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Properties of Dust Responsible for Extinction Laws toward Type Ia Supernovae

- Ia型超新星の減光則を担うダストの性質 -

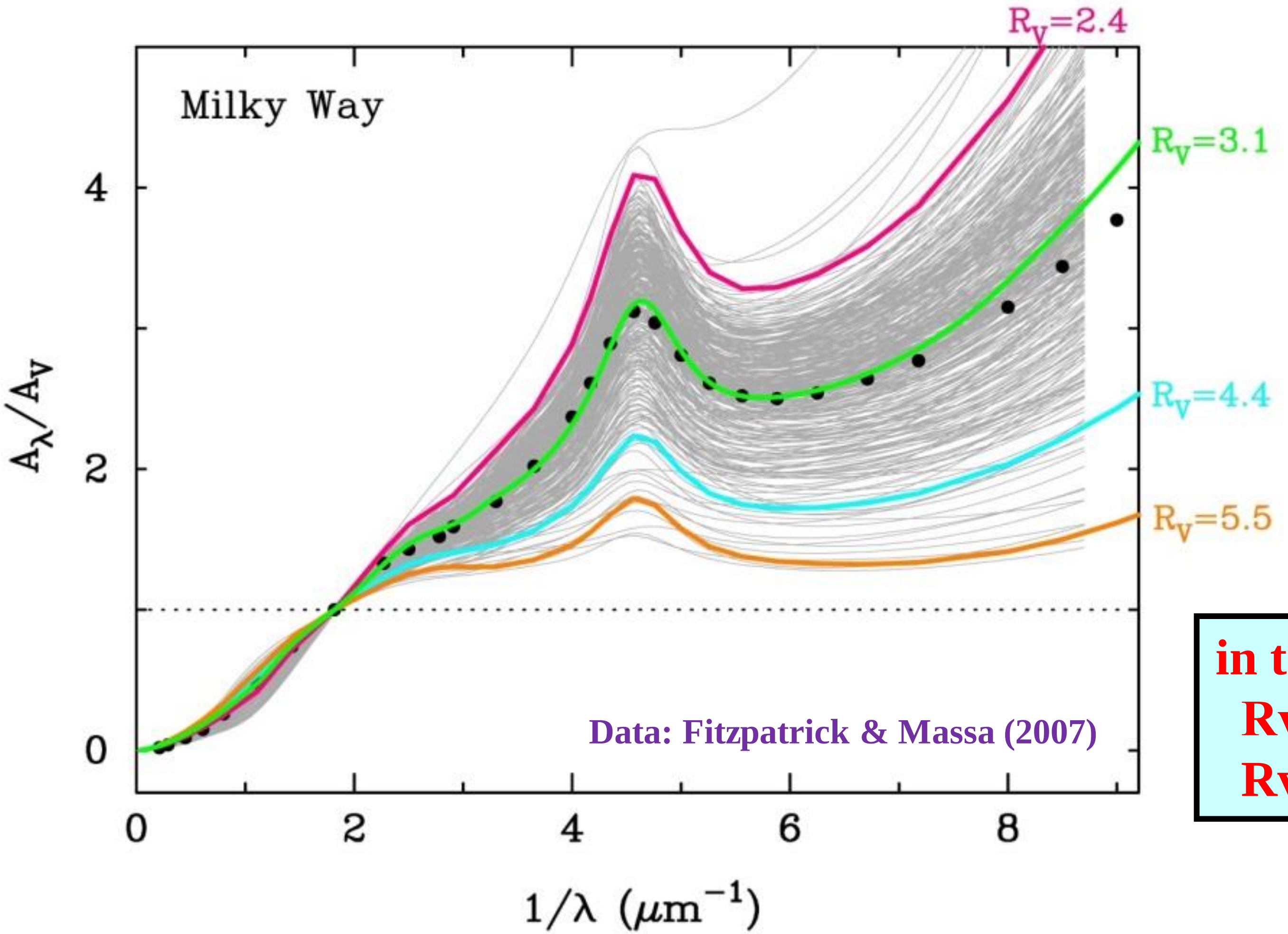
野沢 貴也（Takaya Nozawa）

国立天文台 理論研究部

(National Astronomical Observatory of Japan)

- Nozawa, T. 2016, PSS (special issue for Cosmic Dust VIII), 133, 26
- Nagao, T., Maeda, K., Nozawa, T. 2016, ApJ, 823, 104
- Maeda, K., Nozawa, T., Nagao, T., Motohara, K. 2015, MNRAS, 452, 3281

1-1. Extinction curves in the Milky Way



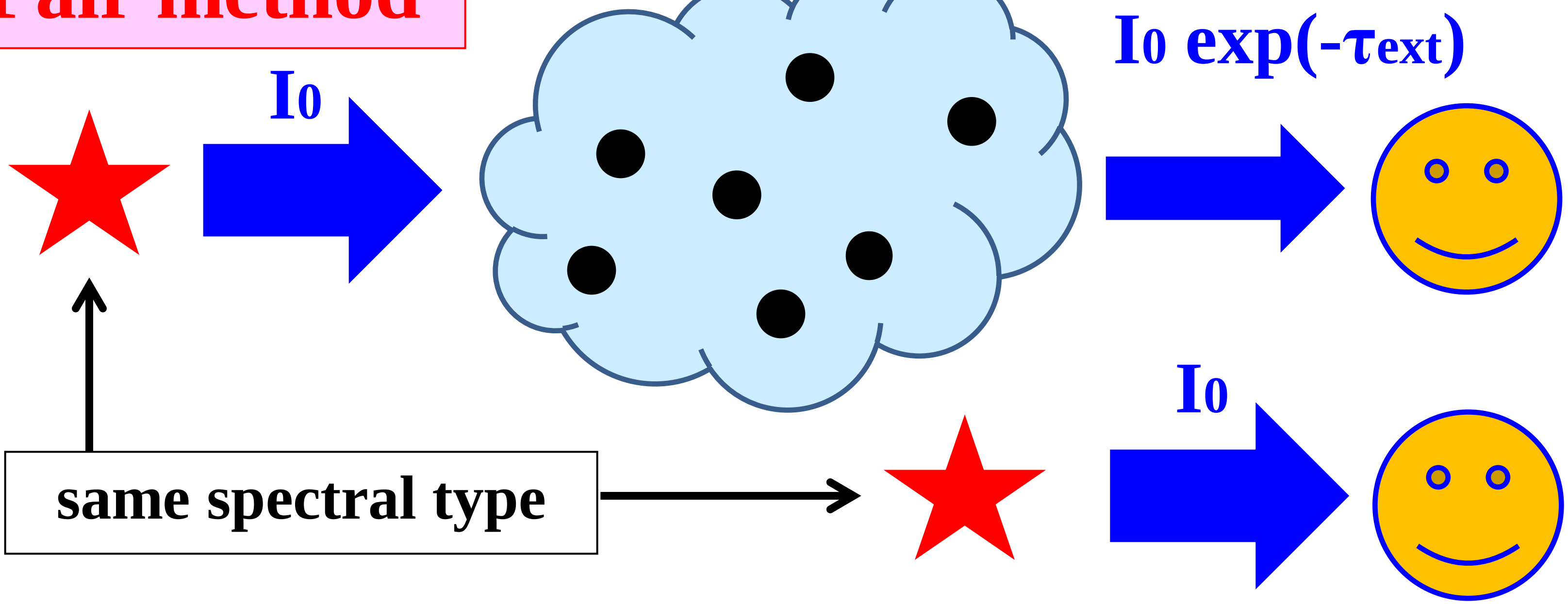
in the MW
Rv = 2.2—6
Rv,ave = 3.1

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

➜ describes the variety of extinction curves in the MW through total-to-selective extinction ratio Rv = Av/E(B-V) = Av/(AB–Av)

