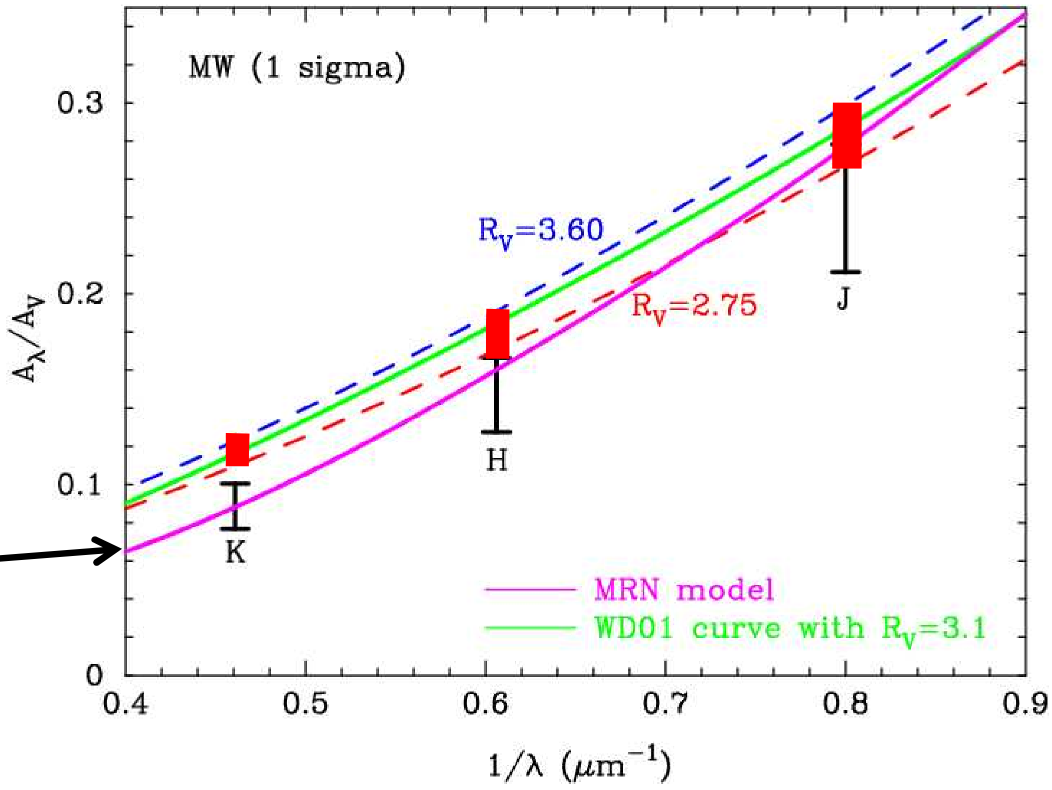
Our goal is to find the dust properties that satisfy these extinction ranges

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

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

(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)

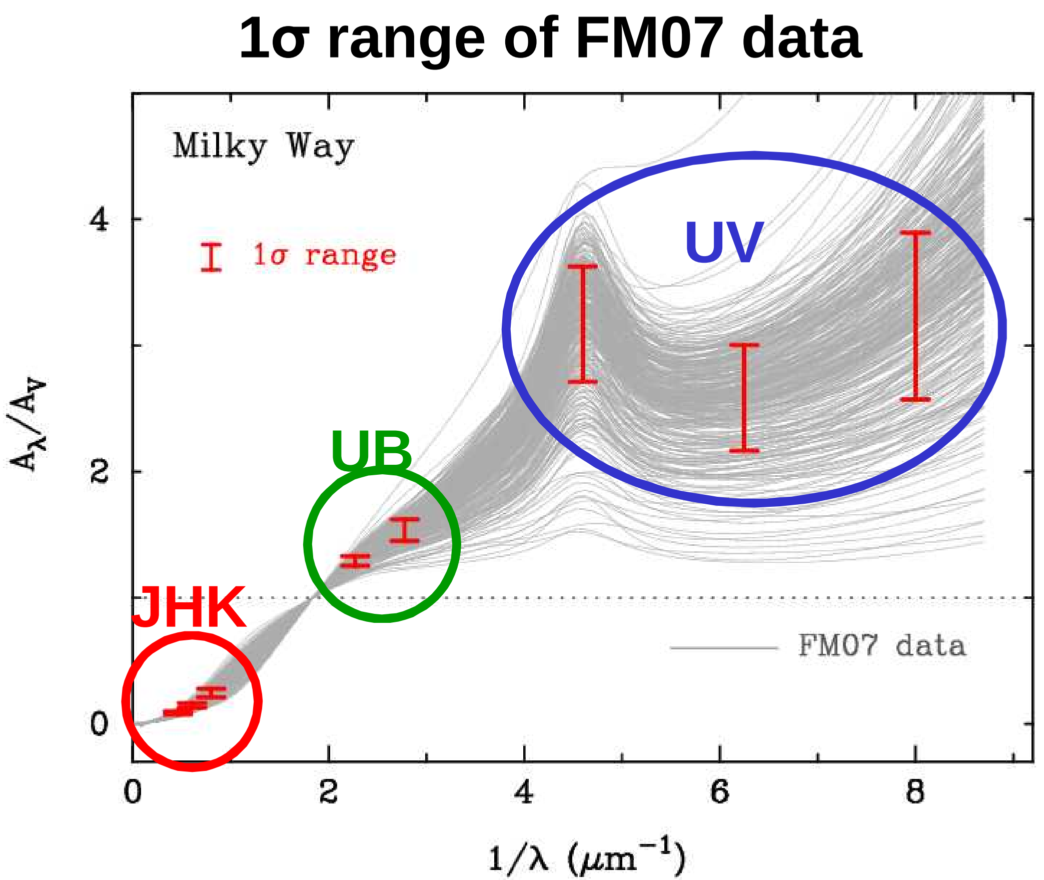
$f_{i,j}$ → a fraction of an element *i* locked up in a grain *j*

