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What can the Interstellar Extinction Curves Tell us About?

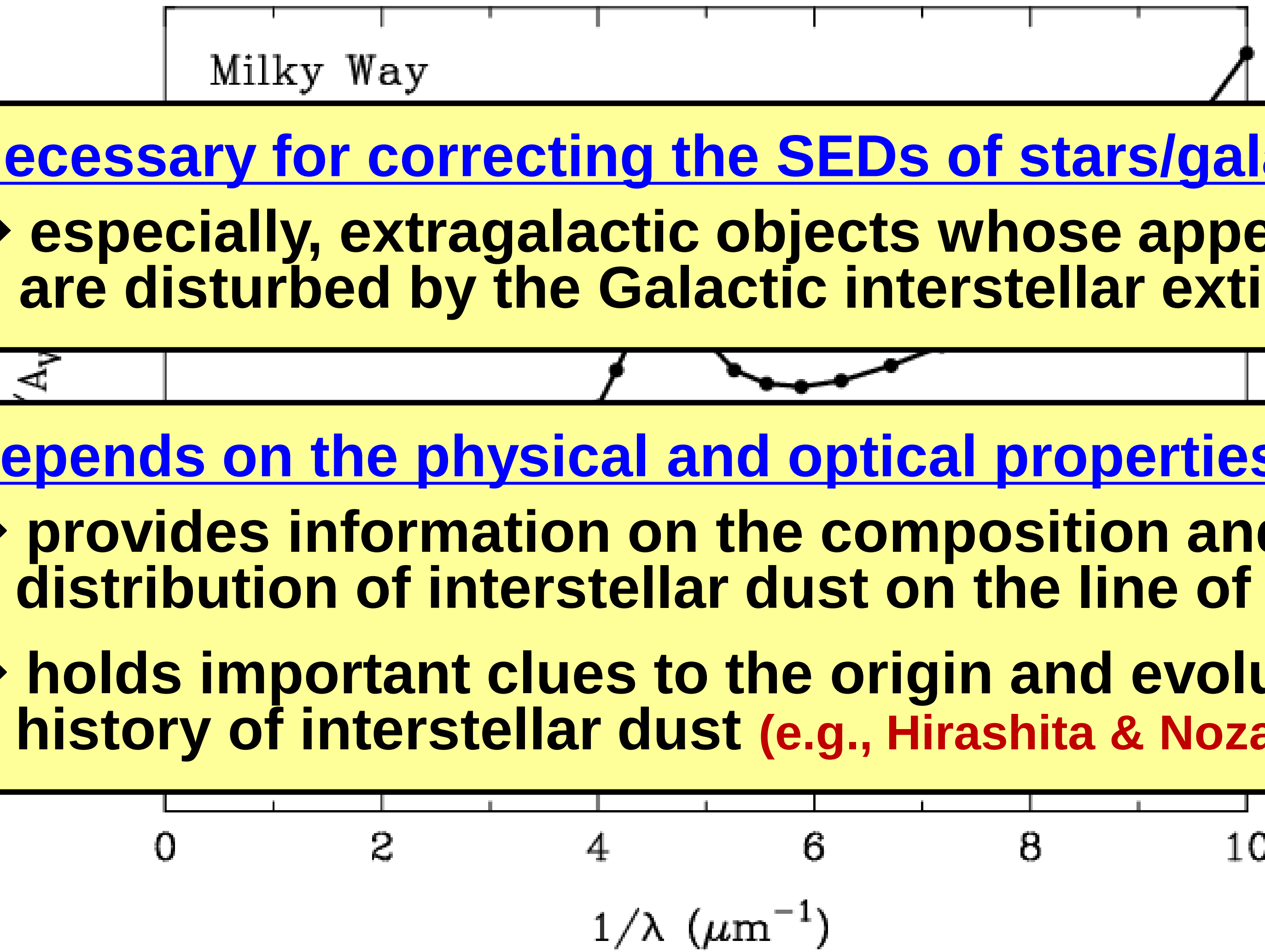
Takaya Nozawa

Masataka Fukugita

(Kavli IPMU, University of Tokyo)

1. Introduction

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



- **necessary for correcting the SEDs of stars/galaxies**

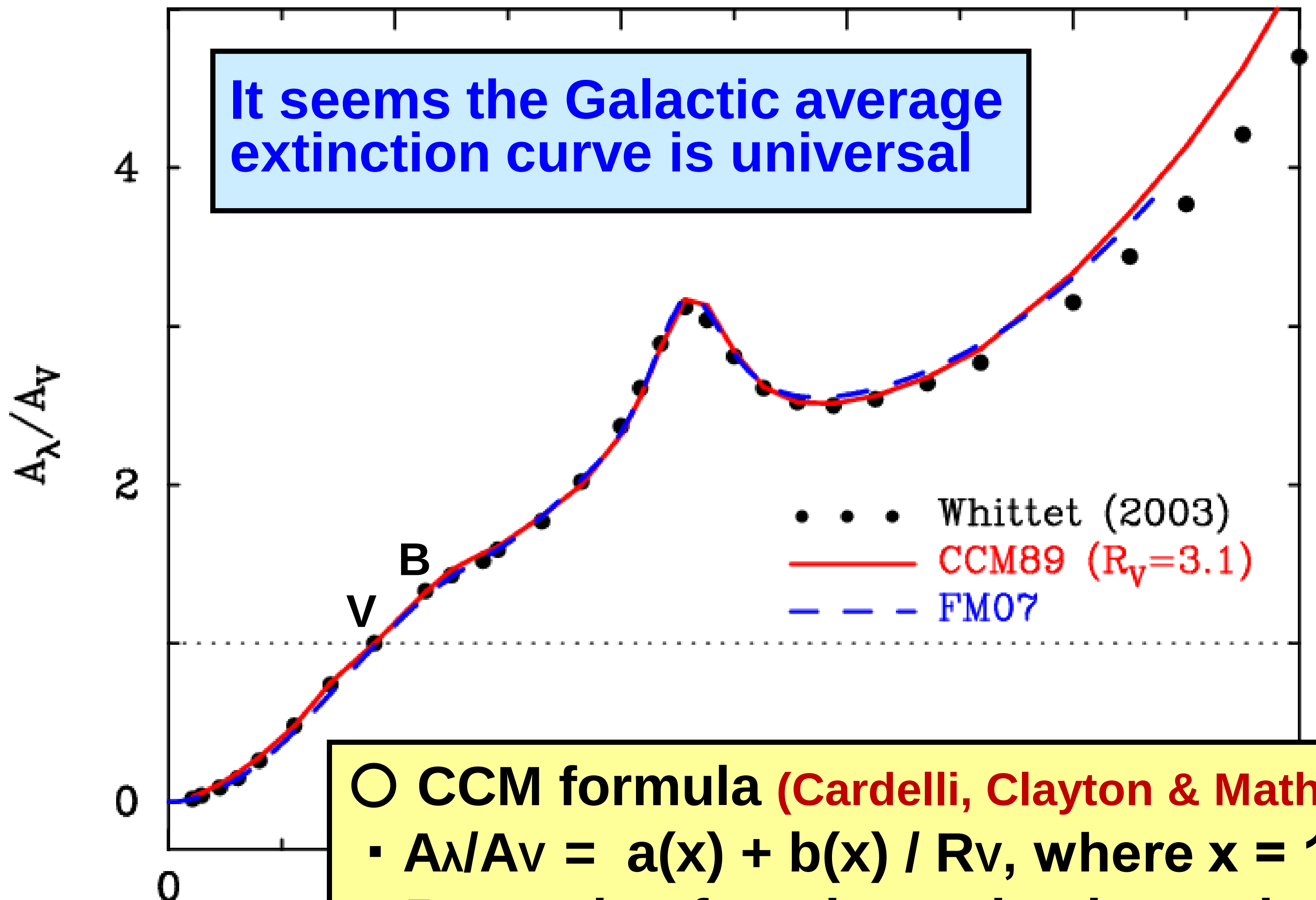
  ➔ **especially, extragalactic objects whose appearances are disturbed by the Galactic interstellar extinction**

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

  ➔ **provides information on the composition and size distribution of interstellar dust on the line of sight**

