

IDMC 2011 - Pune, India (Nov 22-25, 2011)

# Dust in Extragalactic Environments

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# Outline

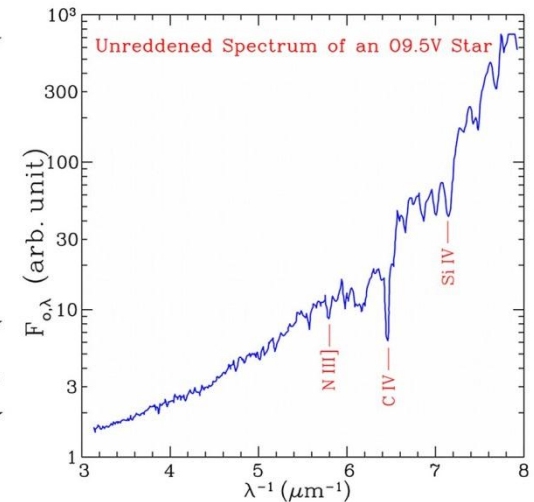
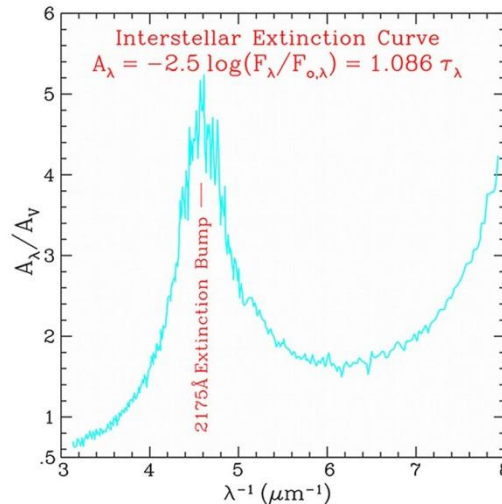
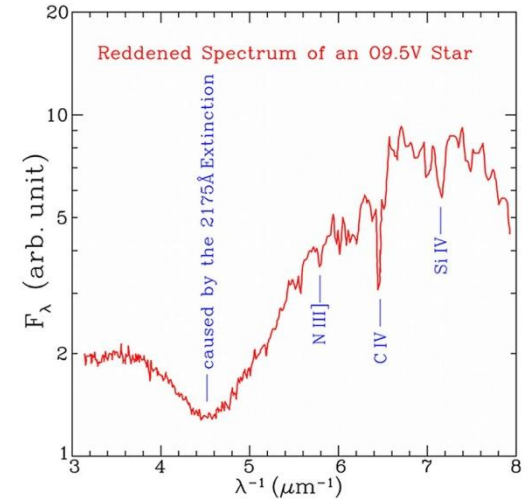
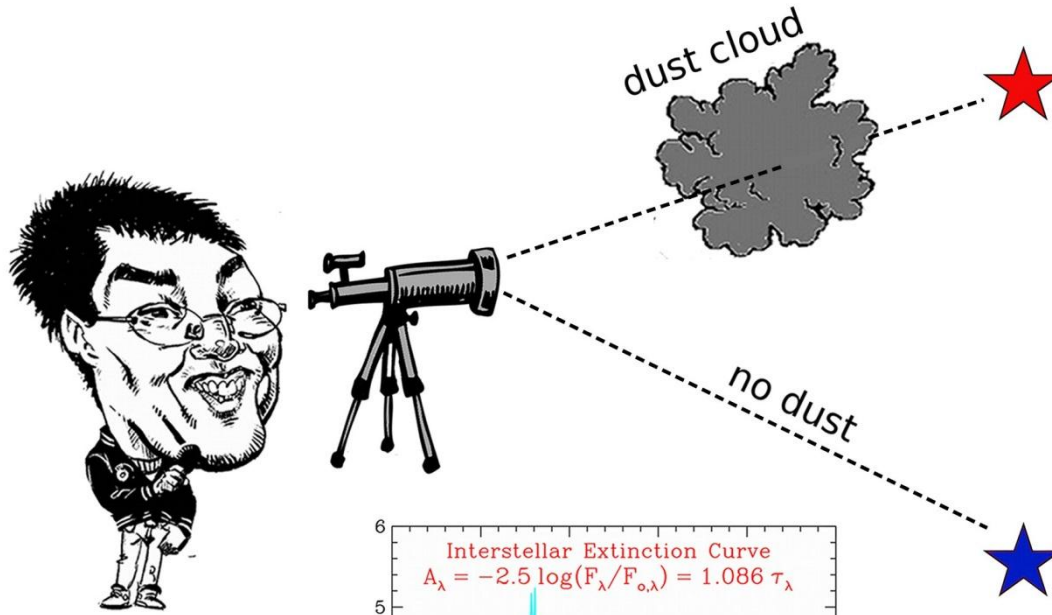
- Galactic Interstellar Dust
  - Extinction  $\Rightarrow$  dust size, composition
  - IR emission  $\Rightarrow$  dust size, composition
  - $R_V = A_V / E(B-V)$   $\Rightarrow$  extinction curve? **NOT** valid for other galaxies!
- Dust at High- $z$ 
  - Whether dust properties evolve with  $z$  ?
- Dust in AGNs
  - Dust size and composition in AGN torus