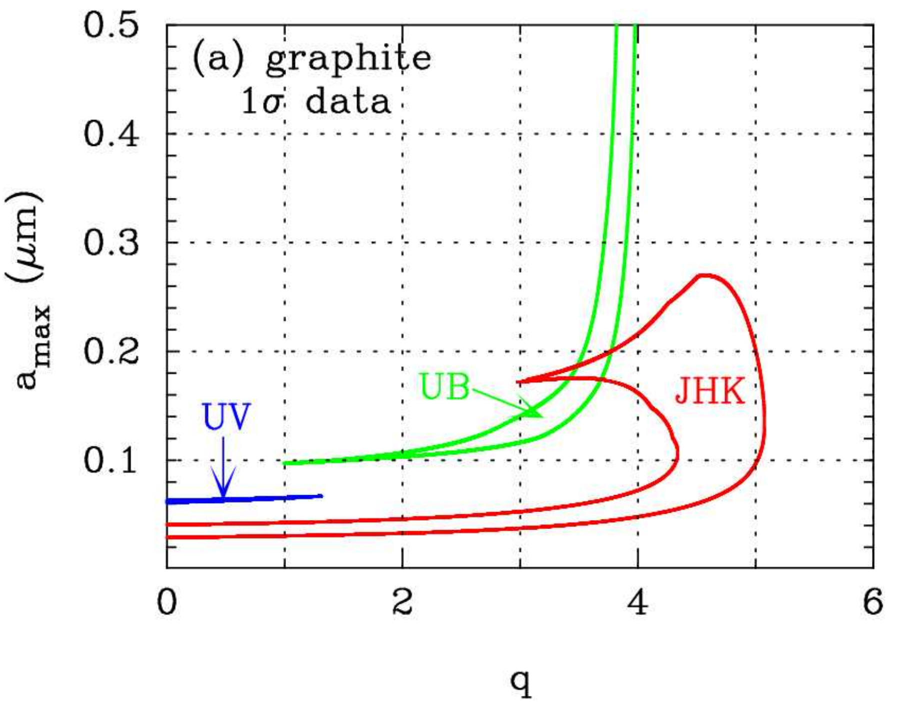
Solar abundance: Grevesse & Sauval (1998)

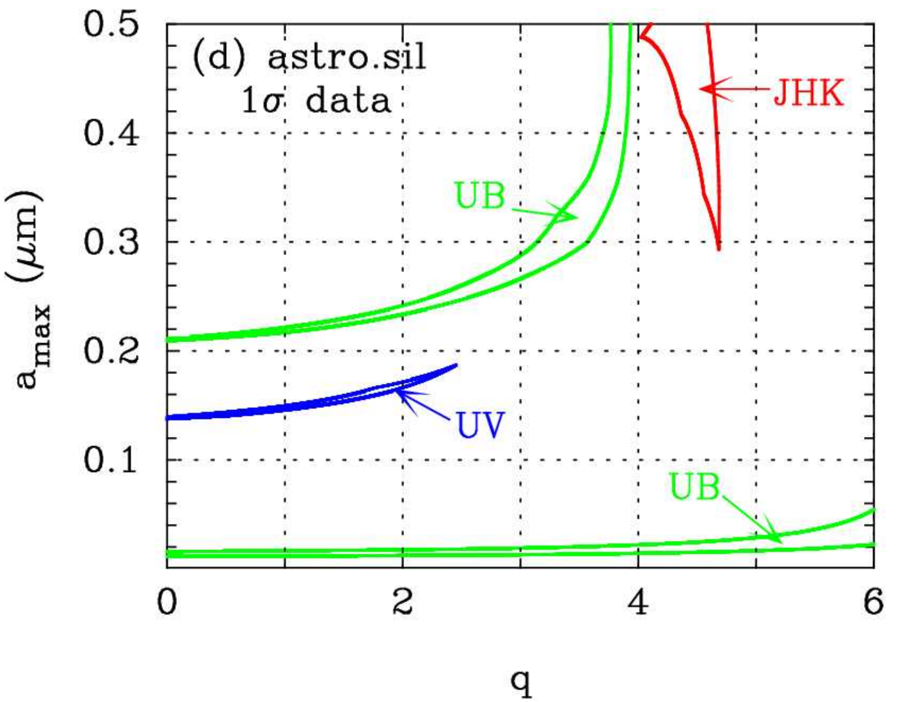
all of Fe (and Mg and Si) are locked in dust grains

- 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







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

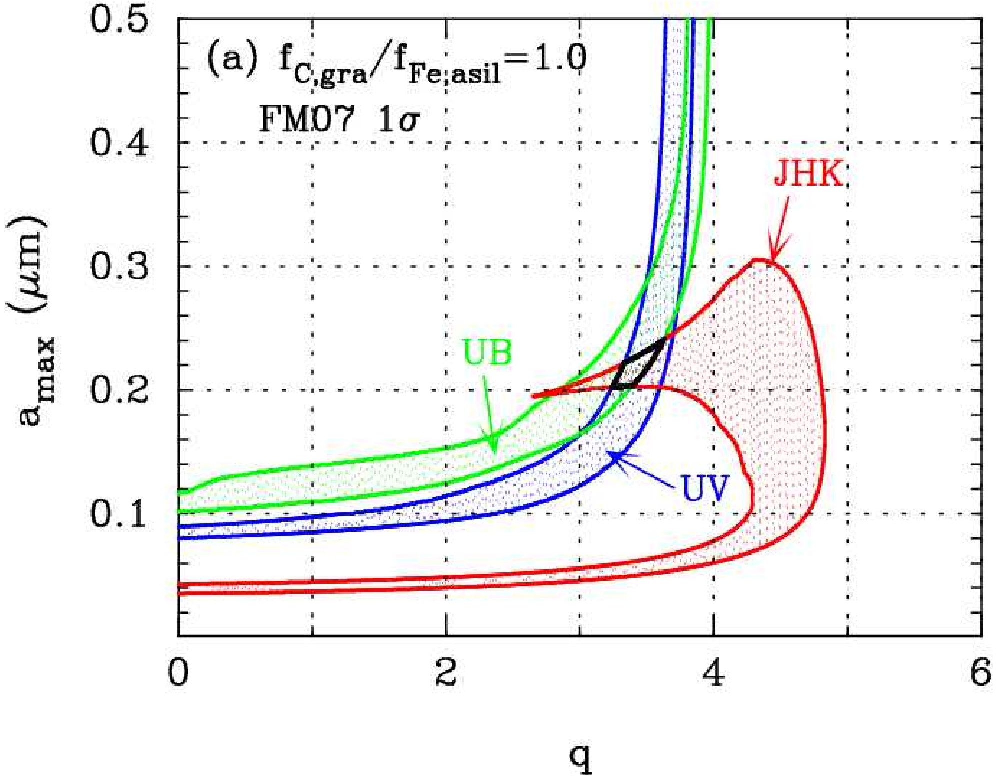
UV: UV bump (0.22 μm), FUV dip (0.16 μm), FUV rise (0.125 μm)