  ➔ **holds important clues to the origin and evolution history of interstellar dust (e.g., Hirashita & Nozawa 2012)**

2. Average interstellar extinction curves in MW



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

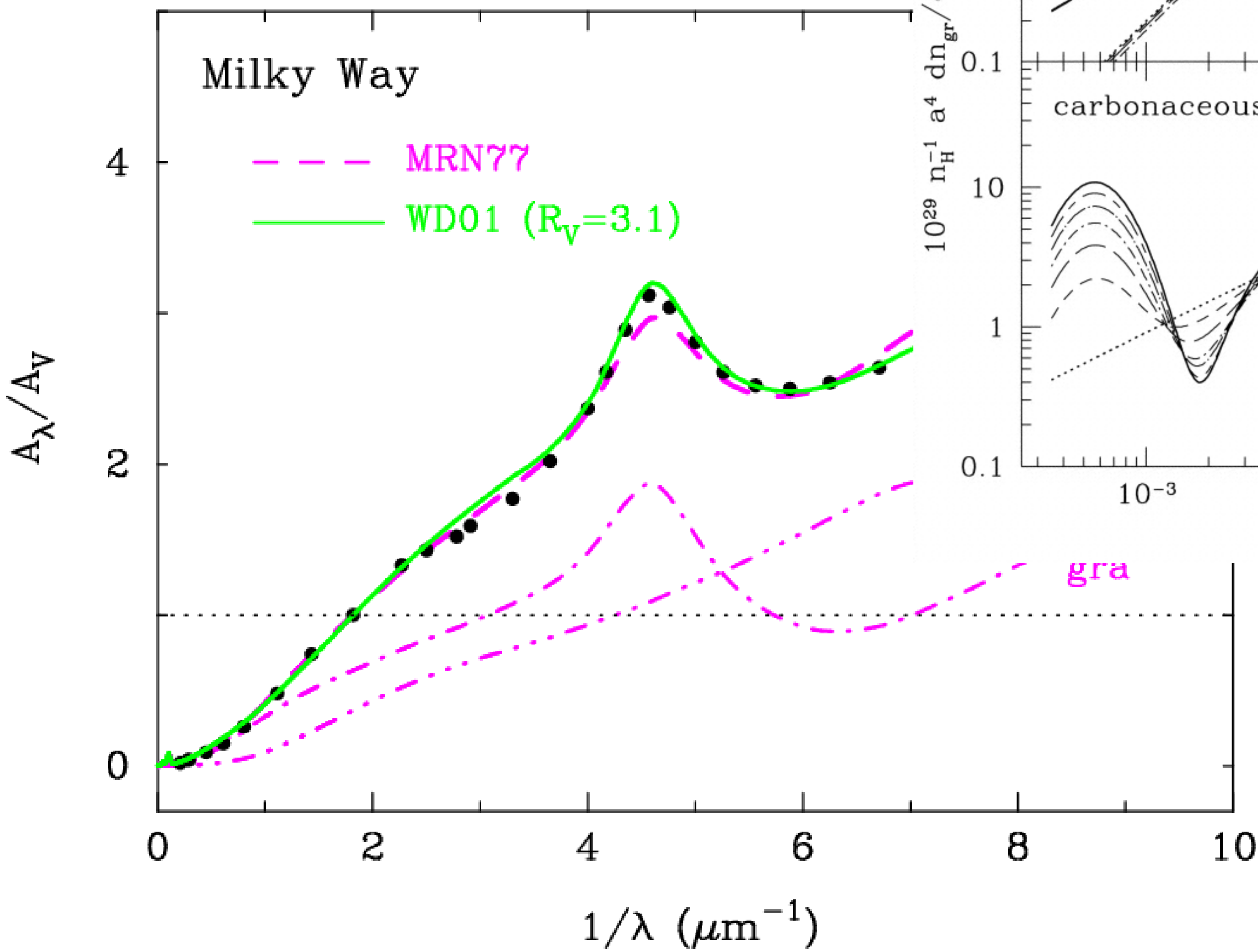
- A_λ/A_V = a(x) + b(x) / R_V, where x = 1 / λ
- R_V : ratio of total-to-selective extinction

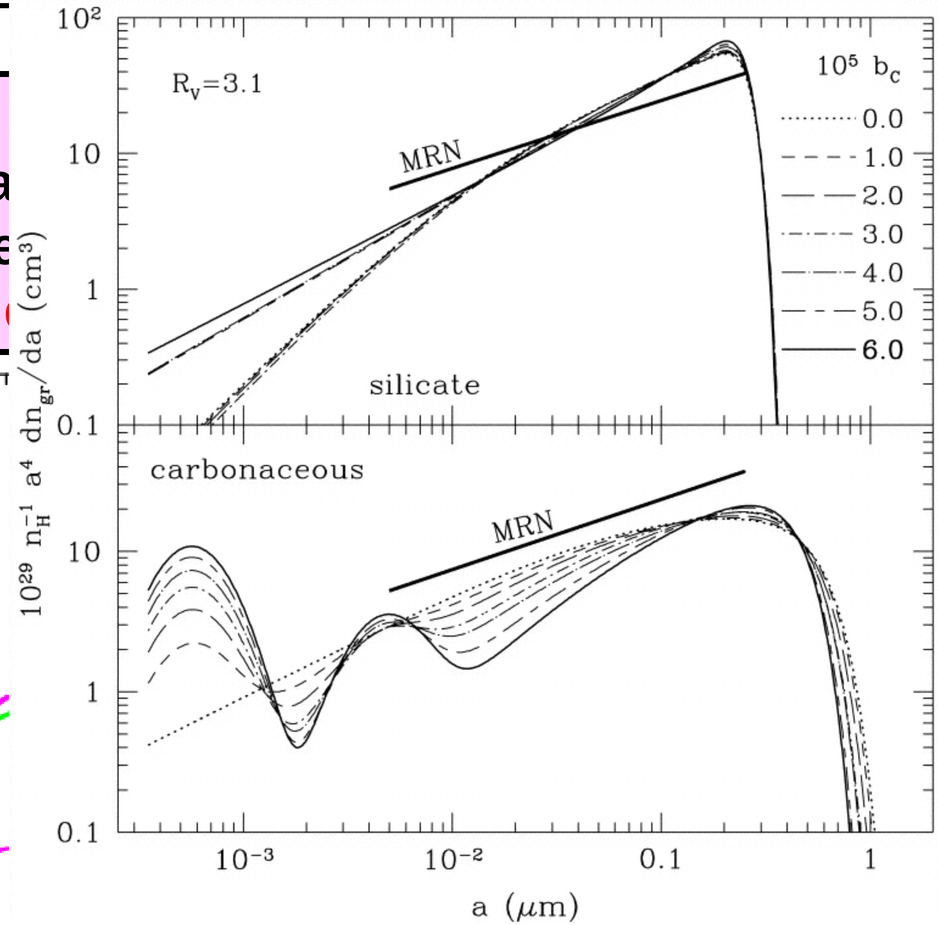
  $R_V = A_V / (A_B – A_V)$ cf. $R_{V,ave}$ = 3.1