Dust **absorbs, scatters, and polarizes** starlight, and re-radiates in the **infrared (IR)**;

- **Power**: in the local Universe, energy of IR/submm background = energy of optical background → **nearly half of the optical light emitted since the Big Bang has been absorbed and re-radiated in the IR by dust!**

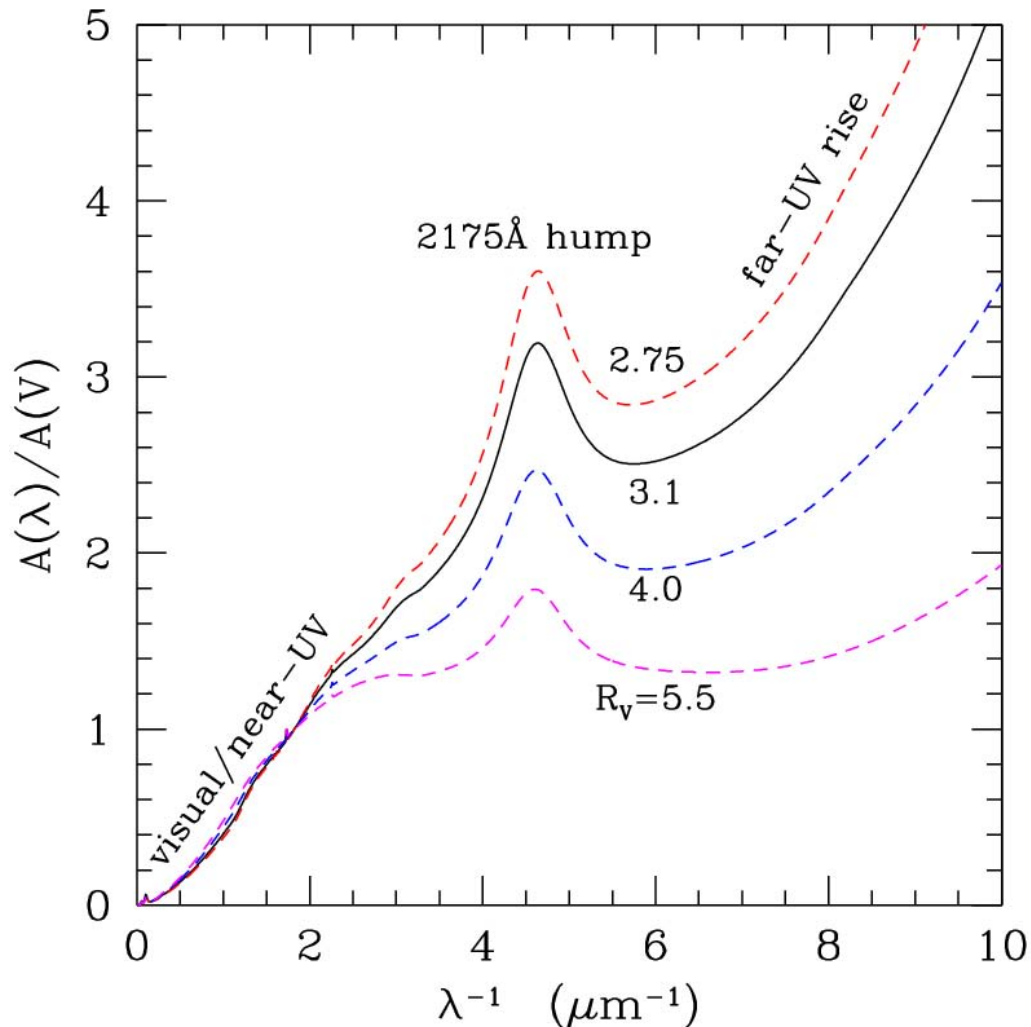
**Key information: dust extinction, IR emission**

# Interstellar extinction → "pair" method: compare spectra of 2 stars with same spectral type, with one star nearby and unreddened