UB: U band and B band

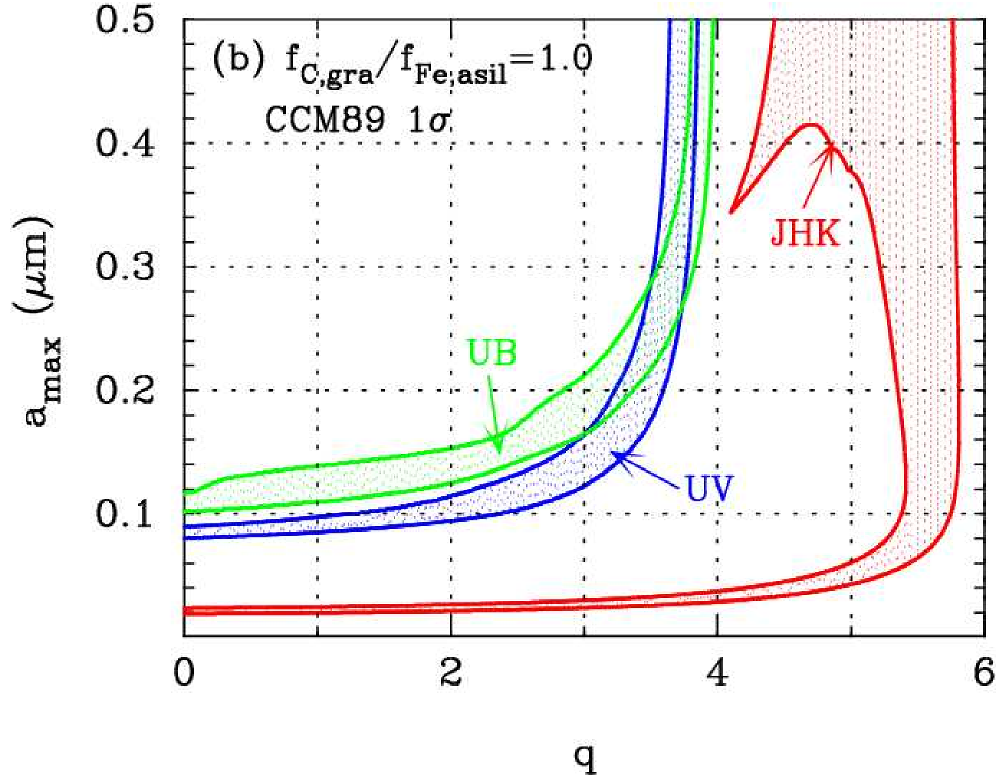
JHK: J band, H band, K band

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

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



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

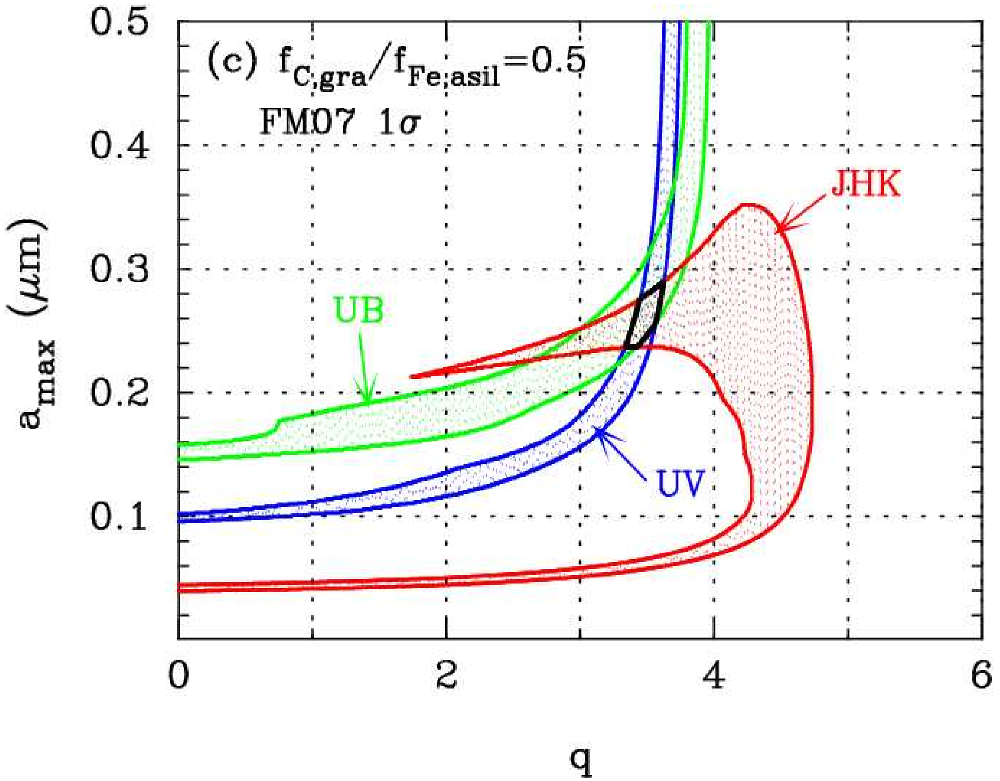


contour plots of a_{max} and q that fulfill the 1σ range of FM07 data for $f_{gra}/f_{sil} = 1.0$ ($M_{gra}/M_{sil} = 0.78$)
blue: constraint from UV/FUV
green: constraint from UB band
red: constraint from JHK band

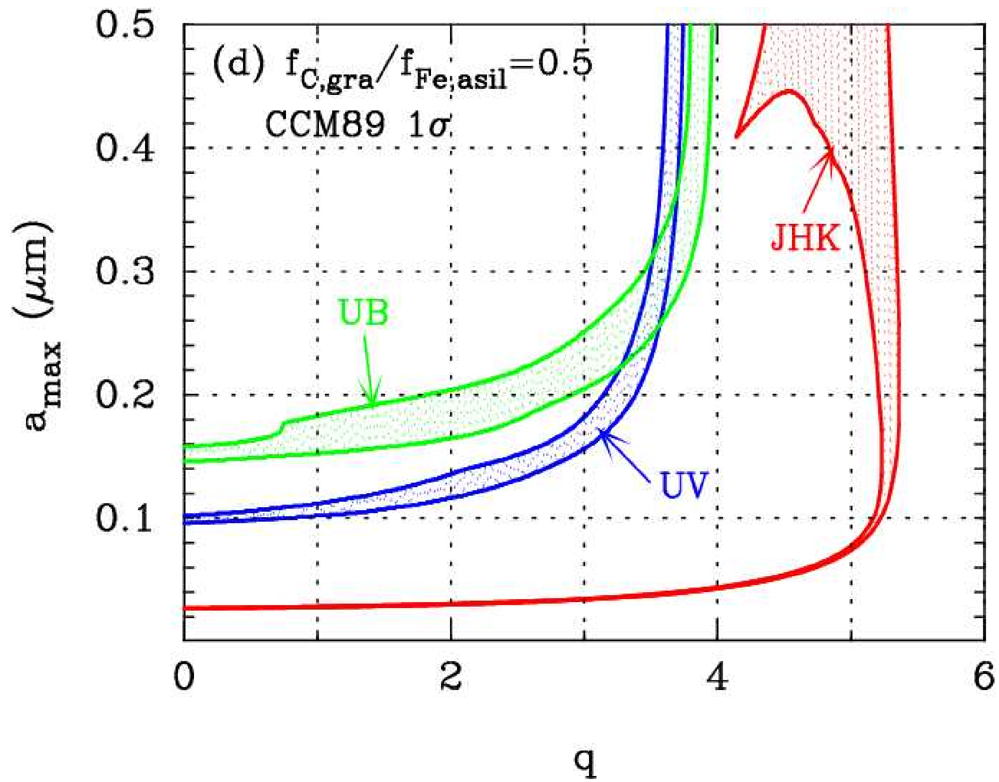
contour plots of a_{max} and q that fulfill the 1σ range of CCM result for $f_{gra}/f_{sil} = 1.0$ ($M_{gra}/M_{sil} = 0.78$)
blue: constraint from UV/FUV
green: constraint from UB band
red: constraint from JHK band