3. Interstellar dust models in MW

○ MRN dust model **(Mathis,**
- dust composition : silica
- size distribution : powe

n(a)da ∝ a^{-q}da with (





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

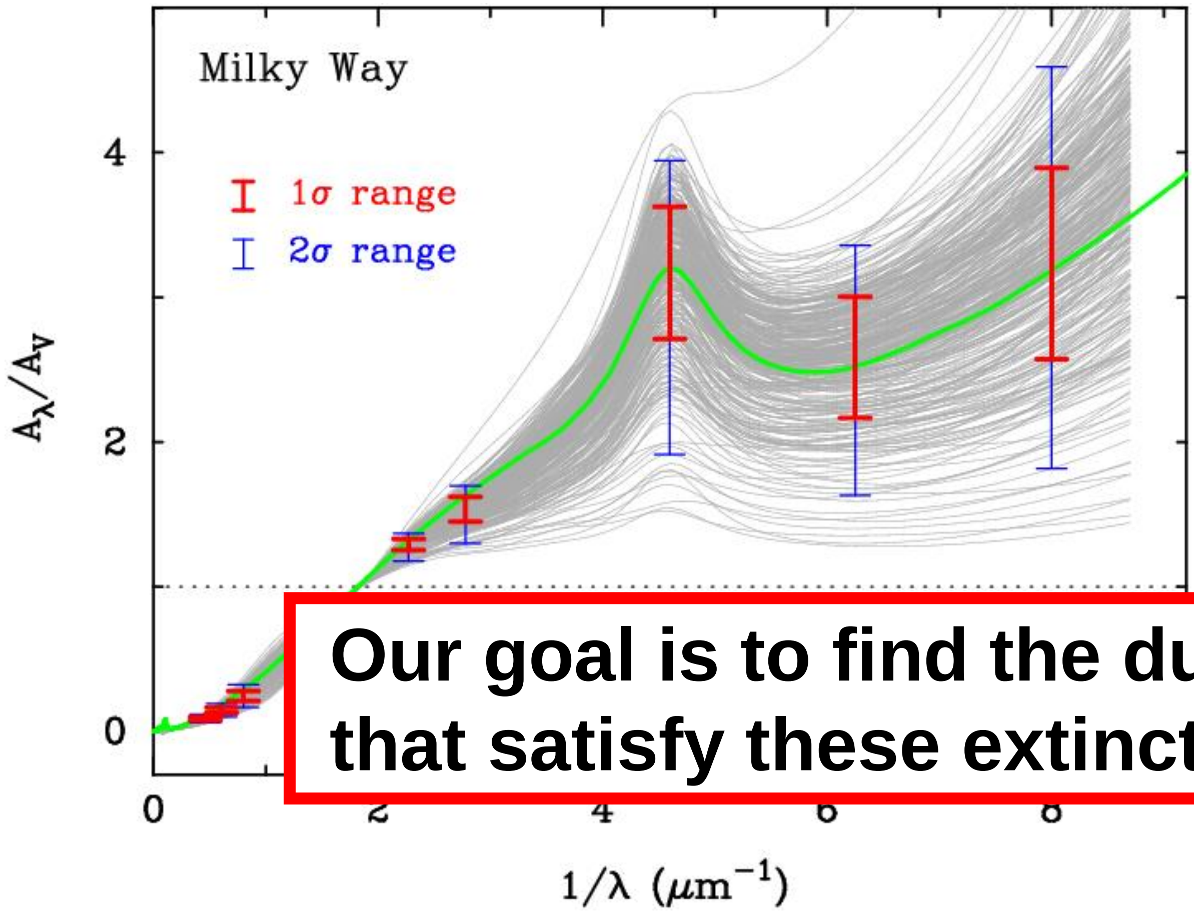
0.3 nm ≤ a ≤ 1 μm

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?**



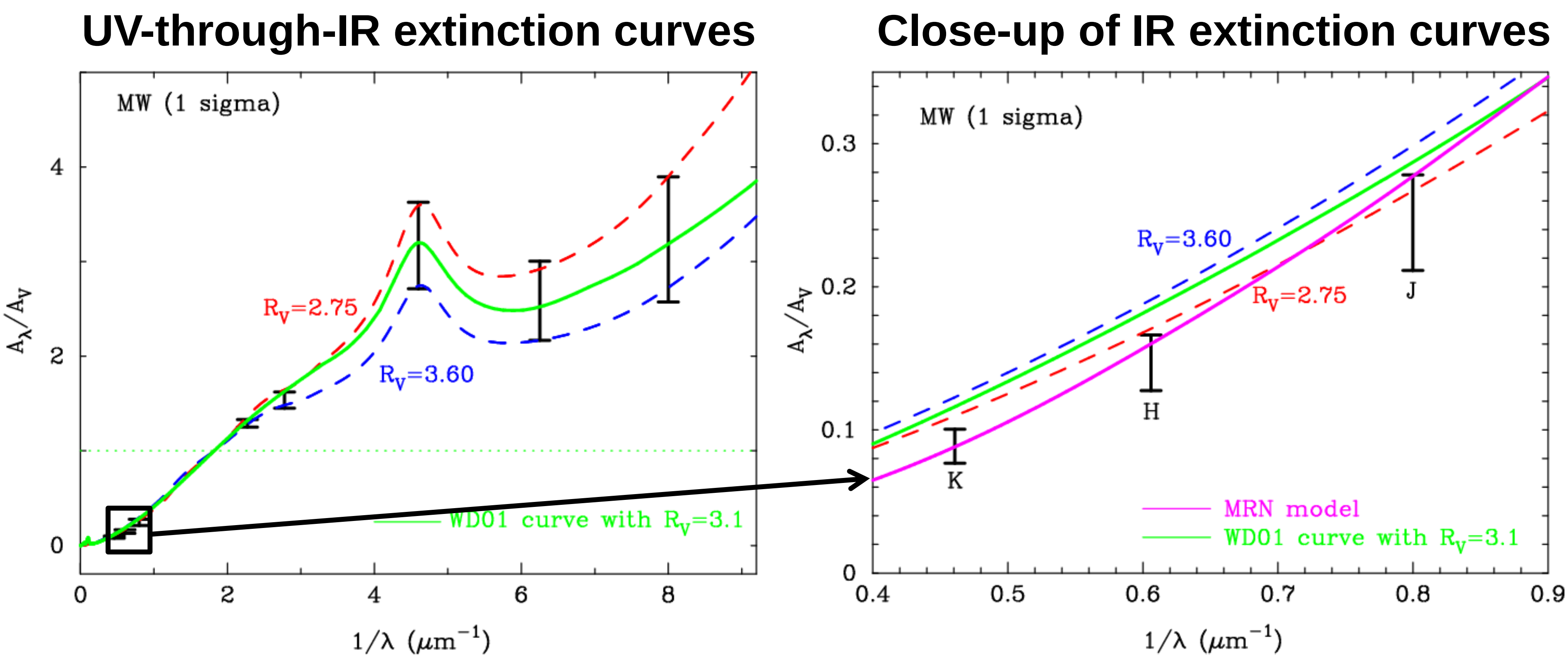
gray curves:
328 extinction curves derived by Fitzpatrick & Massa (2007, FM07)

red bars:
1σ ranges including 224 data

ling
312 data

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

5-1. Comparison between FM07 and CCM89

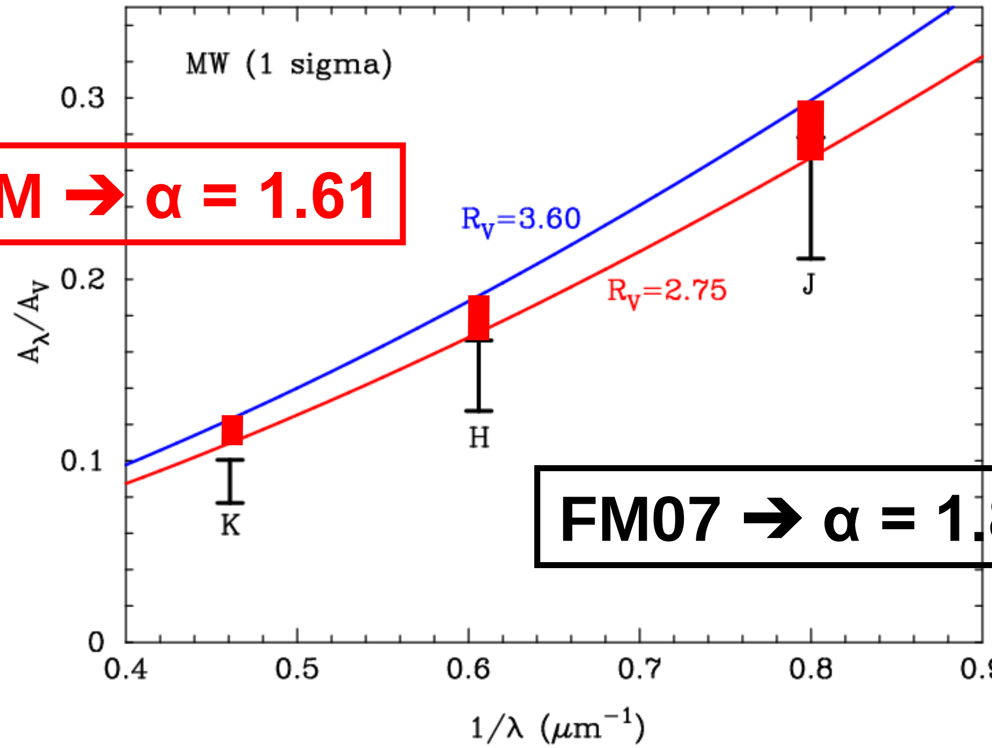


black: 1σ range of the FM07 data
red: CCM curve with Rv = 2.75
blue: CCM curve with Rv = 3.60
green: extinction curve for the case of Rv=3.1 by WD01
fully consistent in UV region

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

5-2. What is the difference in IR extinction?