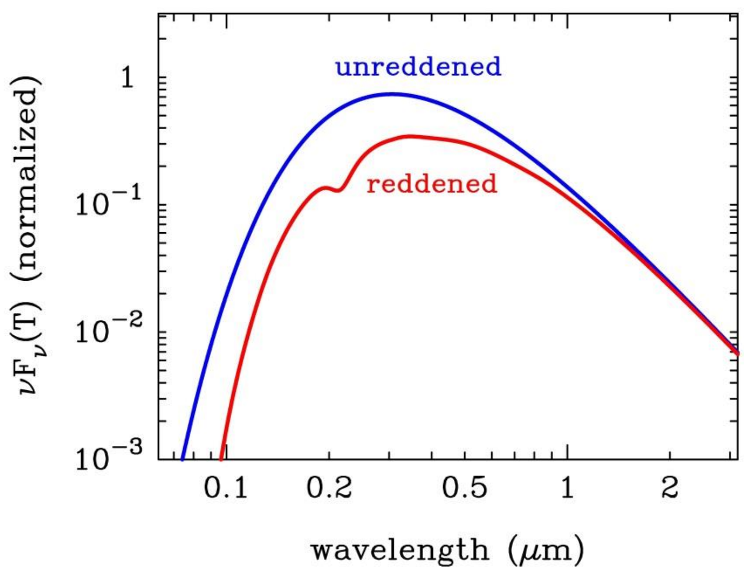
1-2. Deriving extinction curves in the MW

Pair method



○ Light sources: OB stars (or RGs)

- luminous (~ 10^5 L_{sun})
  ➜ we can see a large volume
- UV (or IR) bright
  ➜ variation of extinction curves at UV wavelengths

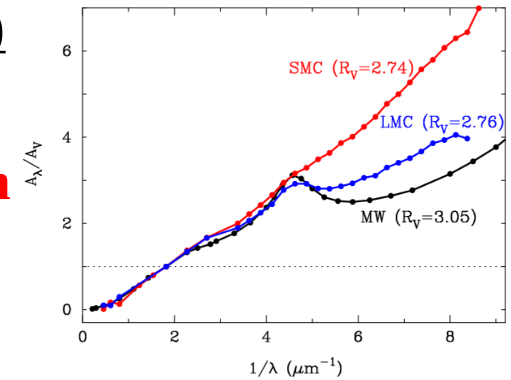


1-3. Applicability of OB stars in pair method

- OB stars can be used only for MW, LMC, SMC, (M31)

  ➜ too faint to be observed in external galaxies

  Extinction curves in external galaxies are poorly known

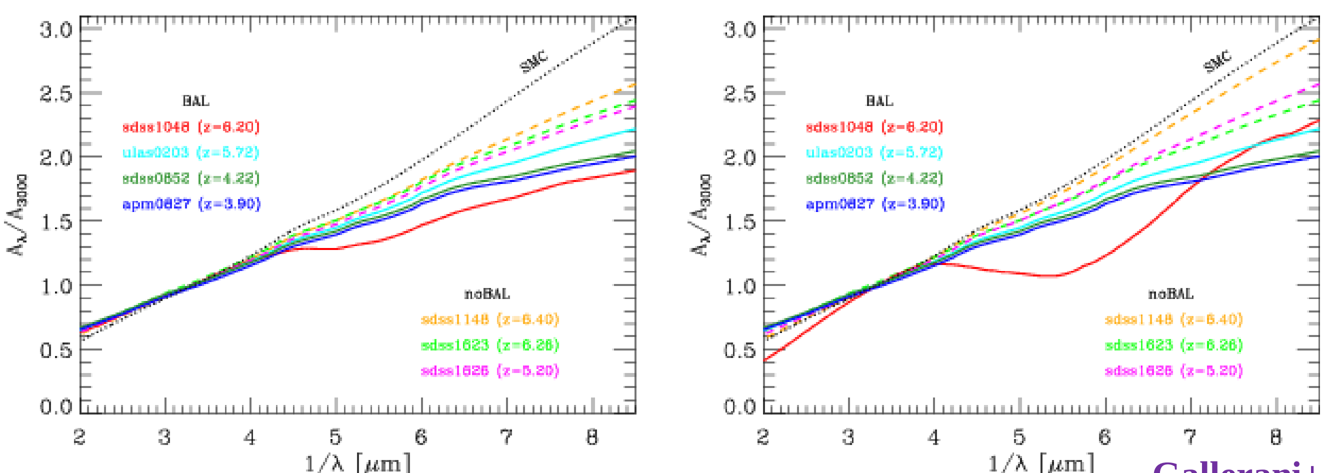


- QSOs and GRB afterglows

  ➜ good light sources to extract the extinction curves at z = 0-6.5

However …

- intrinsic spectral energy distributions are not always established
- local dust may also contribute the observed extinction



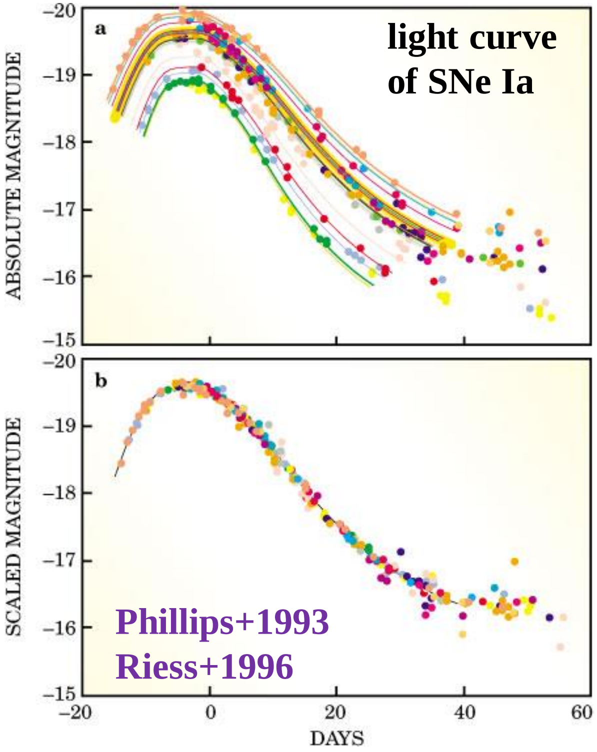
Gallerani+2010

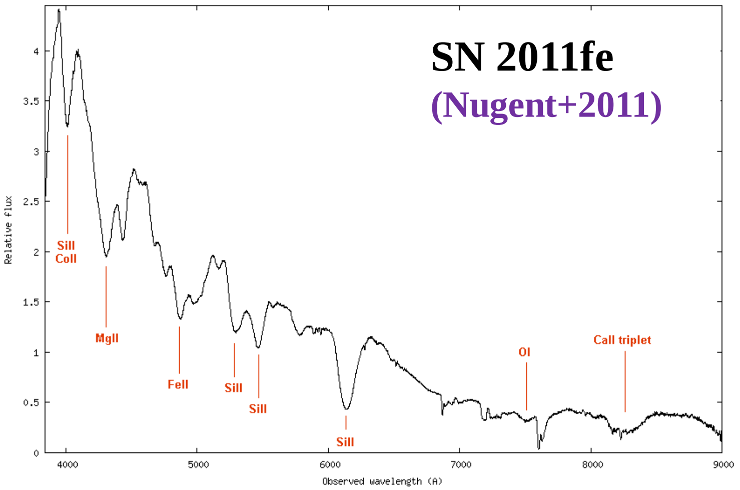
2-1. Type Ia SNe as standard light sources