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

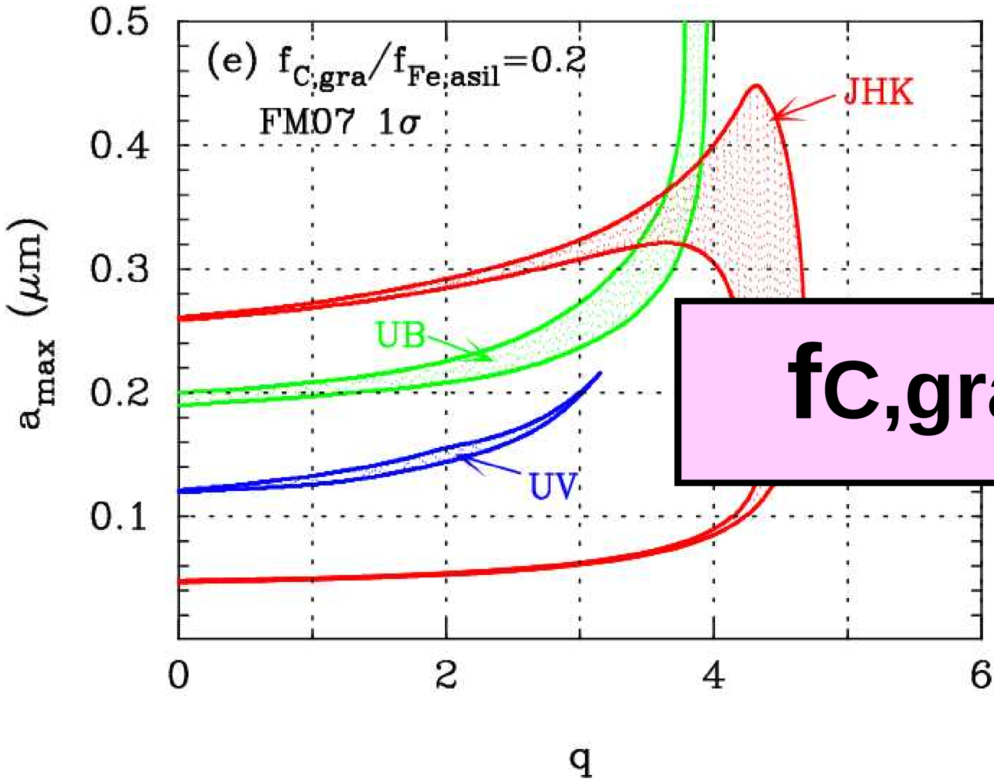


contour plots of a_{max} and q that fulfill the 1σ range of FM07 data for f_{gra}/f_{sil} = 0.5 (M_{gra}/M_{sil} = 0.39)
blue: constraint from UV/FUV
green: constraint from UB band
red: constraint from JHK band

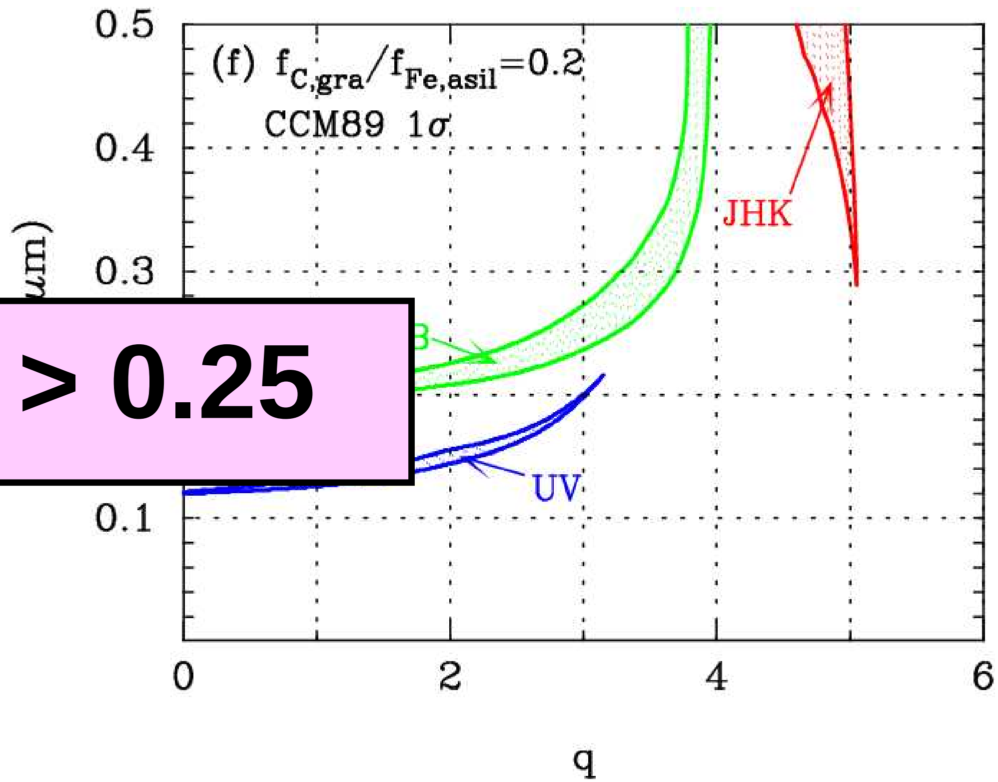
contour plots of a_{max} and q that fulfill the 1σ range of CCM result for f_{gra}/f_{sil} = 0.5 (M_{gra}/M_{sil} = 0.39)
blue: constraint from UV/FUV
green: constraint from UB band
red: constraint from JHK band