NIR extinction is interpolated by power-law formula Aλ/Av ∝ λ^-α



CCM → α = 1.61

FM07 → α = 1.84

CCM : α = 1.61
from Rieke & Lebofsky (1985)

FM07 : α = 1.84
from Martin & Whittet (1990)

α = 1.7 (He et al. 1995)
α = 1.8 (Froebrich et al. 2007)
α = 2.0 (Nishiyama et al. 2006)
α = 2.3 (Larson & Whittet 2005)
α = 2.6 (Gosling et al. 2009)

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

q, a_{max} : parameters (same for different grain species)

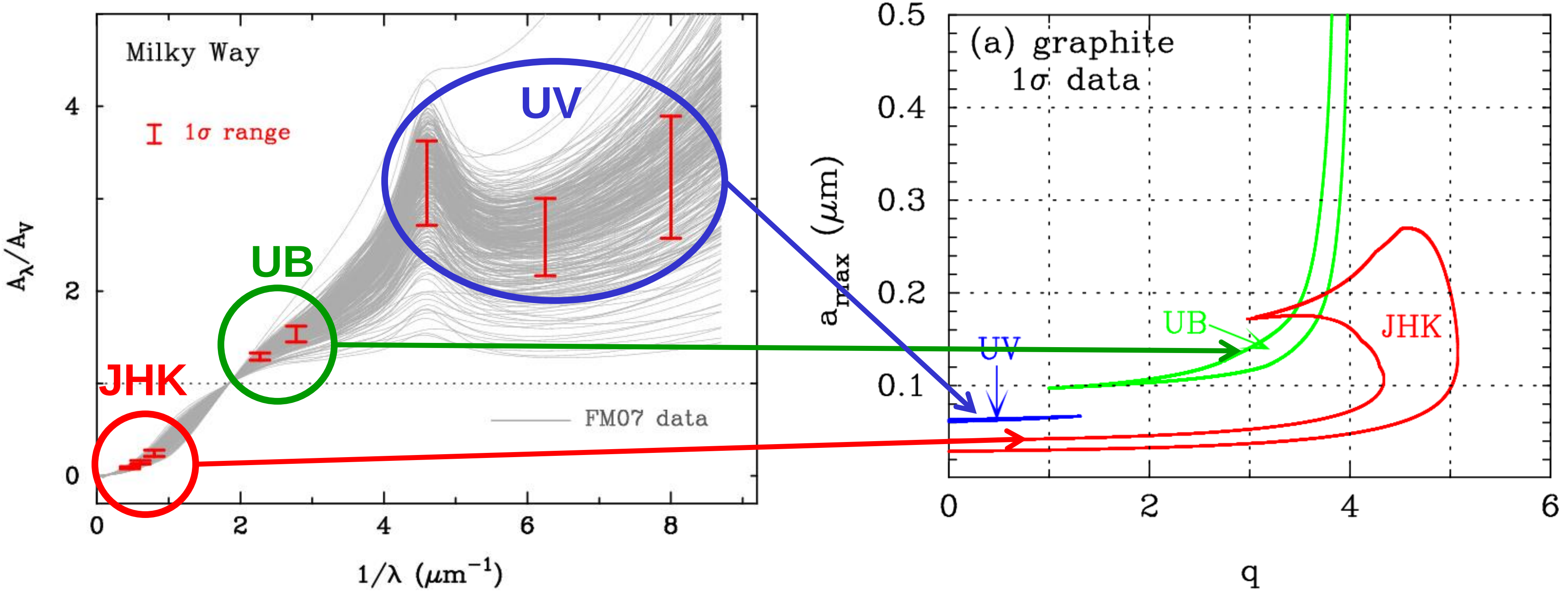
$f_{i,j}$ ➔ a fraction of an element *i* locked up in a grain *j*

- **graphite, glassy carbon, amorphous carbon**
- **astronomical silicate ($MgFeSiO_4$), Mg_2SiO_4**
- **Fe, Fe_3O_4**

to search for the combination of q and a_{max} (and $f_{i,j}$) that fulfill the observed extinction ranges

7. Illustration of contour plots

1σ range of FM07 data | **Contour plots for graphite**

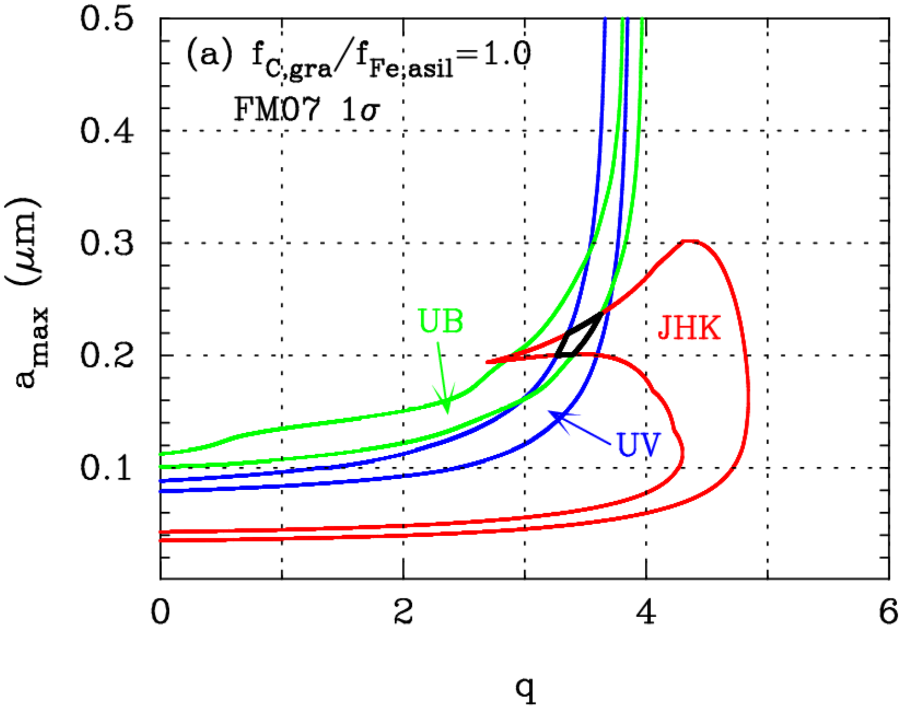


The 1σ ranges from FM07 data are classified into three groups
UV: UV bump (0.22 μm), FUV dip (0.16 μm), FUV rise (0.125 μm)
UB: U band and B band
JHK: J band, H band, K band

A contour plot is depicted for each of the groups defined in the left panel
blue: constraint from UV/FUV
green: constraint from UB band
red: constraint from JHK band