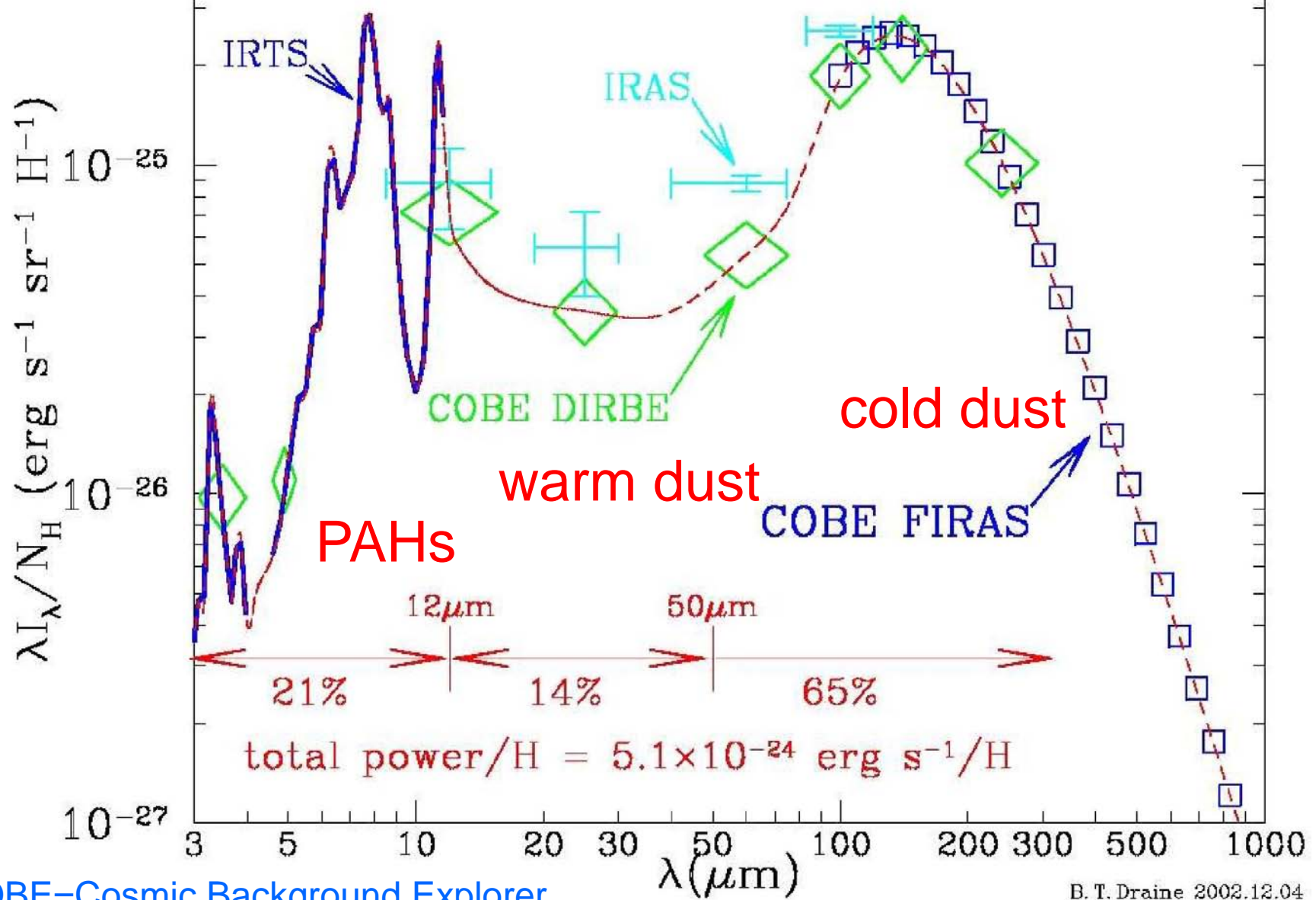
The "Pair" Method  
for Measuring  
Interstellar  
Extinction