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

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



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



$f_{C,gra} > 0.25$

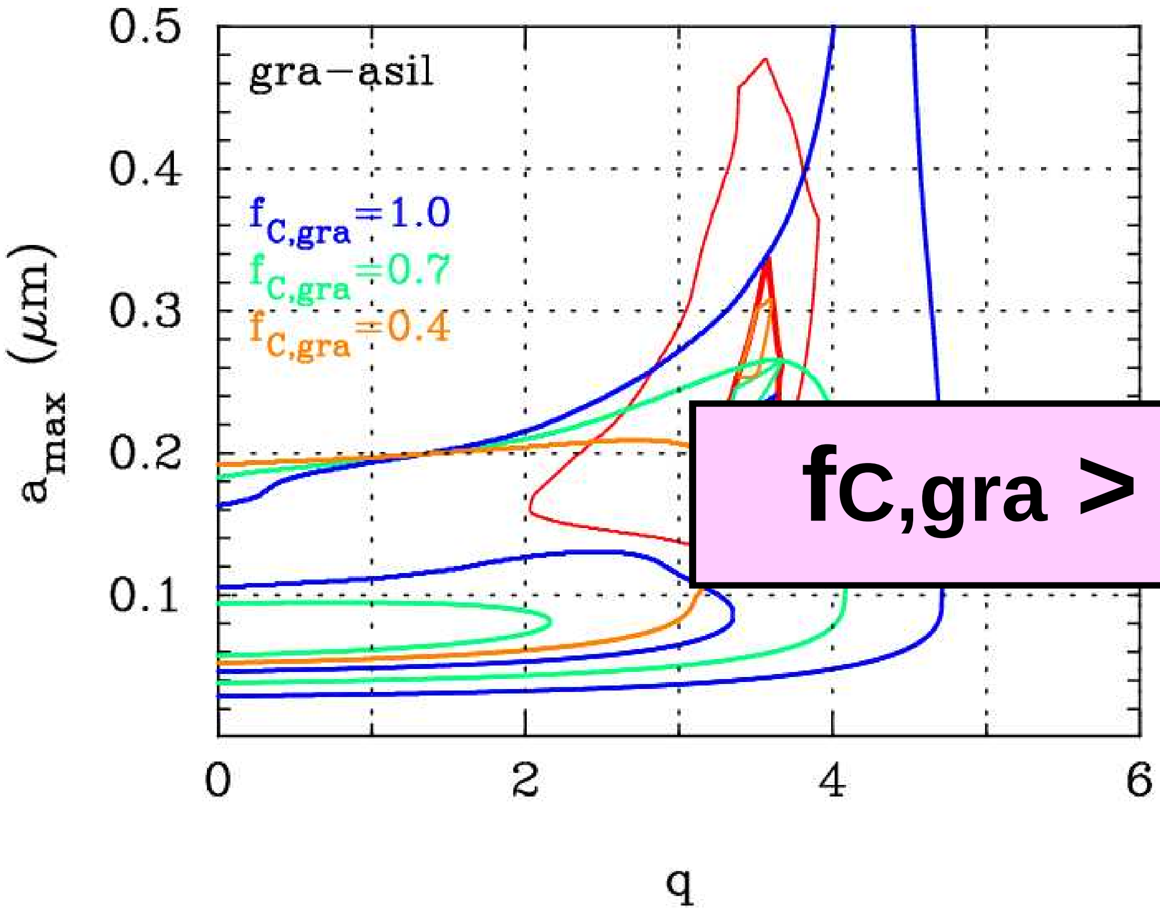
contour plots of a_{max} and q that fulfill the 1σ range of FM07 data for $f_{gra}/f_{sil} = 0.2$ ($M_{gra}/M_{sil} = 0.16$)

- **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



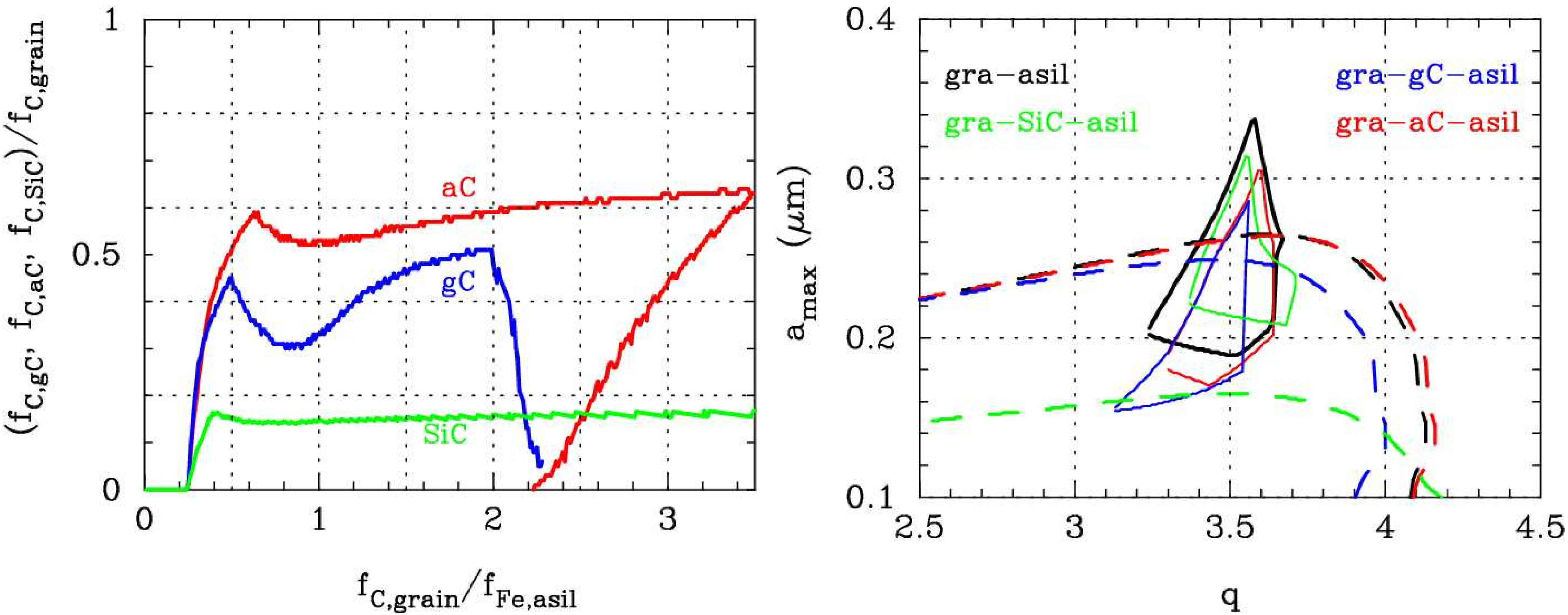
$f_{C,gra} > 0.56$

In this study,
$N_H/E(B-V)$ =
$(5.7 \pm 1.7) \times 10^{21}$ cm^3/mag
(Gudennavar et al. 2012)