○ Type Ia supernovae (SNe Ia)

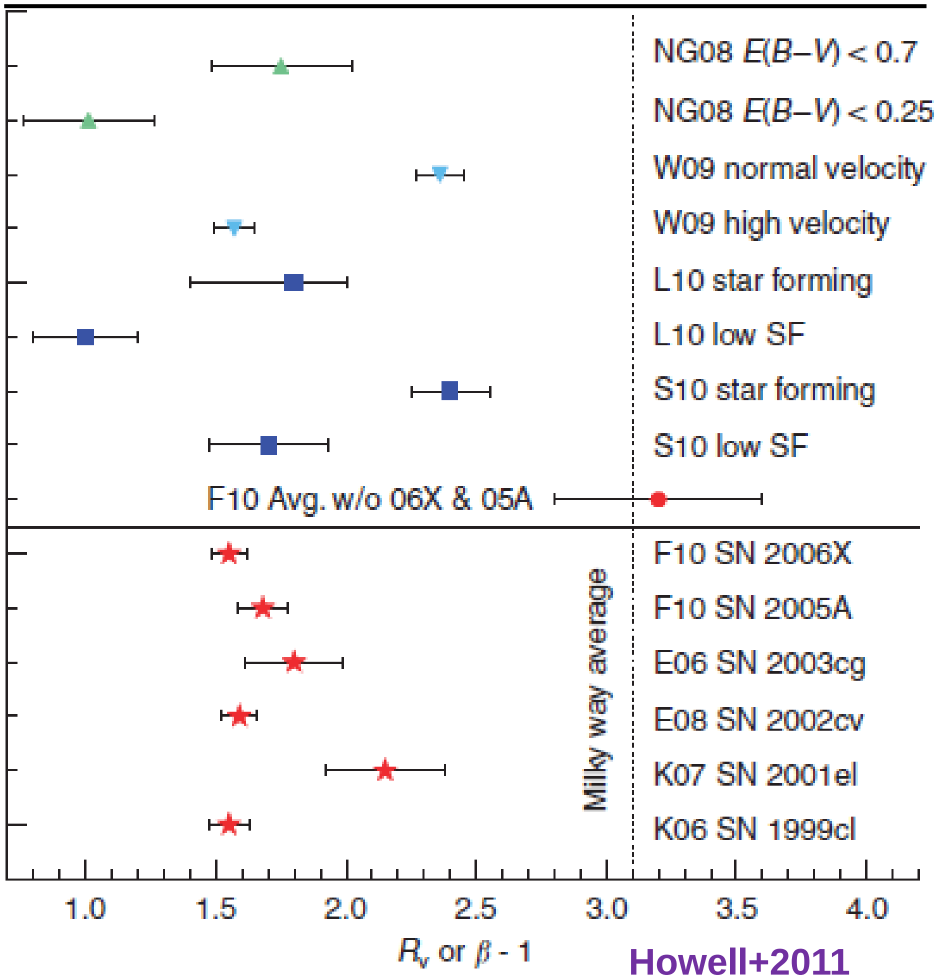
- **thermonuclear explosion of a WD**
- **highly luminous ($L_{peak} \sim 3\times10^{9}\ L_{sun}$)**
  - ➜ **homogeneous peak luminosity**
  - ➜ **used as standard candles**
- **intrinsic opt/IR spectral established**
  - ➜ **SN 2011fe as an unreddened template**
- **discovered in all types of galaxies**
  - ➜ **star-forming, elliptical, spiral etc…**