# Galactic Interstellar Extinction: Grain Size

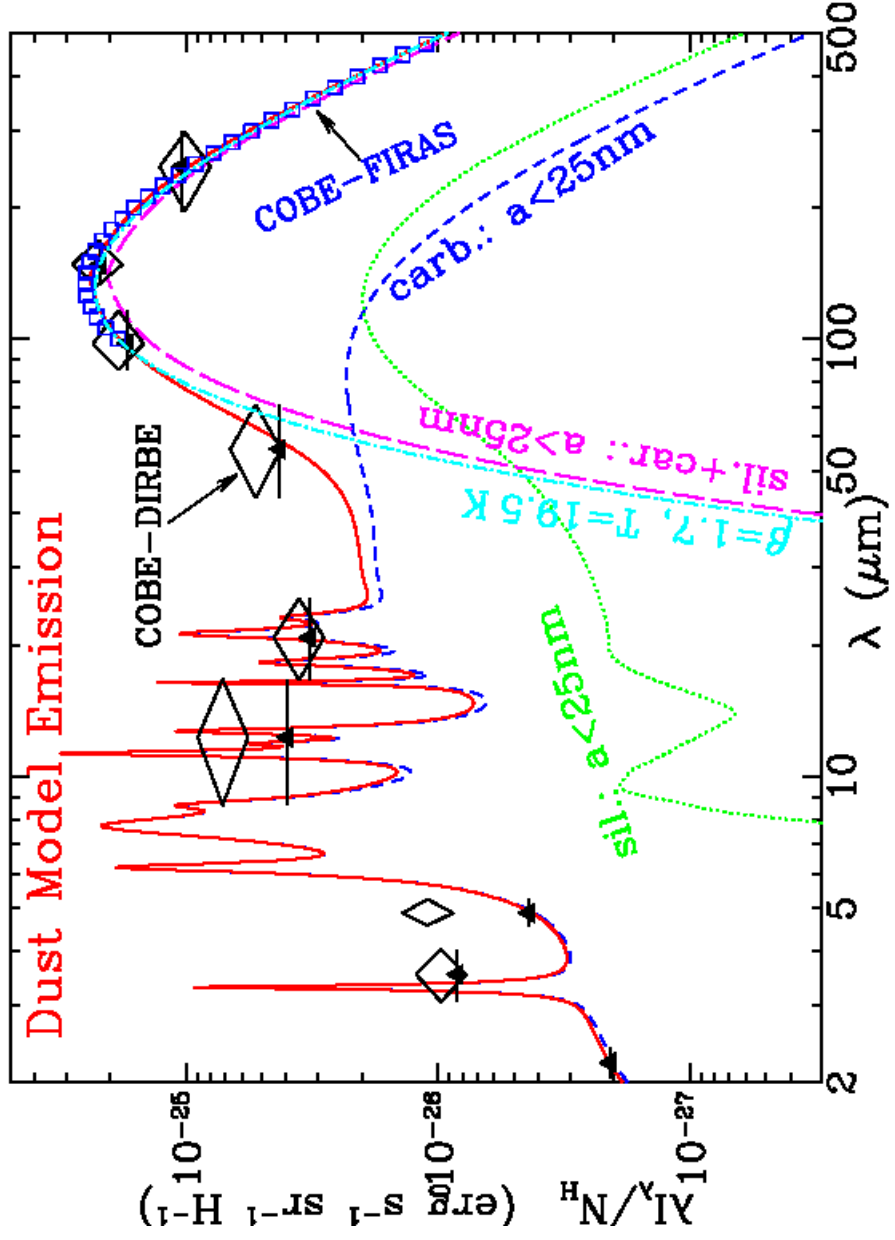


- 2 grain populations:
  - $a < 100 \text{ \AA}$ ;
  - $a > 0.1 \mu\text{m}$ ;
- Characterized by  $R_V = A_V/E(B-V)$ ;
  - dense regions: larger  $R_V$ ;
  - larger  $R_V \rightarrow$  larger grains;
- 2175 Å bump
  - aromatic carbon;
  - small graphitic grains or PAHs;

# Observed Emission from Interstellar Dust



COBE=Cosmic Background Explorer

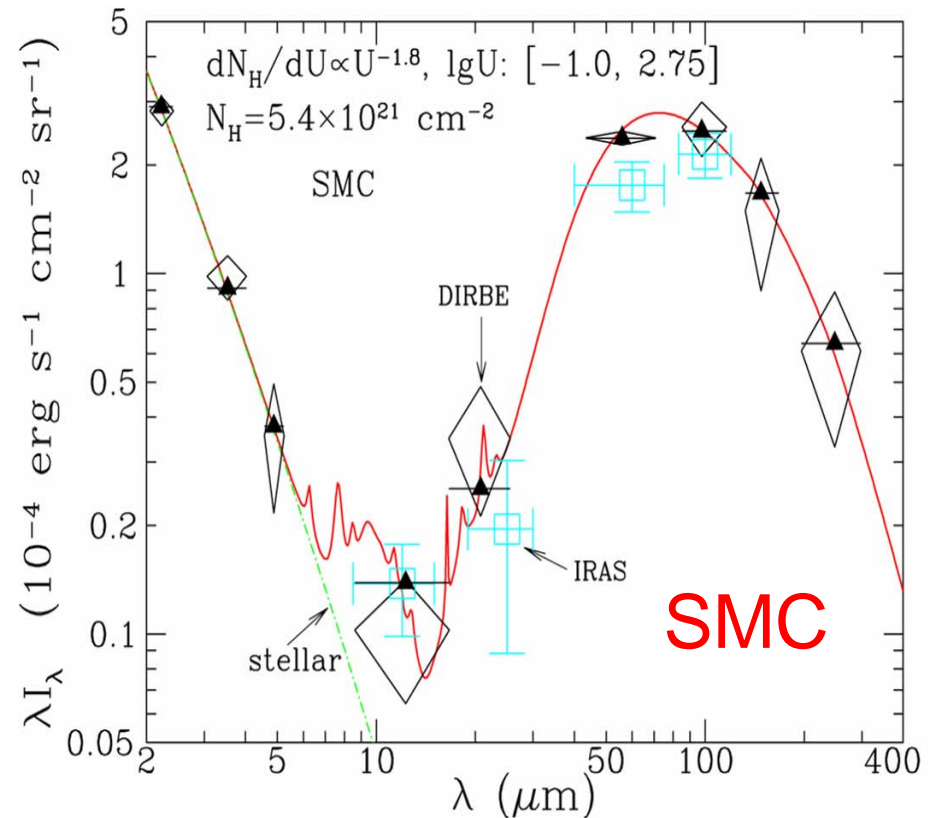
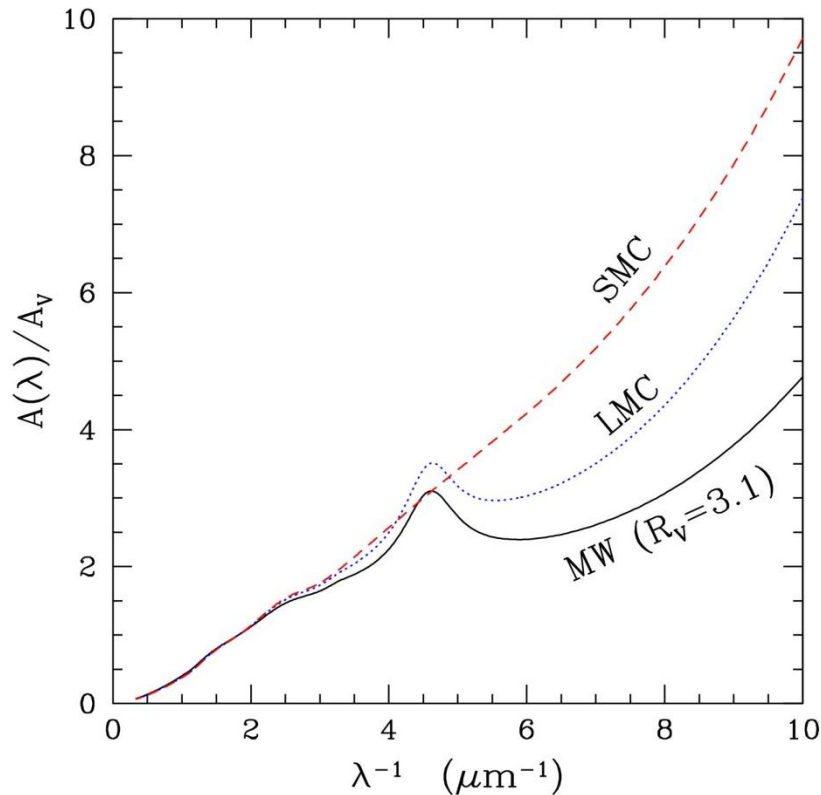