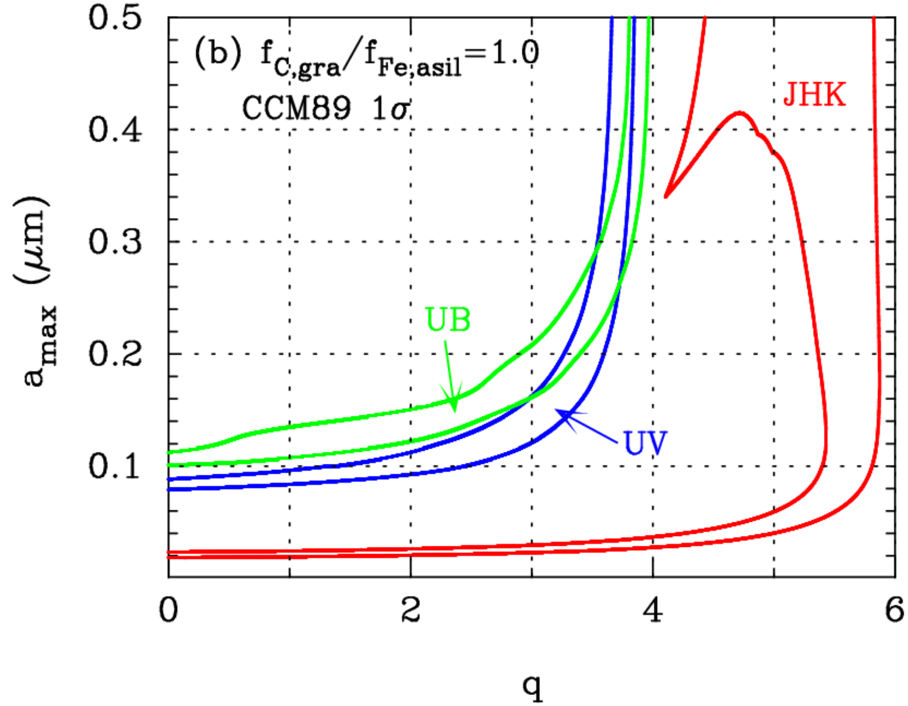
8-1. Contour plots for f_{gra}/f_{sil} = 1.0

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**

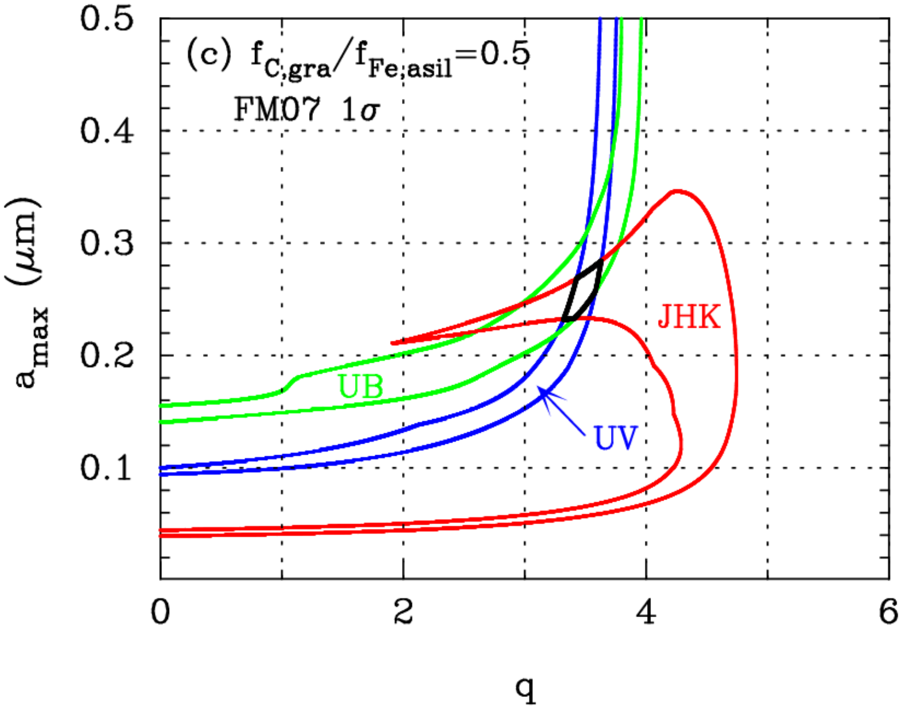
Case of 1σ data, f_{gra}/f_{sil} = 1.0



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**

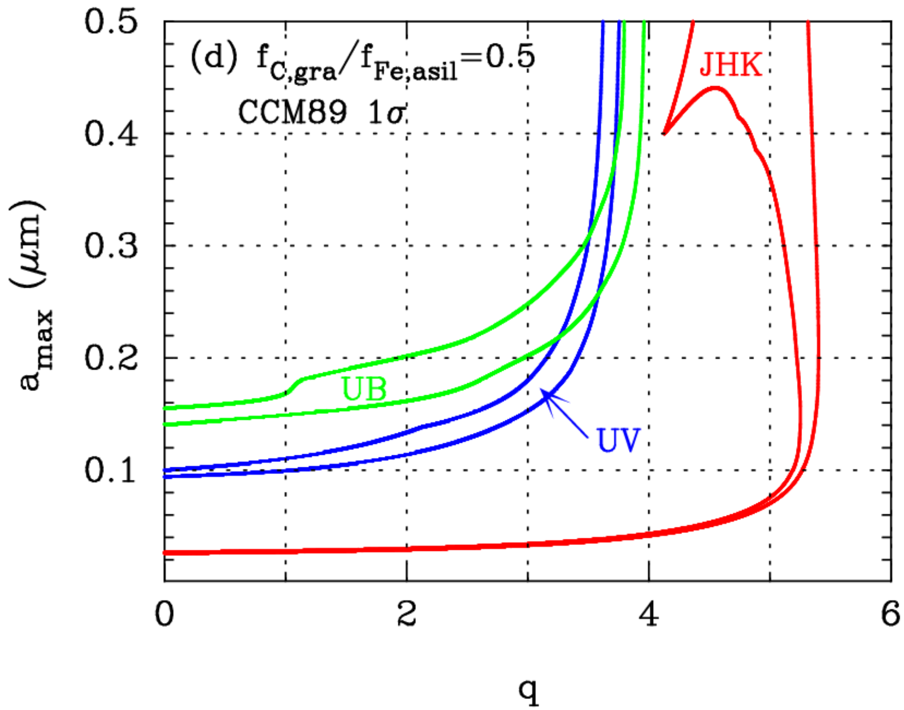
8-2. Contour plots for f_{gra}/f_{sil} = 0.5