good targets to probe the extinction (dust) properties in external galaxies

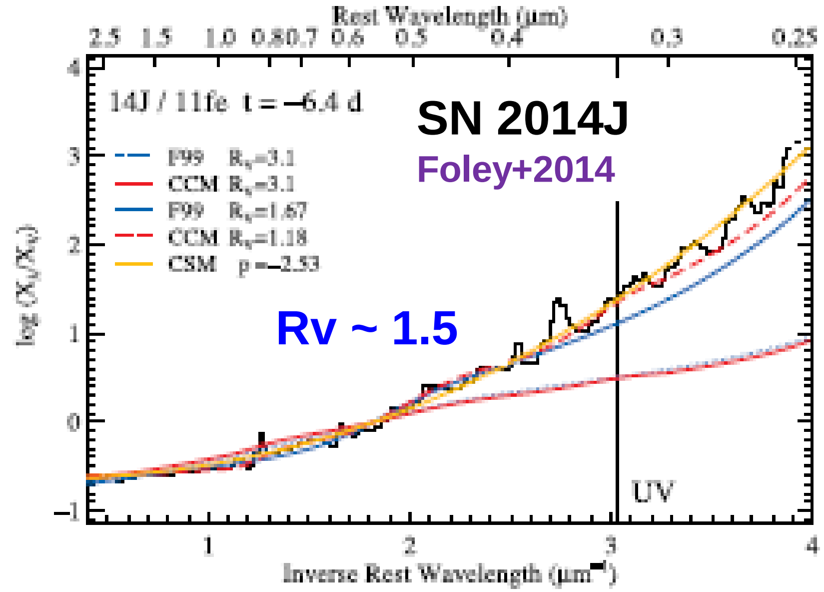




2-2. Extinction laws measured for SNe Ia



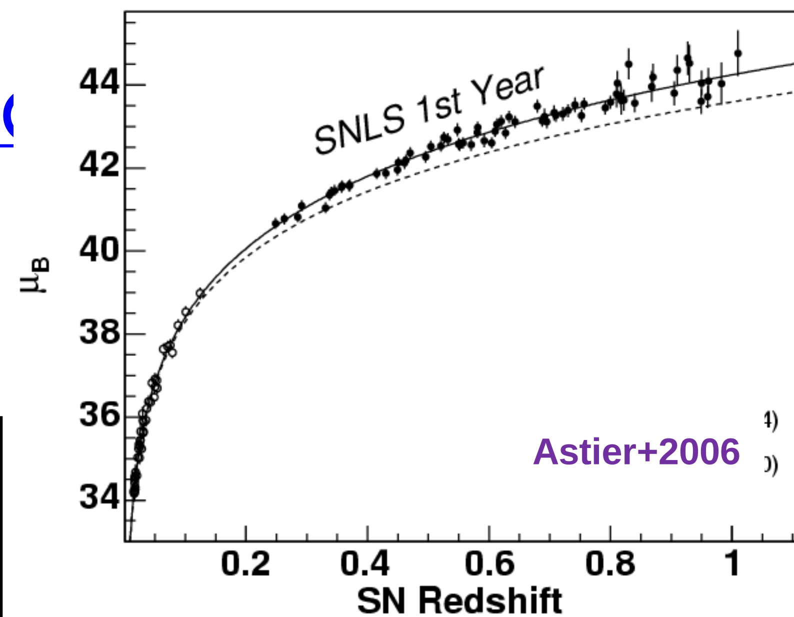
Howell+2011



SN 2014J

Foley+2014

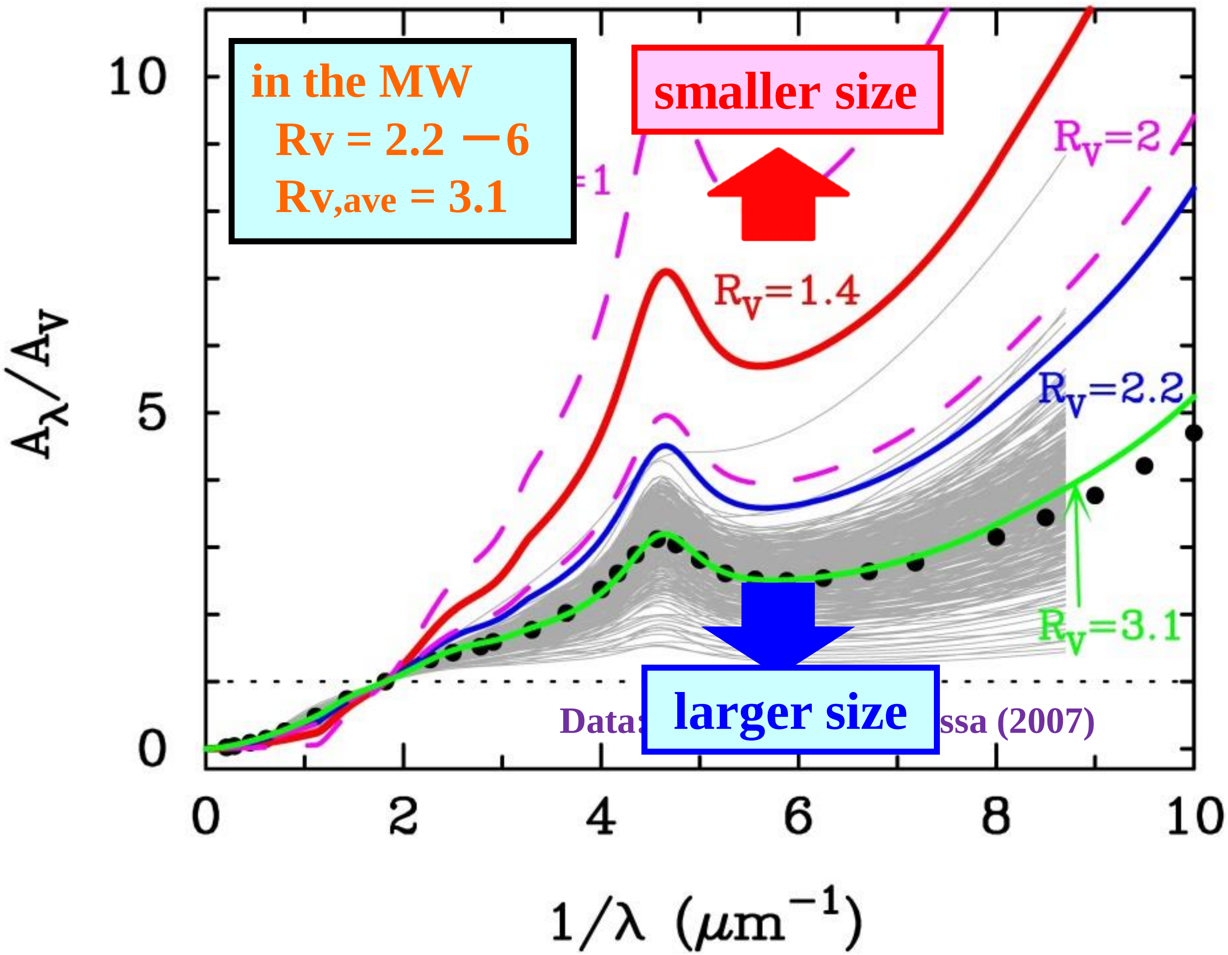
Rv ~ 1.5



Astier+2006

Rv values measured for SNe Ia are unusually low (Rv ~ 1.0-2.5)

2-3. How peculiar is SNe Ia extinction curves?



○ **CCM relation**

(Cardelli, Clayton, Mathis 1989)

Rv : total-to-selective extinction ratio

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

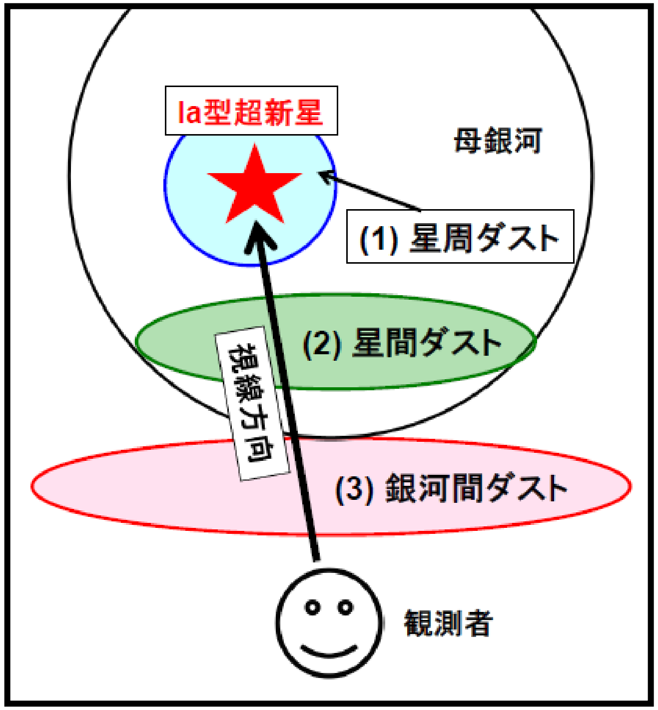
$= A_V / (A_B - A_V)$

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

where $x = 1 / \lambda$

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

3-1. What is the cause for unusually low Rv?