# Two Grain Populations in interstellar space

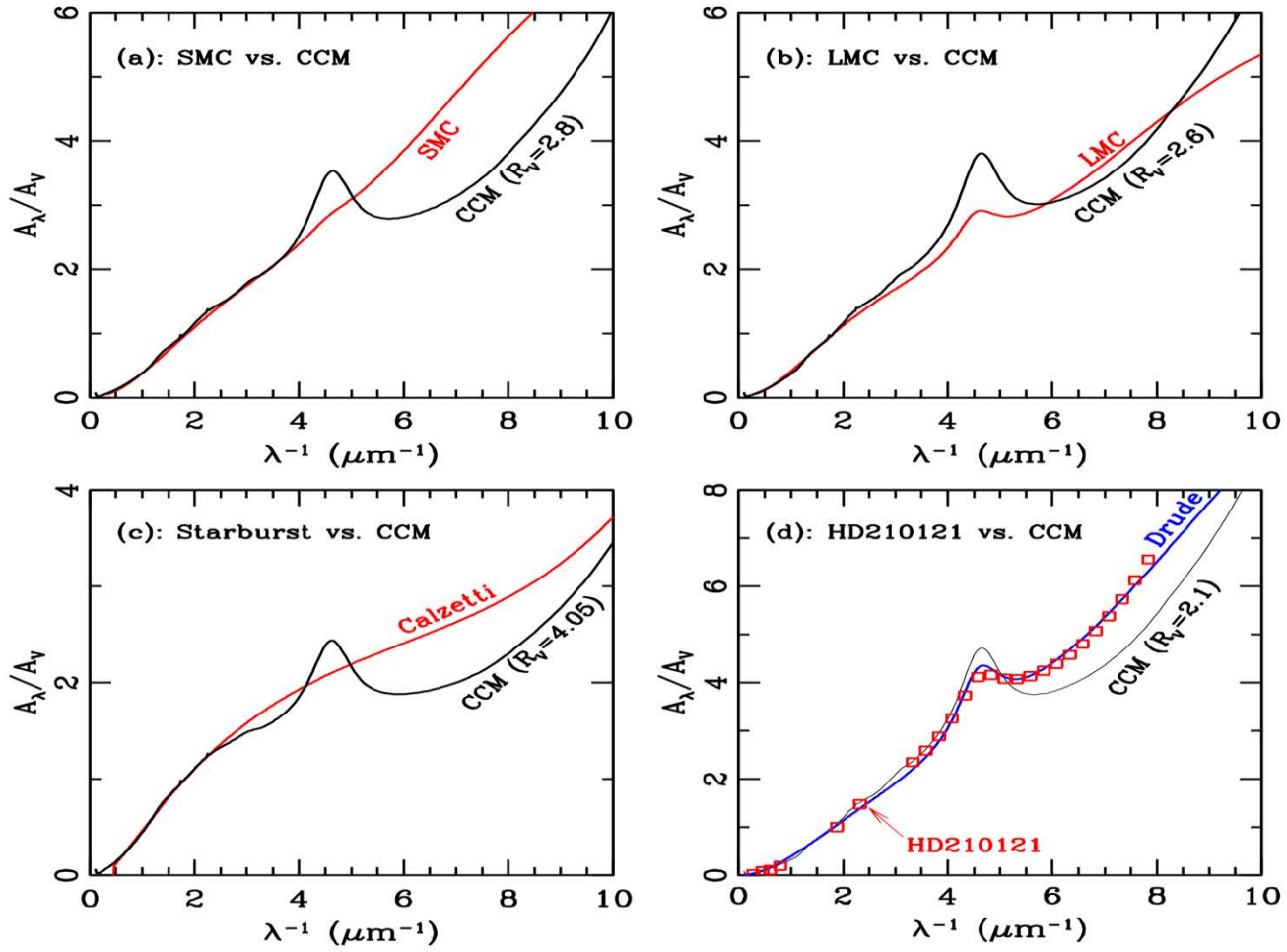
- The sizes of interstellar dust extends over 3 orders of magnitude, from a few angstrom to  $\sim 1\mu\text{m}$ ;
- “classical” grains with  $10\text{nm} < a < 0.3\mu\text{m}$ 
  - account for nearly all optical extinction;
  - heated by starlight, cooled by far-IR emission;
  - $T_d \sim 20\text{ K}$ ;
  - responsible for the IR emission at  $\lambda > 60\ \mu\text{m}$ ;
  - $\sim 65\%$  of emitted power;
- “nano grains” with  $a < 10\text{nm}$ ,
  - important contribution to ultraviolet (UV) extinction;
  - heated by starlight, cooled by IR emission;
  - Single starlight photon heated to  $T \gg 20\text{K}$ , undergo “temperature fluctuation”;
  - responsible for the IR emission at  $\lambda < 60\ \mu\text{m}$ ;
  - $\sim 35\%$  of emitted power;