In previous studies,
$N_H/E(B-V) = N_H/(A_B - A_V)$
$= 5.8 \times 10^{21}$ cm^3/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



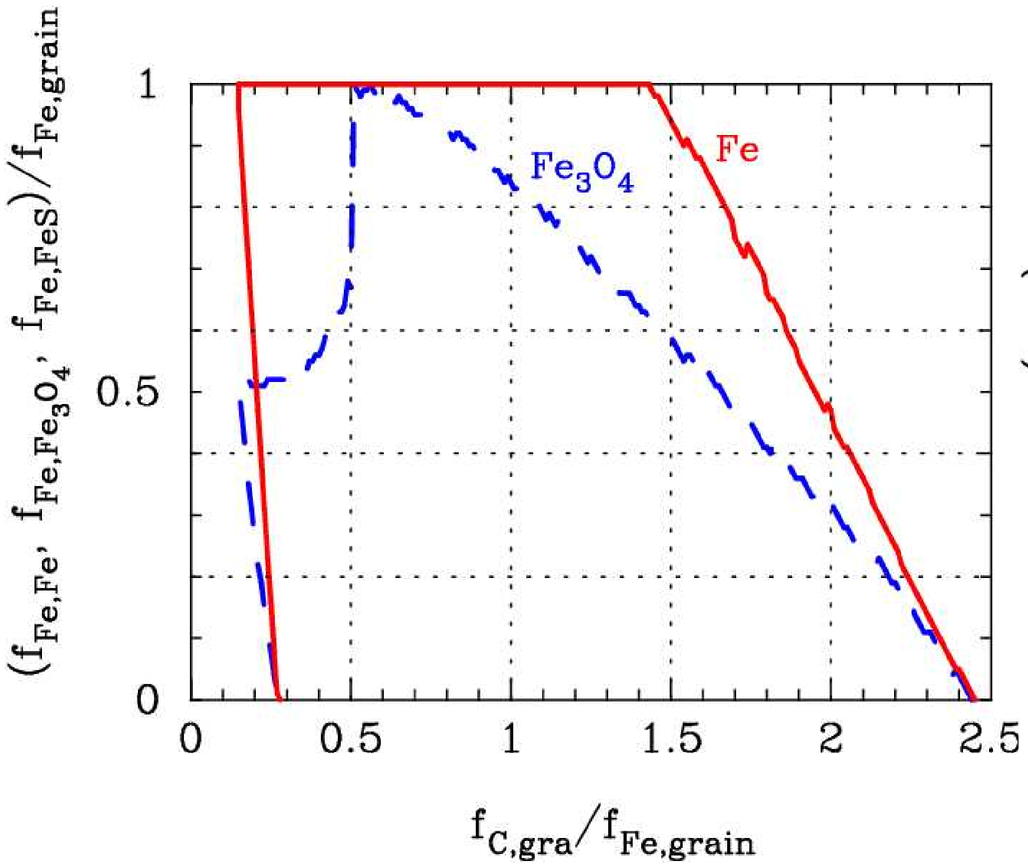
amorphous C ➔ up to ~60 %
glassy C ➔ up to ~50 %
SiC ➔ up to ~15 %

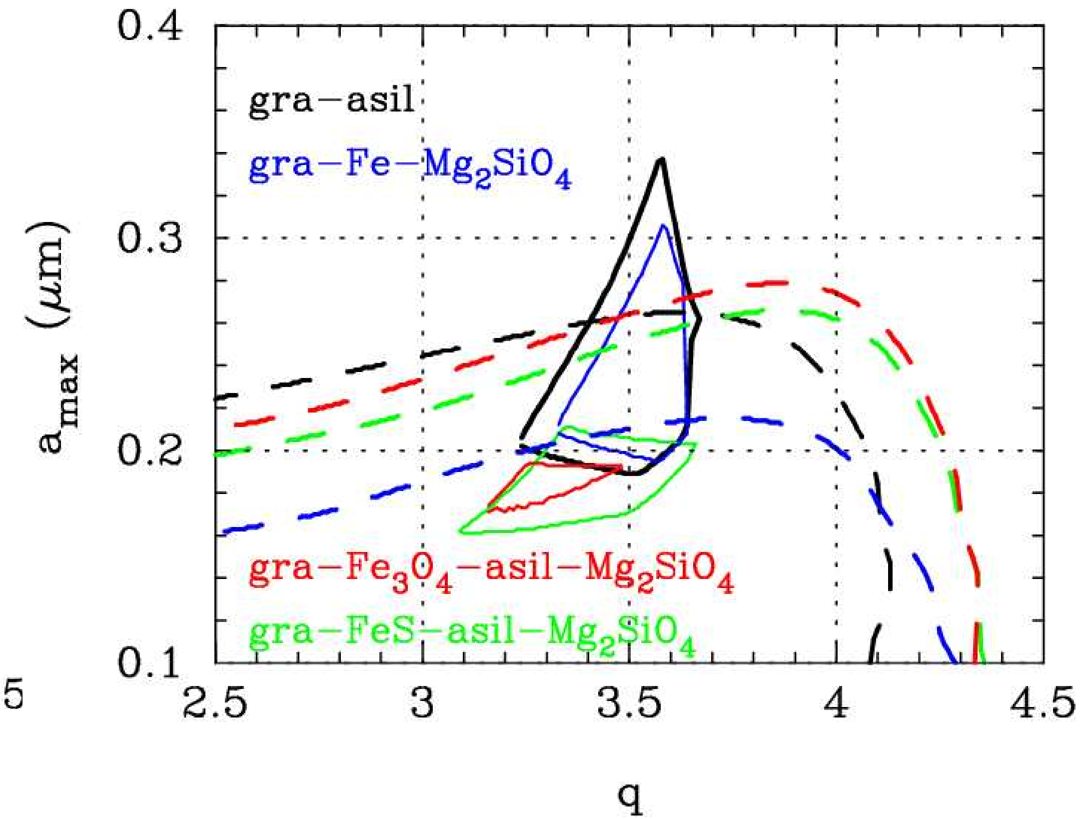
more than 40 % carbon are needed to be locked in graphite