(1) Unique properties or effects of circumstellar dust around SN Ia

(2) Peculiar properties of interstellar dust in host galaxies of SN Ia

(3) Non-standard properties of extragalactic dust ➜ unlikely

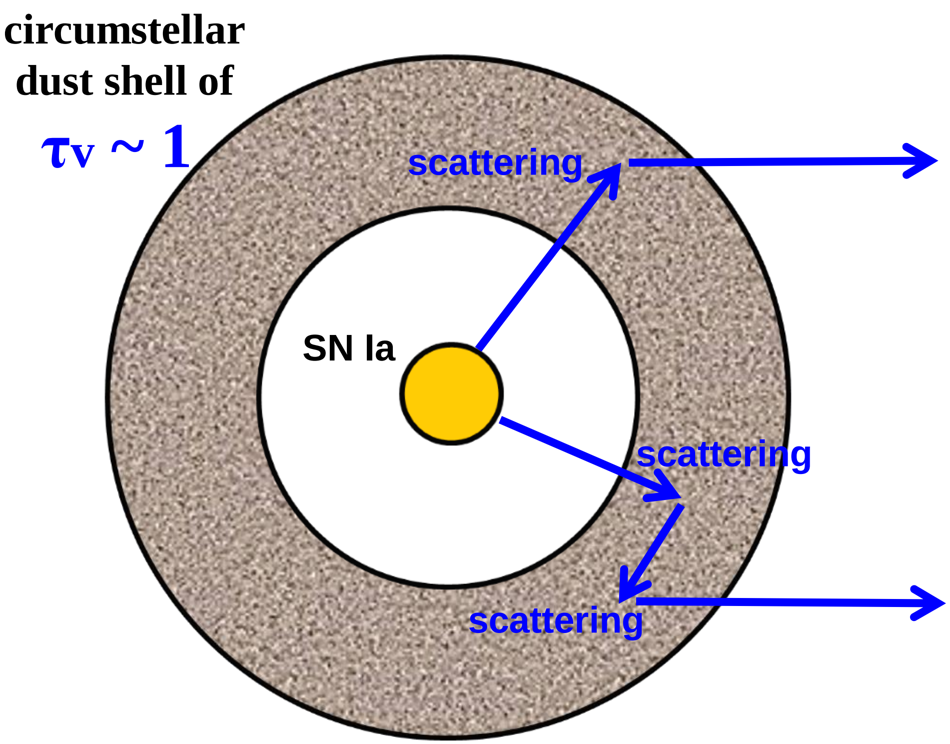
(4) Something is wrong in deriving the extinction laws toward SNe Ia

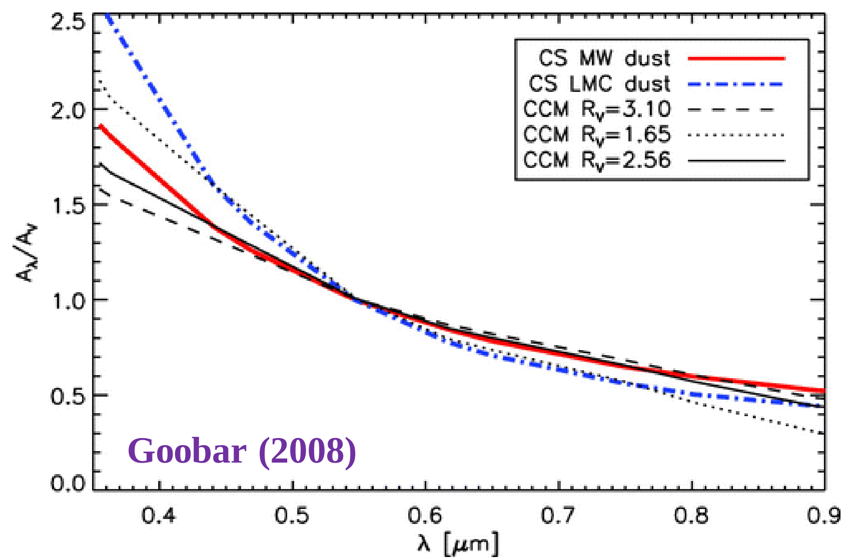
3-2. Multiple scattering scenario by local dust

○ Multiple scattering scenario

- multiple scattering by circumstellar dust steepens extinction curves

(Wang 2005; Goobar 2008; Amanullah & Goobar 2011)



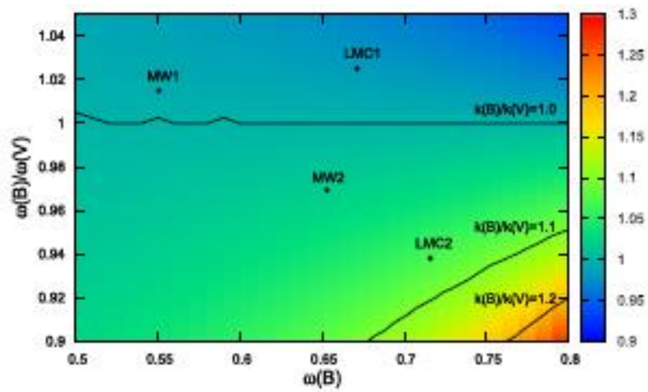


radiative transfer calculations

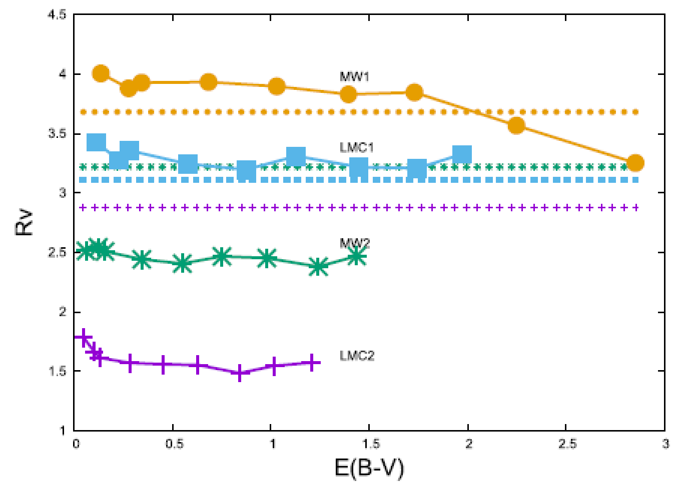
3-3. Concern for multiple scattering scenario

○ Goobar (2008)

- LMC dust (WD01) : ω(B)/ω(V) < 1 ➜ steepen
- MW dust (WD01) : ω(B)/ω(V) < 1 ➜steepen
- SMC dust (WD01) : ω(B)/ω(V) > 1 ➜ flatten



Nagao, Maeda, TN (2016)



○ Nagao, Maeda, TN (2016)

- LMC dust (MRN77) : ω(B)/ω(V) > 1 ➜ flatten
- MW dust (Pei92) : ω(B)/ω(V) > 1 ➜ flatten
- SMC dust (Pei92) : ω(B)/ω(V) > 1 ➜ flatten

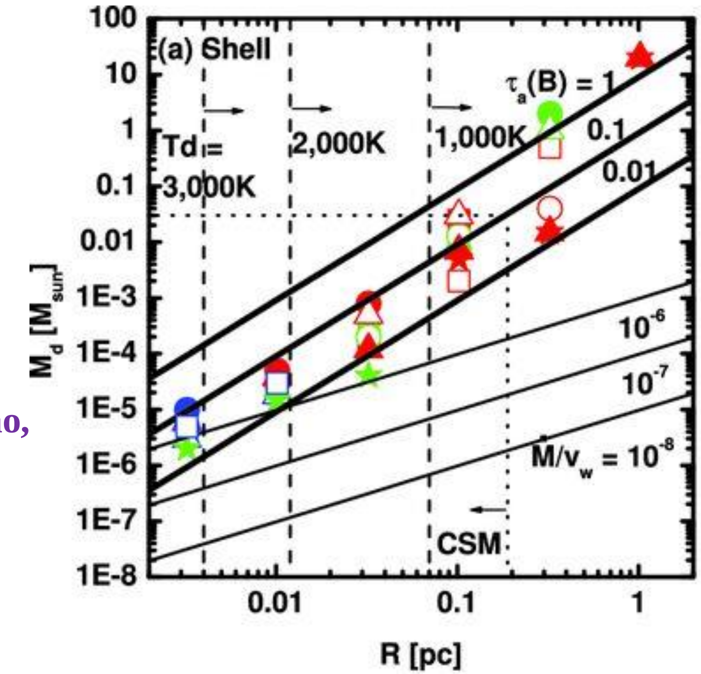
highly model-dependent !!