# Dust in Other Galaxies

Far-UV extinction, 2175Å bump, "PAH" emission: dust size and composition different



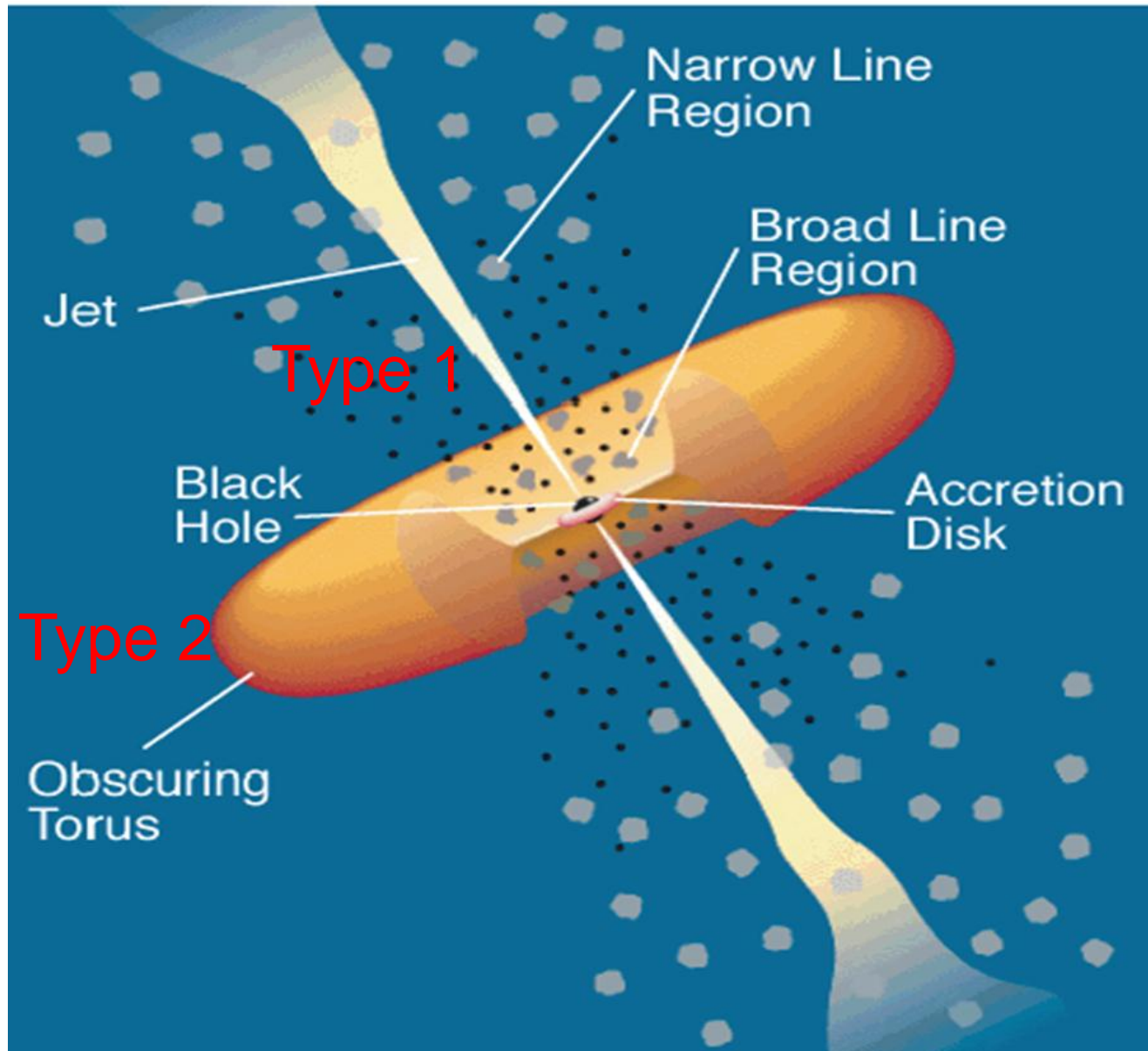
The **CCM** formula: very nice: knowing  $R_V$ , the entire extinction curve is known! But **this does not apply to external galaxies**, even not for LMC, SMC!