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





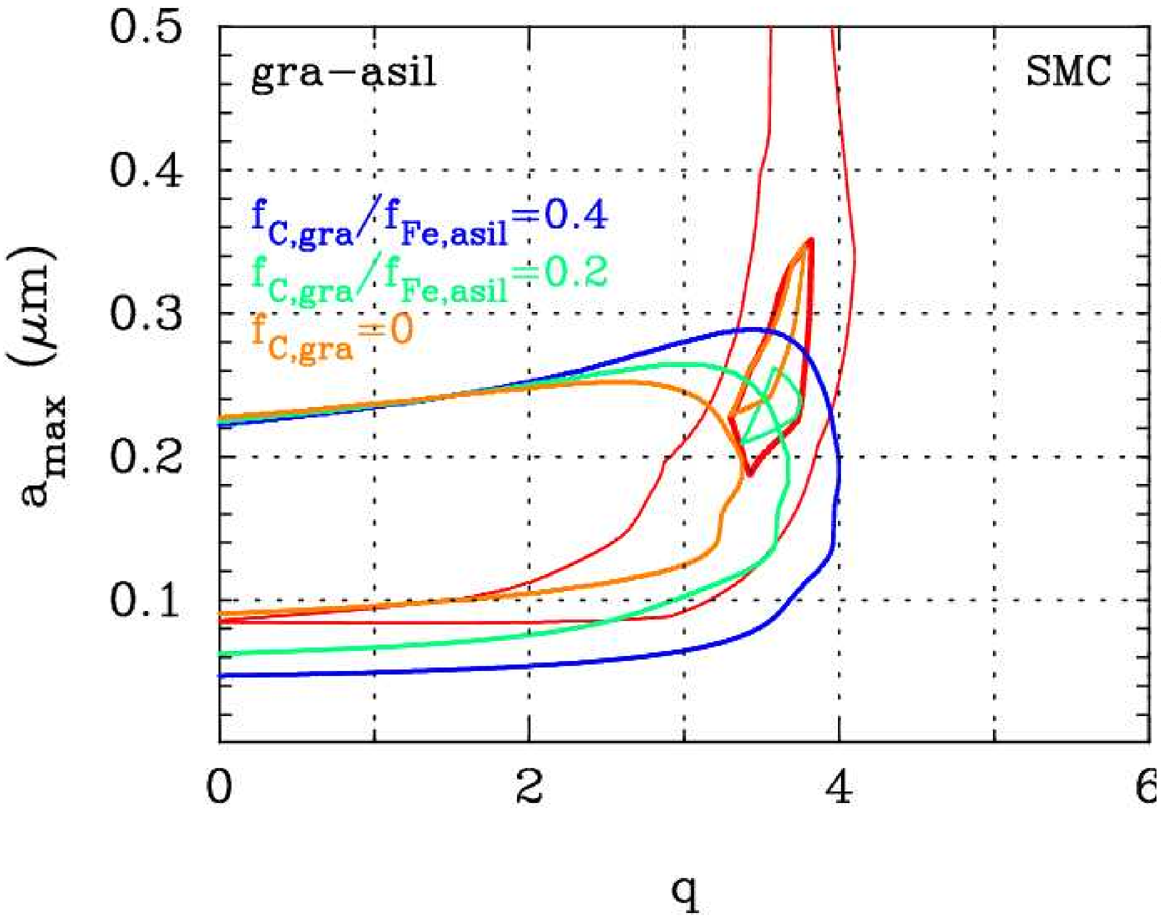
Fe ➔ up to 100 %
Fe_3O_4 ➔ up to ~80 %
FeS ➔ up to 100 %

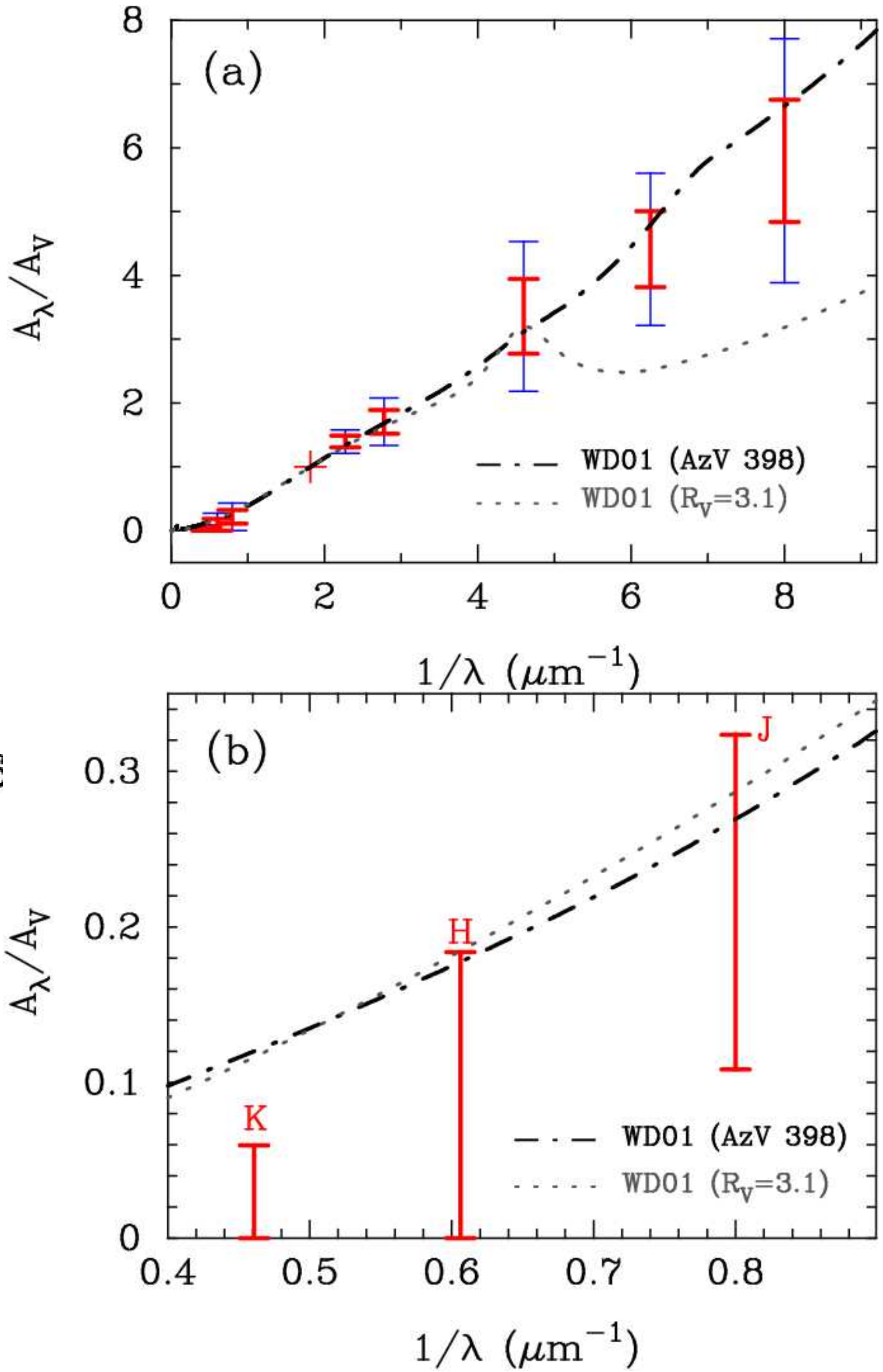
many Fe atoms are not always needed to be locked in silicate