Multiple scattering does not always steepen the extinction curves

3-4. Problem on multiple-scattering scenario

○ No excess of NIR emission

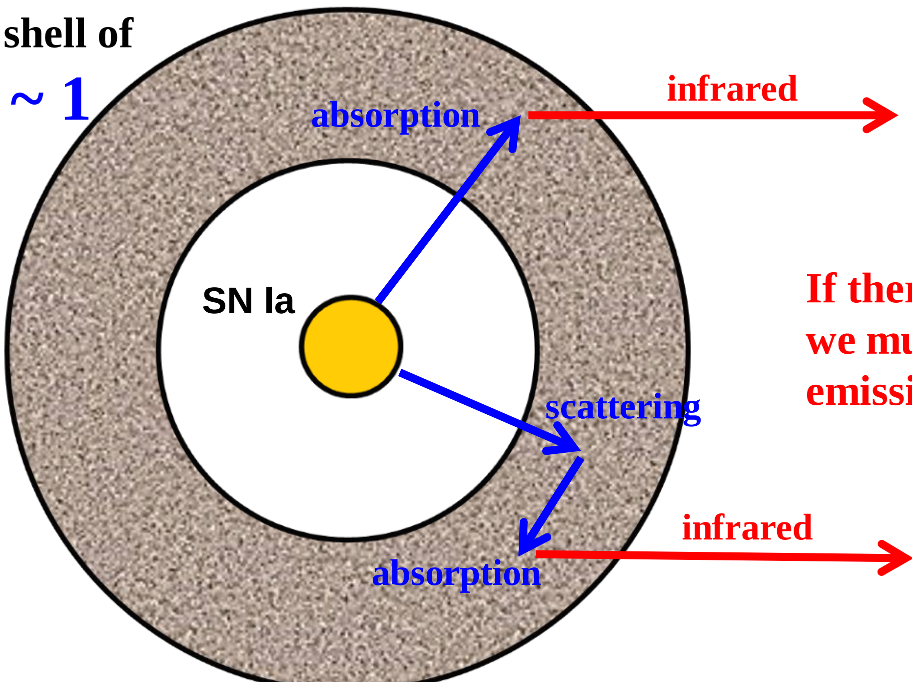
- conservative upper limits of optical depth in B band is $\tau_B < \sim 0.1$
- no massive dusty envelope around SNe Ia



Maeda, TN, Nagao, Motohara (2015)

circumstellar dust shell of

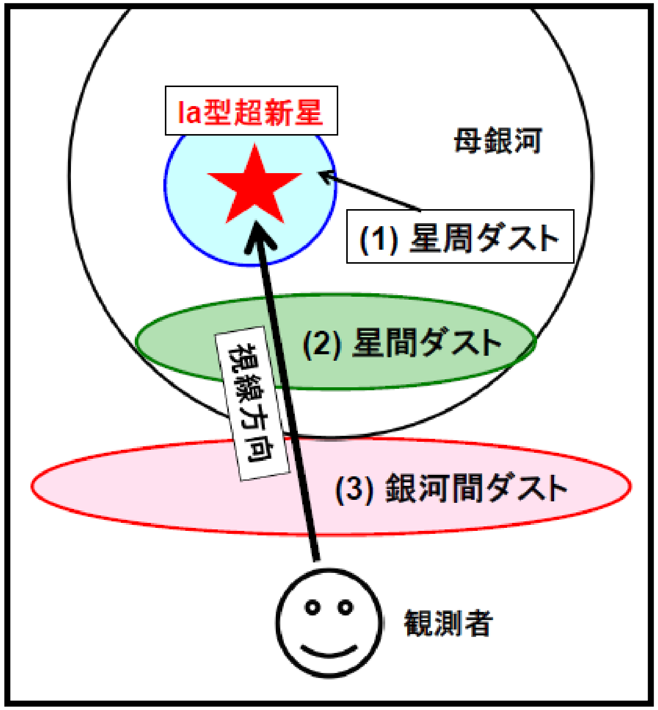
$\tau_V \sim 1$



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

3-5. What is the cause for unusually low Rv?

(1) Unique properties or effects of circumstellar dust ➜ unlikely



(2) Peculiar properties of interstellar dust in host galaxies of SN Ia

(3) Non-standard properties of extragalactic dust ➜ unlikely

(4) Something is wrong in deriving the extinction laws toward SNe Ia

4-1. Fitting to CCM curves with Rv = 1-2

What properties of dust cause steep extinction curves?

○ Data on extinction curves to be fitted

CCM extinction curves with Rv = 2.0, 1.5, 1.0 at representative photometric bands

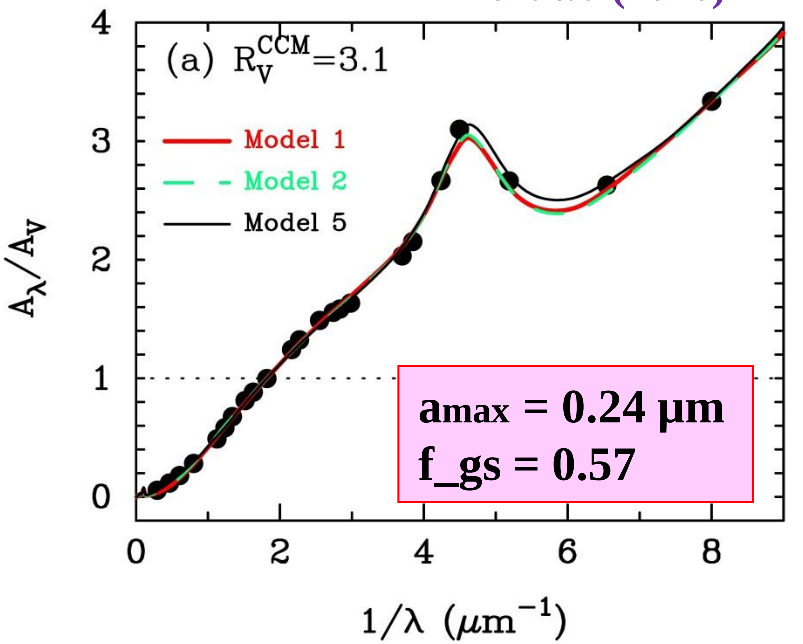
○ Interstellar dust model

(e.g., Mathis+1977, Draine & Lee 1984)

- graphite & astronomical silicate
- power-law grain size distribution
- Model 1 (simplest model)
  same size distribution with q = -3.5 and a_{min} = 0.005 μm for two grain species

parameters:
- a_{max} (upper cutoff radius)
- f_gs (graphite-to-silicate mass ratio)