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

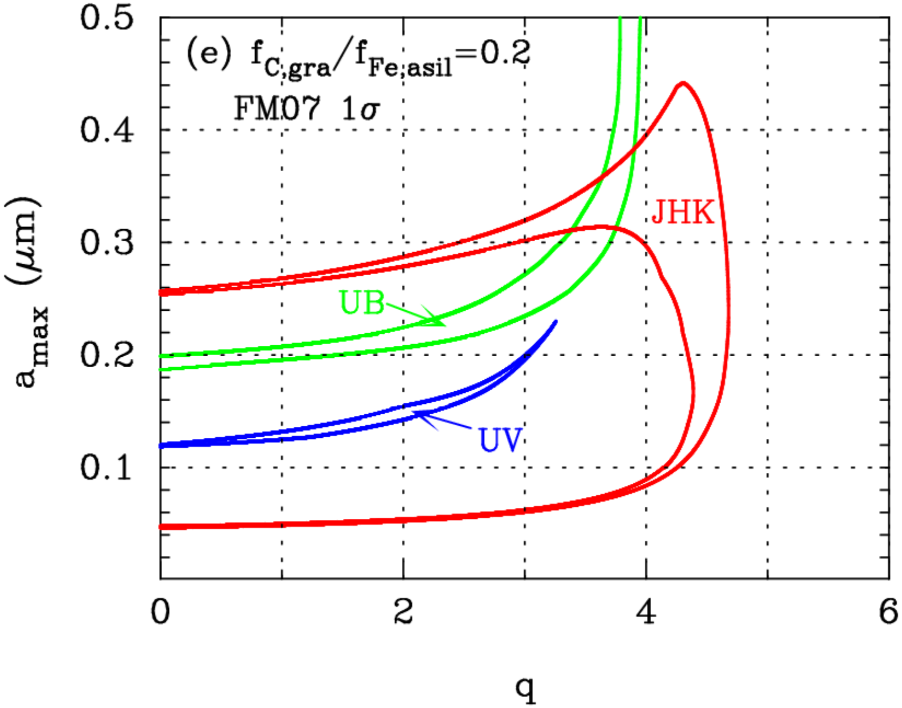
Case of 1σ data, f_{gra}/f_{sil} = 0.5



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

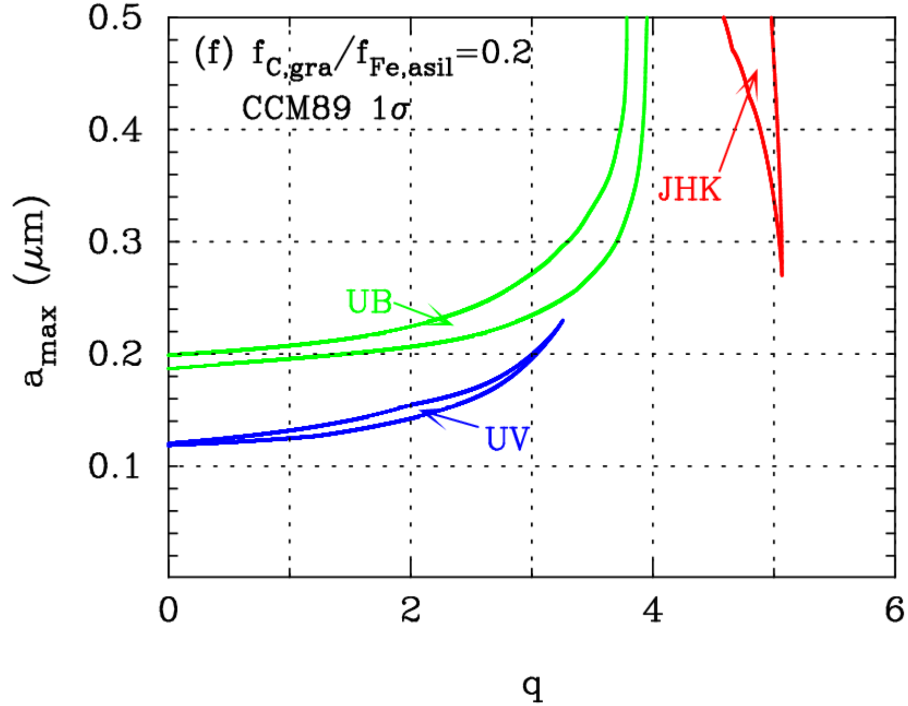
8-3. Contour plots for f_{gra}/f_{sil} = 0.2

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

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



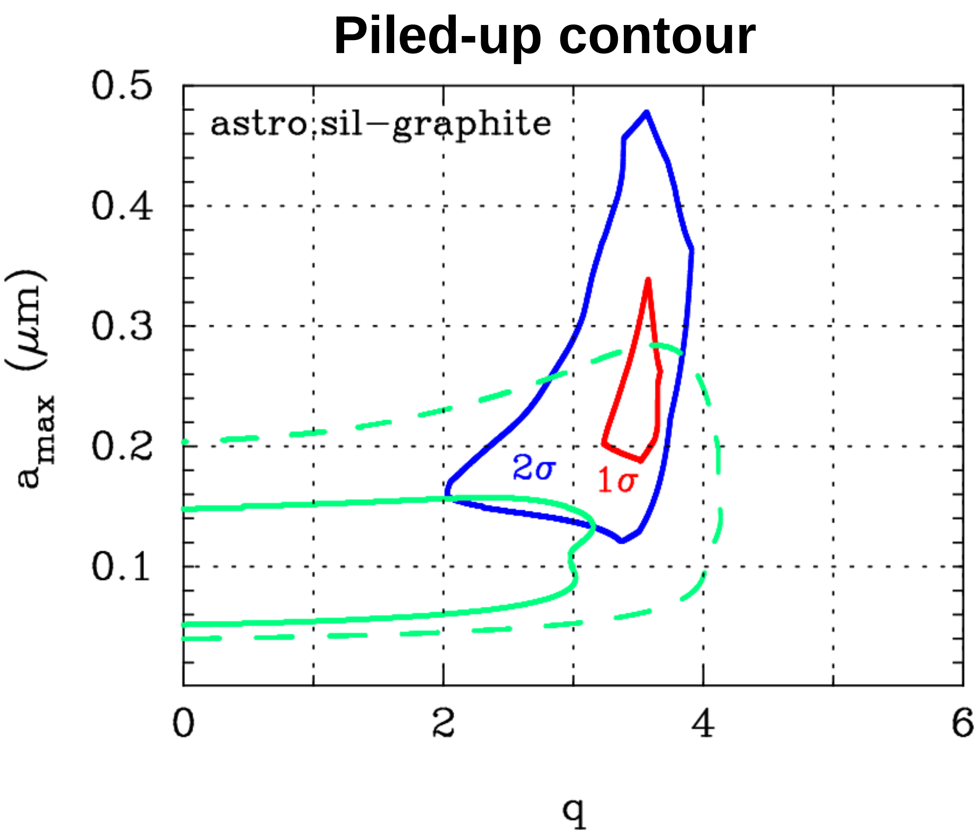
contour plots of a_{max} and q that fulfill the 1σ range of CCM result for f_{gra}/f_{sil} = 0.2 (M_{gra}/M_{sil} = 0.16)
blue: constraint from UV/FUV
green: constraint from UB band
red: constraint from JHK band