# Dust in AGNs

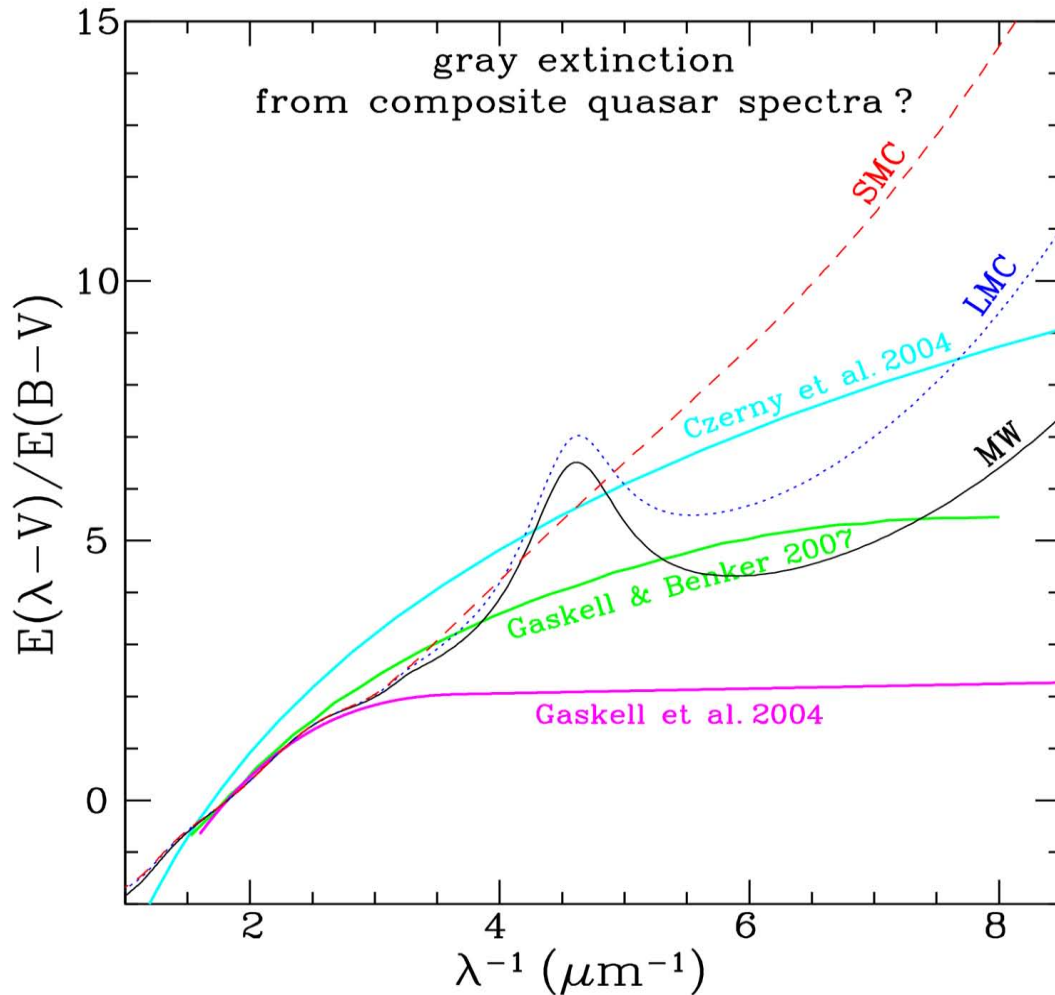
- Dust plays an important role in the “Unified Theory of AGNs”;
  - orientation-dependent obscuration by dust torus  
⇒ Seyfert 1 vs. Seyfert 2;
- IR emission accounts for  $\sim 10\%$  of the bolometric luminosity of Type 1 AGNs,  $> 50\%$  of Type 2;
  - Heated dust  $\rightarrow$  IR emission;
  - IR emission modeling  $\rightarrow$  circumnuclear structure (critical to the growth of supermassive black hole);