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



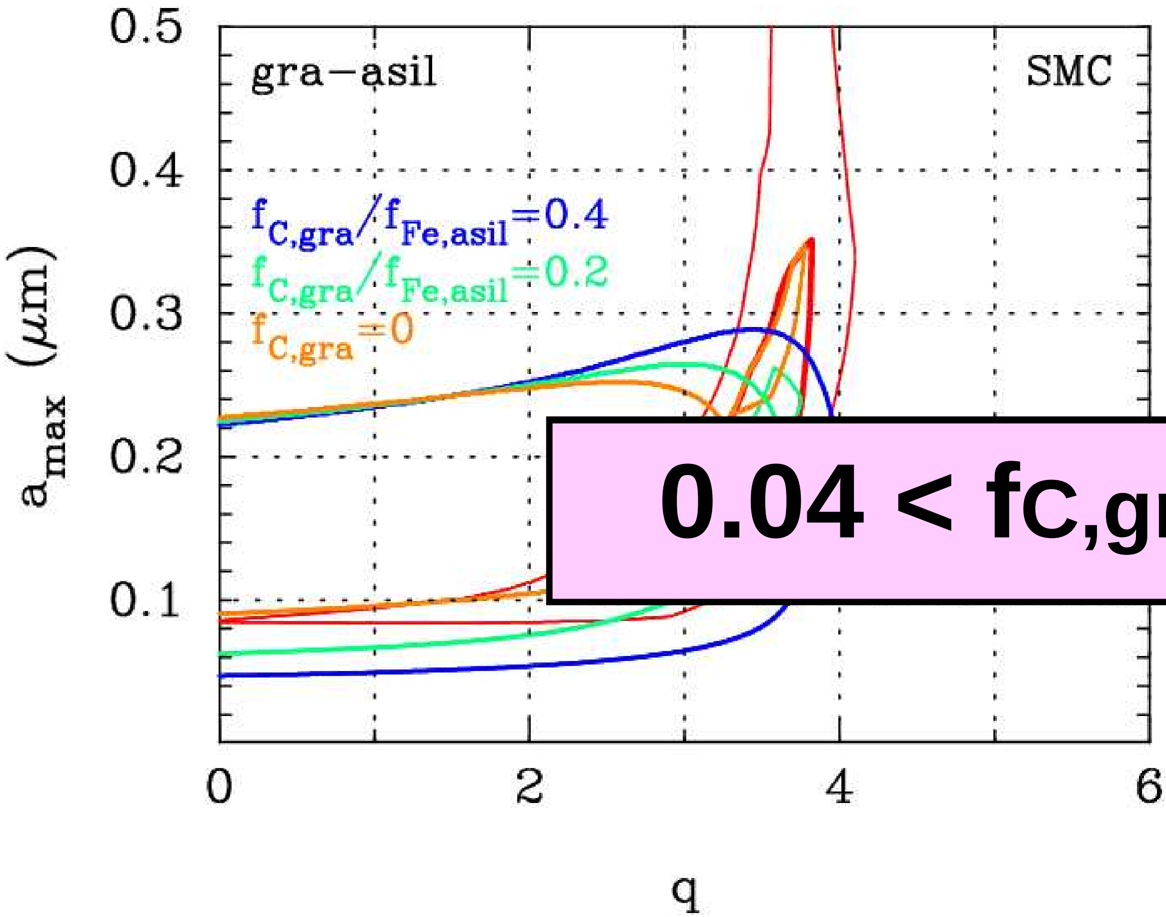


Values of q and amax that meet the extinction ranges in SMC are confined to be narrow ranges

3.2 < q < 3.8

0.19 um < amax < 0.35 um

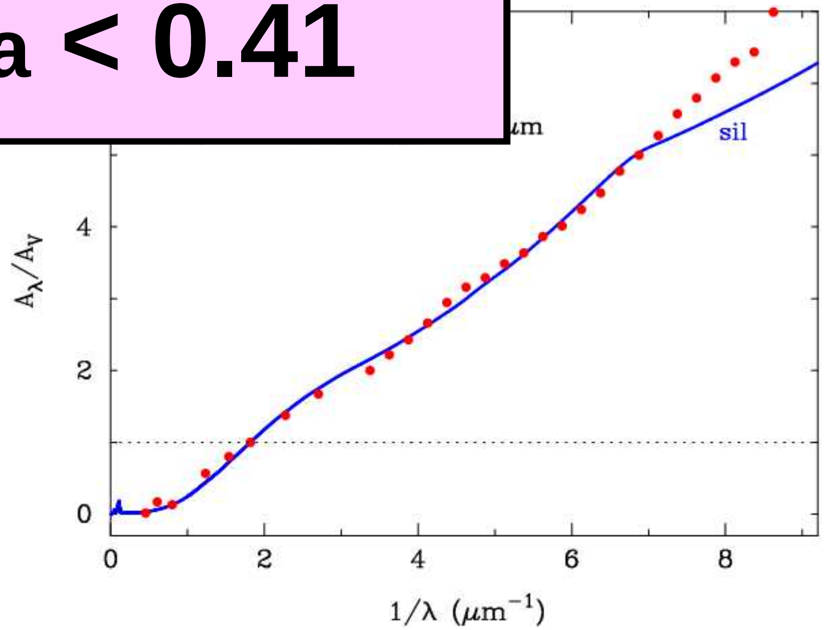
9-2. Dust properties in SMC



For SMC, $N_H/E(B-V)$ = $(2.3\pm2.2)\times10^{22}$ cm^3/mag
(Welty et al. 2012)

For MW, $N_H/E(B-V)$ = $(5.7\pm1.7)\times10^{21}$ 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