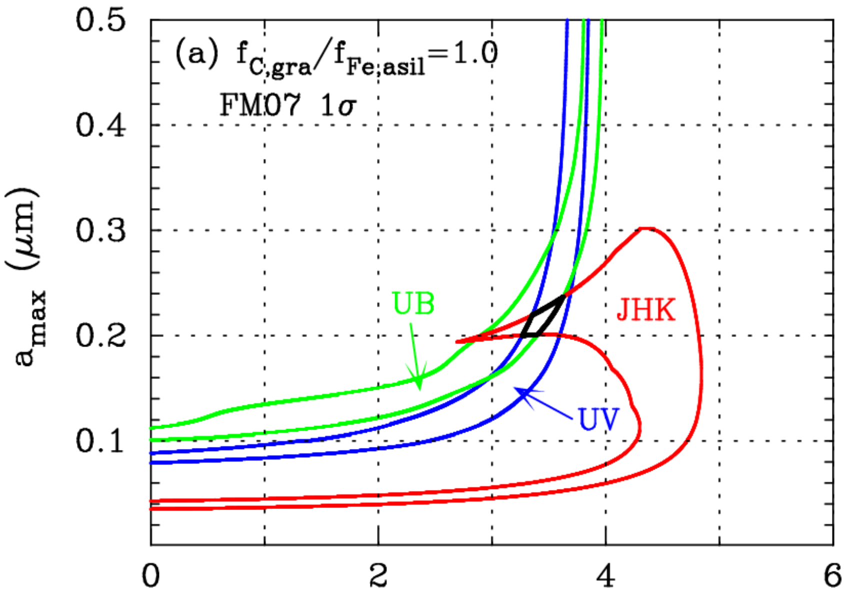
8-4. Brief summary of our results

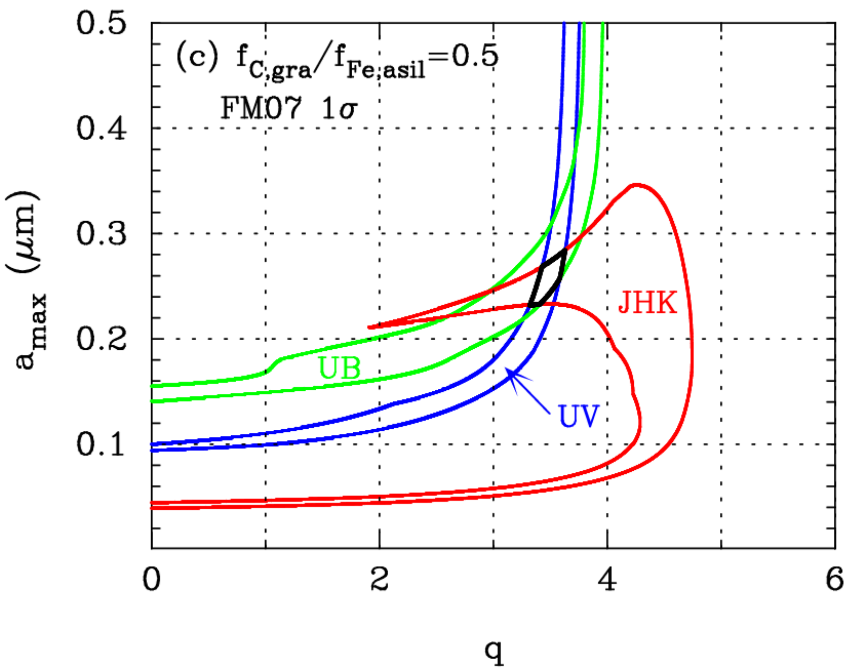
Conbination of Dust Grains	FM07 1 σ	CCM 1 σ
(1) Graphite–Astronomical Silicate	Yes	No
(2) Glassy Carbon–Astronomical Silicate	No	No
(3) Amorphous Carbon–Astronomical Silicate	No	No
(4) Graphite–Glassy Carbon–Astronomical Silicate	Yes	No
(5) Graphite–Amorphos Carbon–Astronomical Silicate	Yes	No
(6) Graphite–Fe	Yes	No
(7) Graphite–Fe_3O_4	No	No
(8) Graphite–Astronomical Silicate–Fe	Yes	No
(9) Graphite–Astronomical Silicate–Fe_3O_4	Yes	Yes
(10) Graphite–Mg_2SiO_4	Yes	No
(11) Graphite–Mg_2SiO_4–Fe	Yes	No
(12) Graphite–Mg_2SiO_4–Fe_3O_4	Yes	Yes

Almost all of the dust models considered here do not have combinations of q and a_{max} that meet extinction ranges when the CCM NIR extinction is considered

9-1. Piled-up contour for graphite-astro.sil







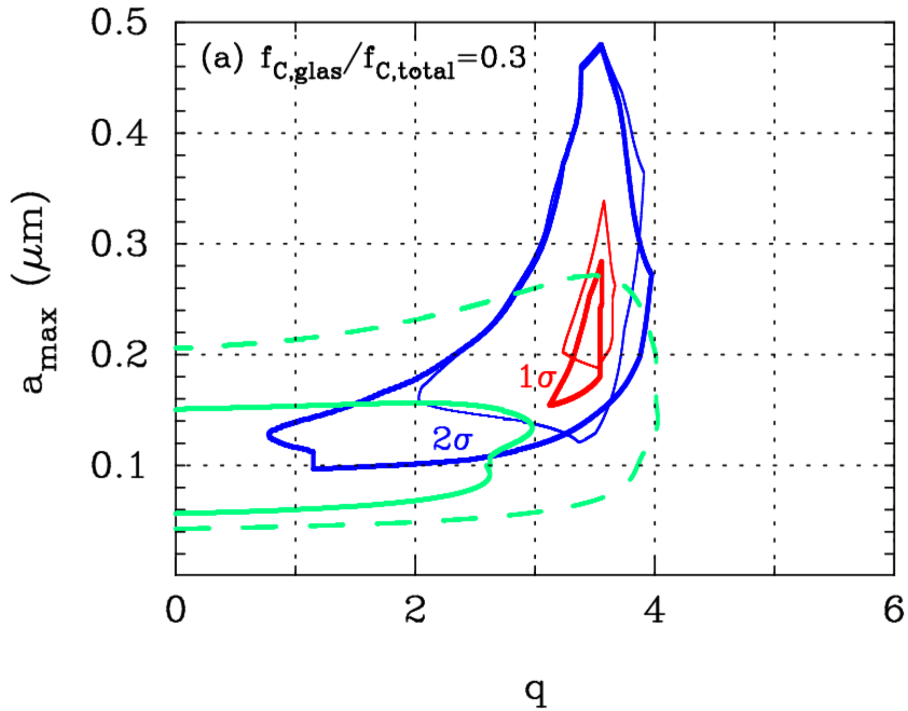
Values of q and a_{max} that meet the 1σ range of FM07 data are confined to be narrow ranges

3.2 < q < 3.7

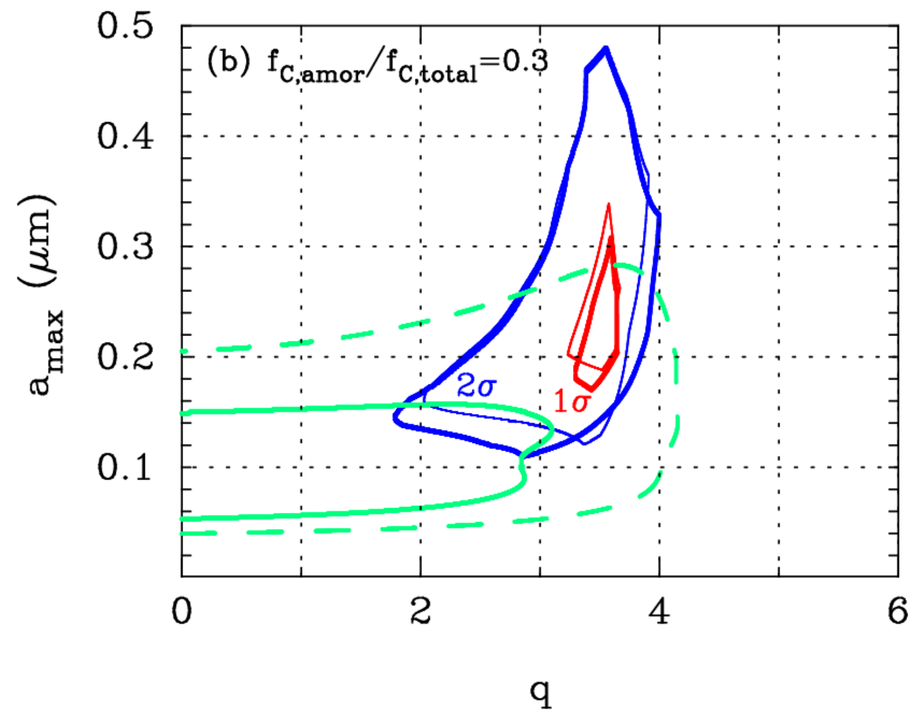
0.19 um < a_{max} < 0.34 um

9-2. Piled-up contour for carbon-astro.sil

30 % of C included in glas.car



30 % of C included in amor.car



70 % of C ➔ graphite
30 % of C ➔ glassy carbon

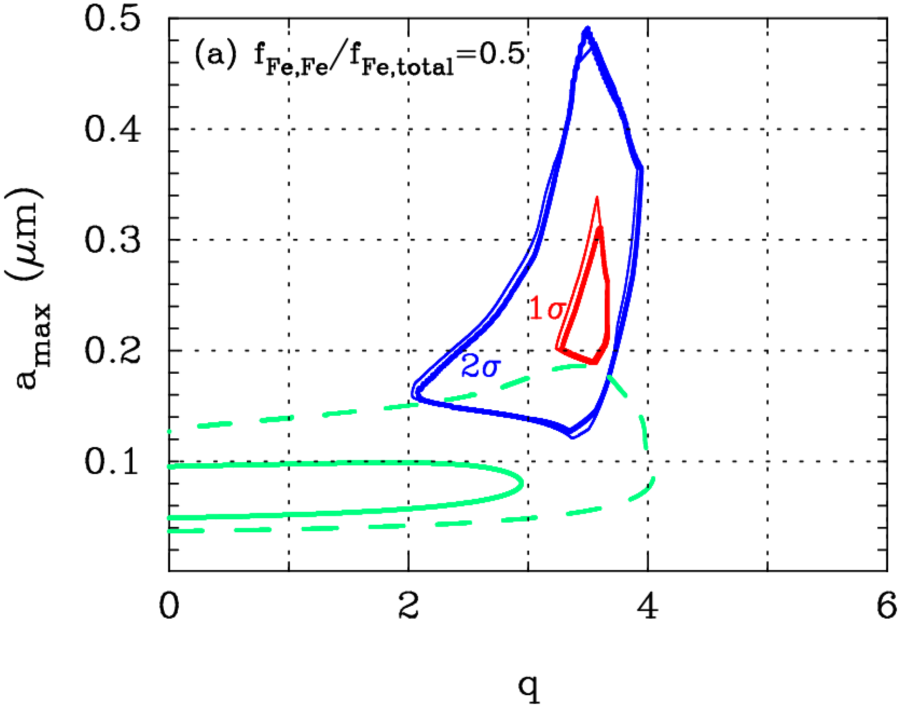
The thin lines are for graphite-astronomical silicate