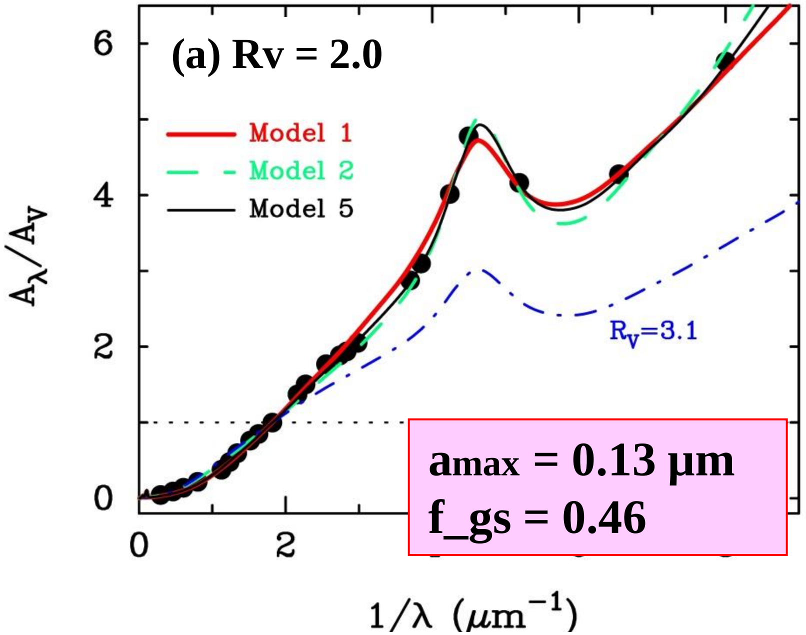
Nozawa (2016)

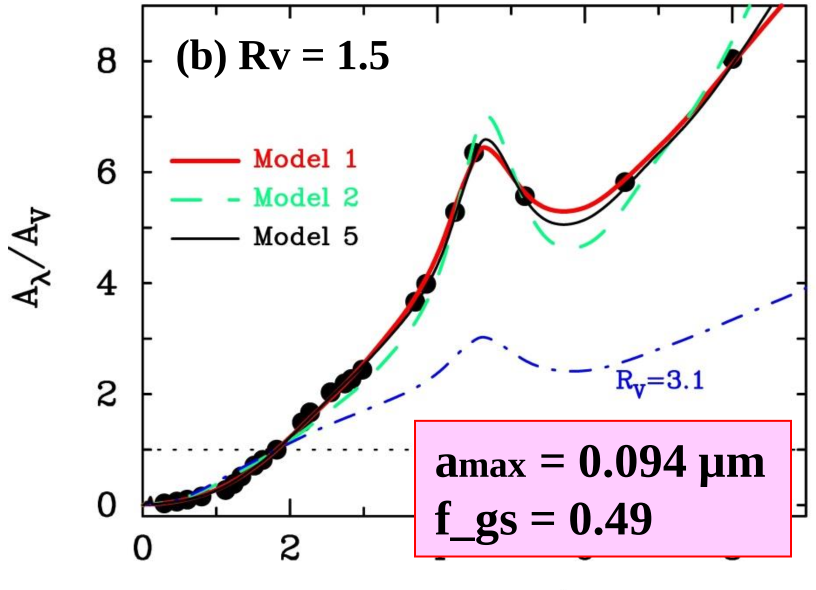


a_{max} = 0.24 μm
f_gs = 0.57

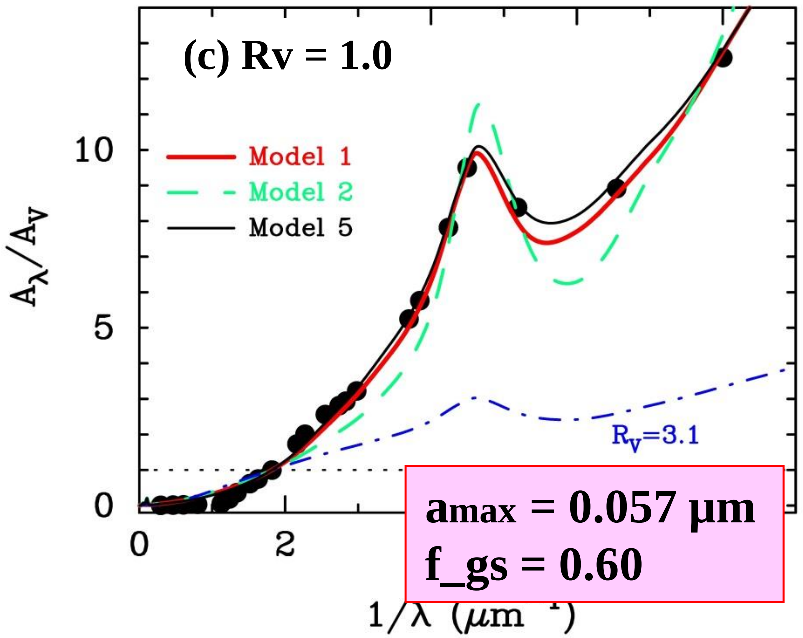
black dots: data of extinction $A\lambda_i/Av$ derived from the CCM formula at photometric bands

4-2. Results of fitting calculations





Nozawa (2016)

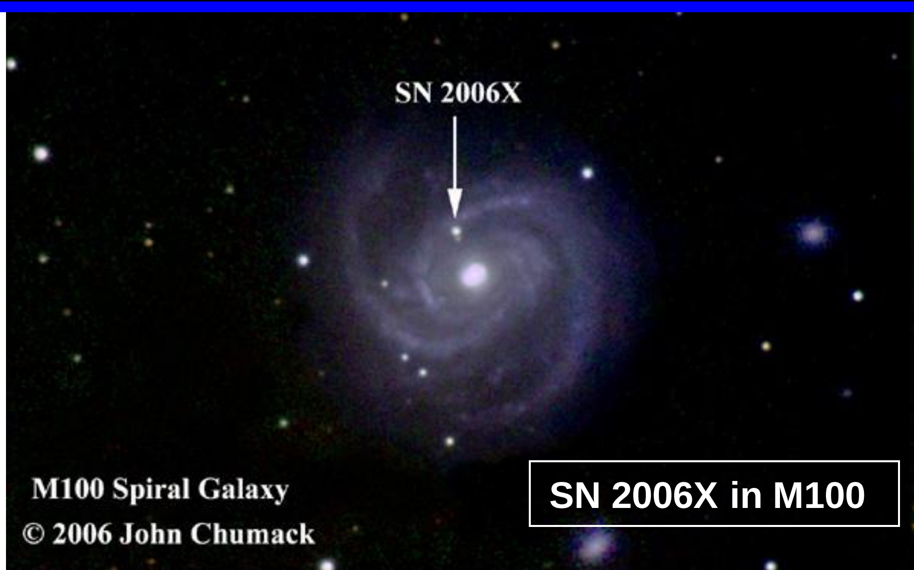


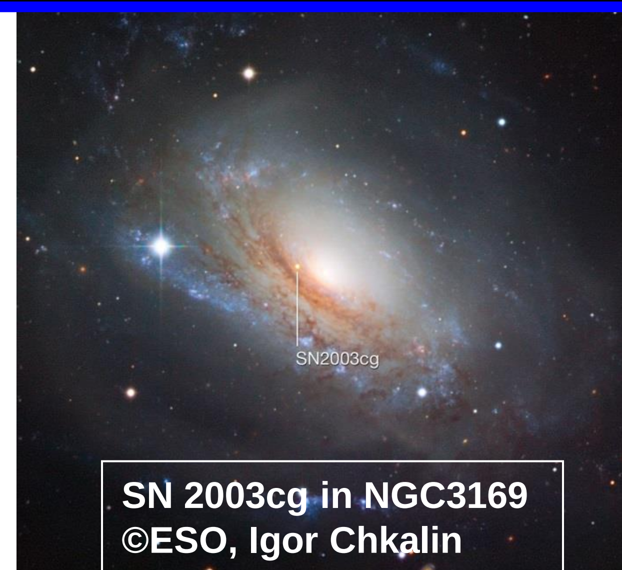
- steep extinction curves with Rv=1-2 can be described by the power-law grain model
- f_gs = 0.45-0.6
  ➜ M_{gra}/M_{total} = 0.3-0.4

cf. f_gs = 0.3-0.7 in the MW
(Nozawa & Fukugita 2013)