70 % of C ➔ graphite
30 % of C ➔ amorphous carbon

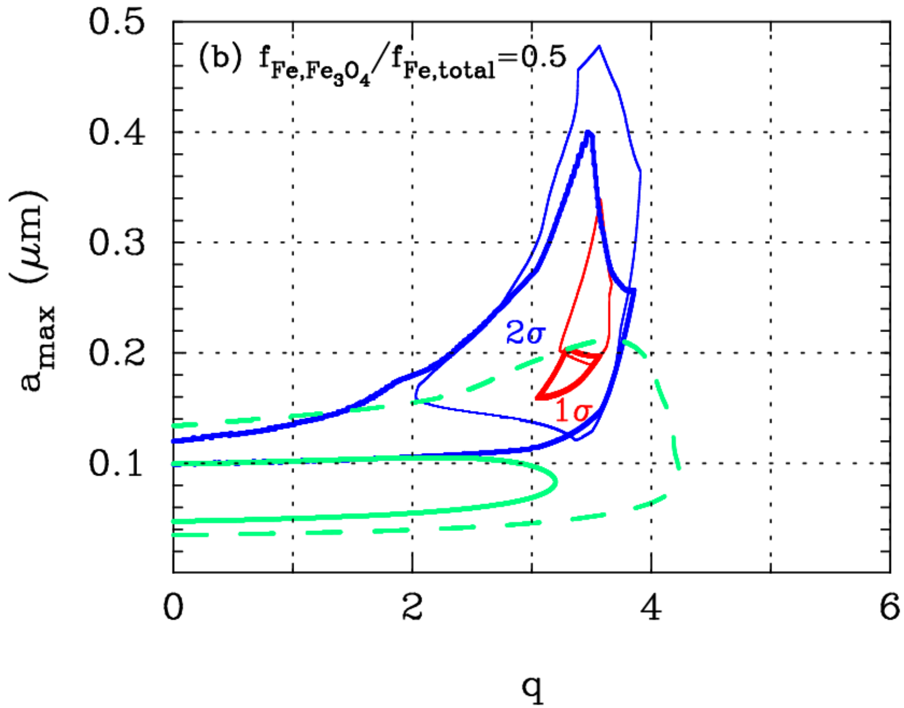
The thin lines are for graphite-astronomical silicate

9-3. Piled-up contour for carbon-asil-Fe bearing

50 % of Fe included in Fe grain



50 % of Fe included in Fe_3O_4



50 % of Fe ➔ astron.silicate
50 % of Fe ➔ Fe grains

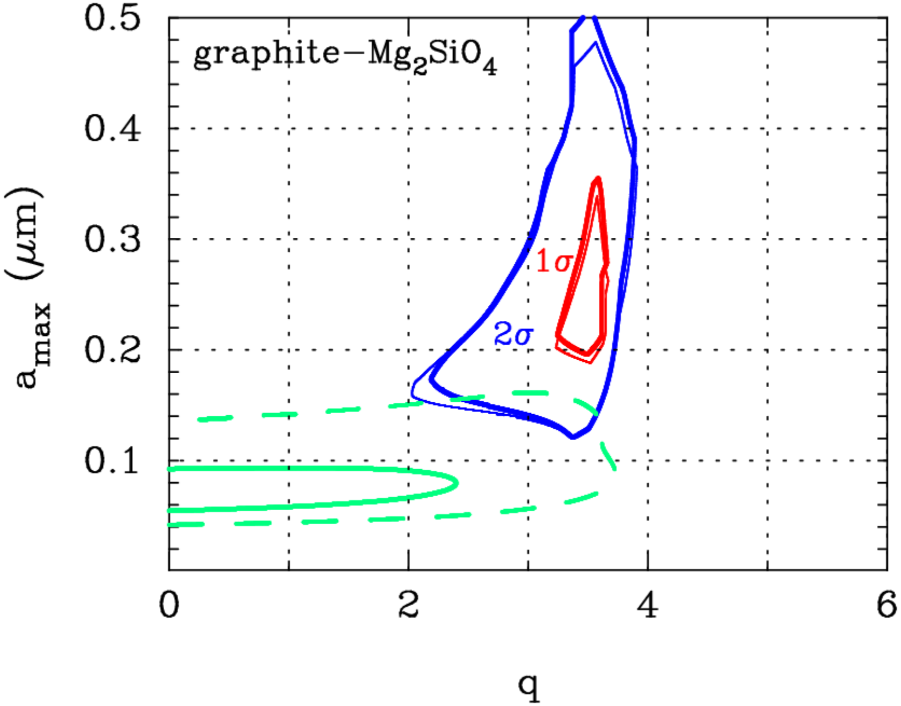
The thin lines are for graphite-astronomical silicate

50 % of Fe ➔ astron.silicate
50 % of Fe ➔ Fe_3O_4 grains

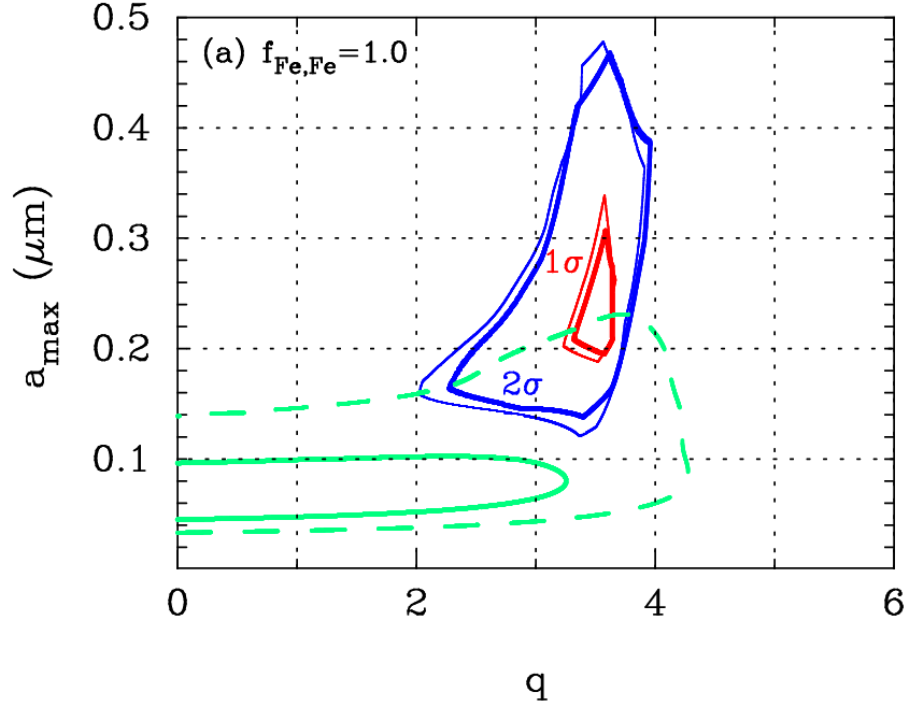
The thin lines are for graphite-astronomical silicate

9-4. Piled-up contour for graphite-Mg_2SiO_4

Graphite-Mg_2SiO_4



Graphite-Mg_2SiO_4-Fe



astronomical silicate ($MgFeSiO_4$) is replaced with Mg_2SiO_4

The thin lines are for graphite-astronomical silicate

all of Fe atoms are locked up in Fe grains

The thin lines are for graphite-astronomical silicate

10. Summary

- **The observed ranges of NIR extinction from FM07 do not match with the results from the CCM formula**

  ➔ **The average interstellar extinction curve is not necessarily universal in NIR regions**

- **For the power-law grain-size distribution**

  — **The values of q and a_{max} that satisfy the observed 1σ ranges of FM07 are confined to narrow ranges**

  — **There is no combination of q and a_{max} that satisfy the observed ranges when CCM results are adopted**

  — **For any combinations of grain species considered, the values of q and a_{max} that meet the observed extinction are distributed around 3.5 and 0.25 um**