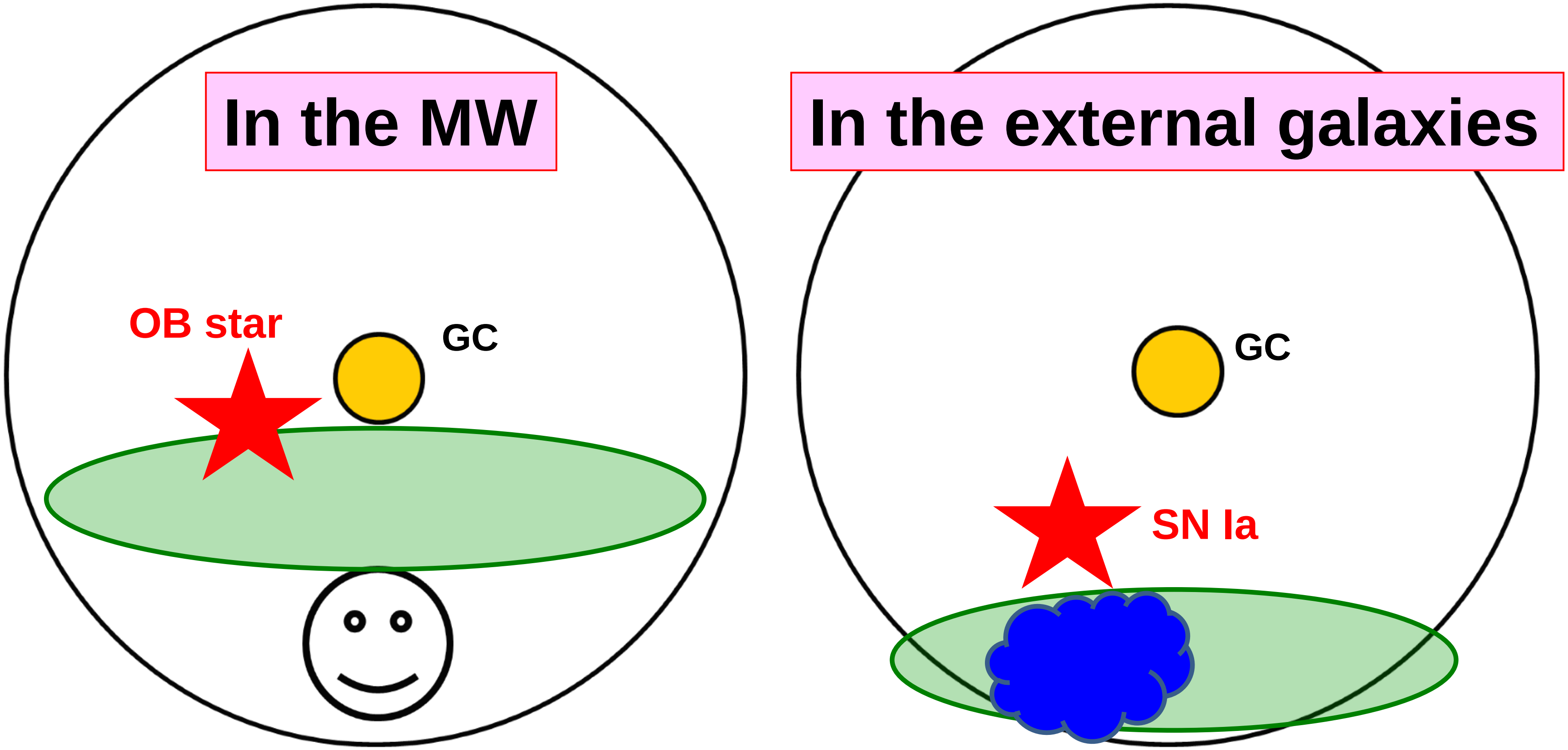
4-3. Unusual dust properties: selection bias?

SNe Ia appear in any type of galaxies!



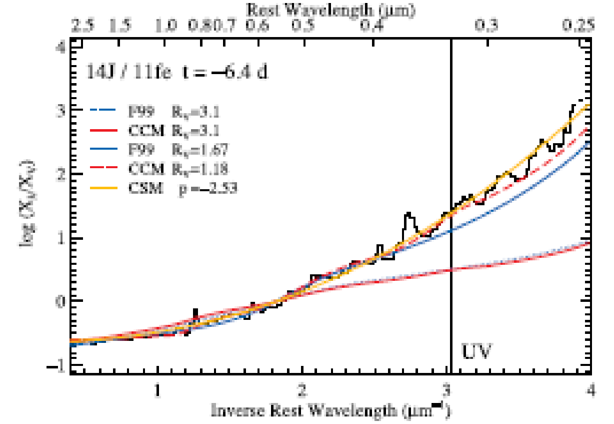


4-4. Selection effects of sightlines?

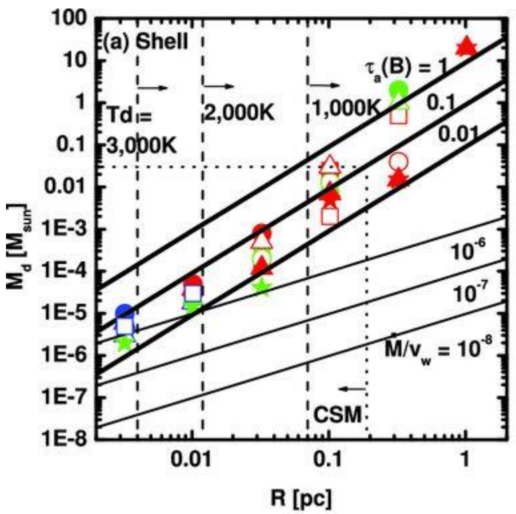


Reddened SNe Ia:
high Av but small Rv !

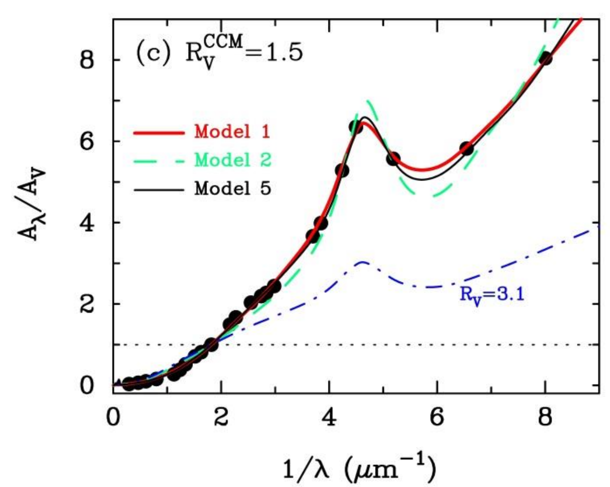
5. Summary of this talk



1) Many studies suggest that Rv values toward SNe Ia are very low (Rv = 1-2), compared with Rv = 3.1 in the MW



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



3) The CCM curves with Rv = 1-2 can be nicely fitted by power-law grain size distributions with a_{max} = 0.05-0.15 μm