# AGN = active galactic nuclei



# AGN Dust Extinction: flat/gray?

⇒ large grains?



Czerny et al. (2004): 5 SDSS composite quasar spectra → flat extinction

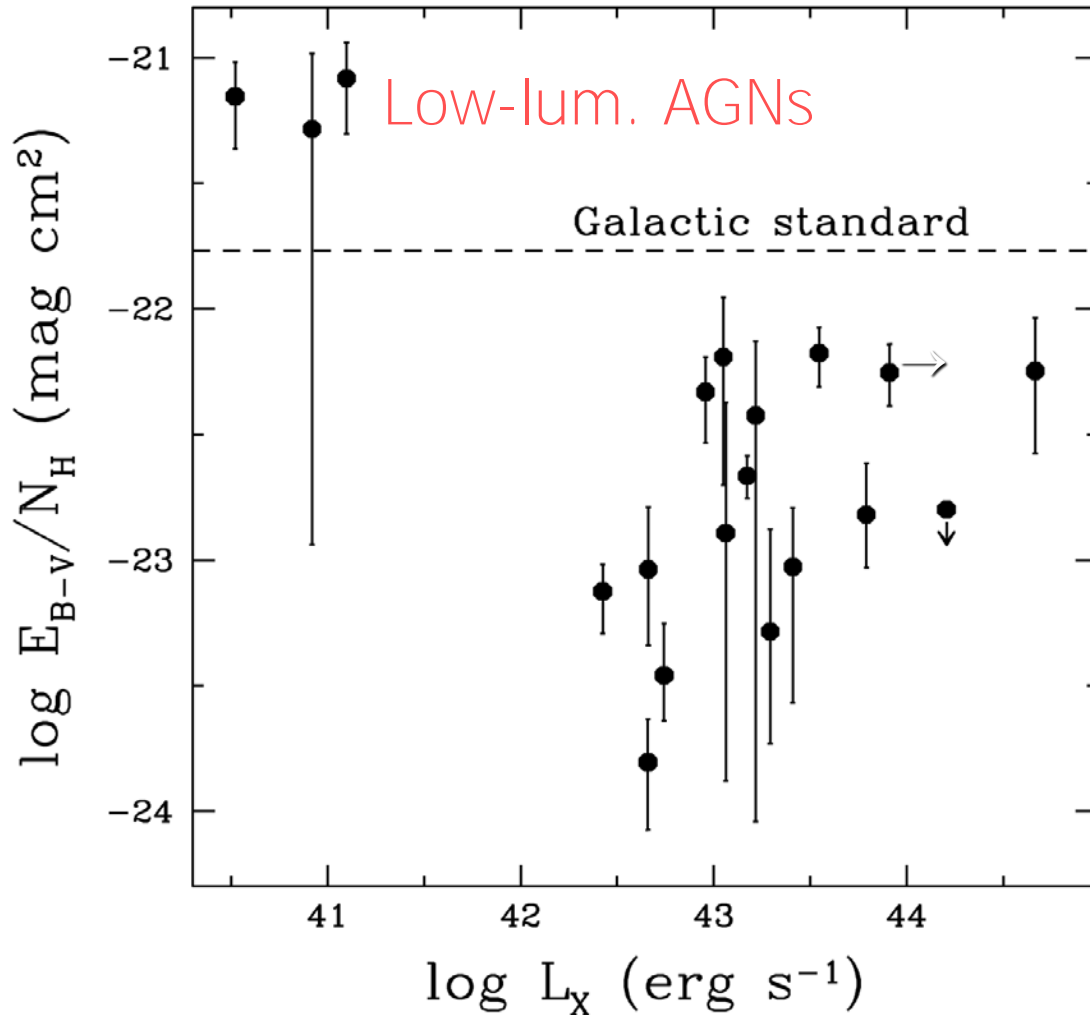
- Amorphous carbon with  $dn/da \sim a^{-3.5}$ ,  $0.016 \leq a \leq 0.12 \mu\text{m}$ ;
- But only am.carbon? impossible! (+silicates!)

Gaskell et al. (2004): 72 radio-loud, 1018 radio-quiet AGNs → flat extinction;

# AGN Dust Extinction:

## Lower $E(B-V)/N_H$ and $A_V/N_H$ ratios

⇒ large grains?

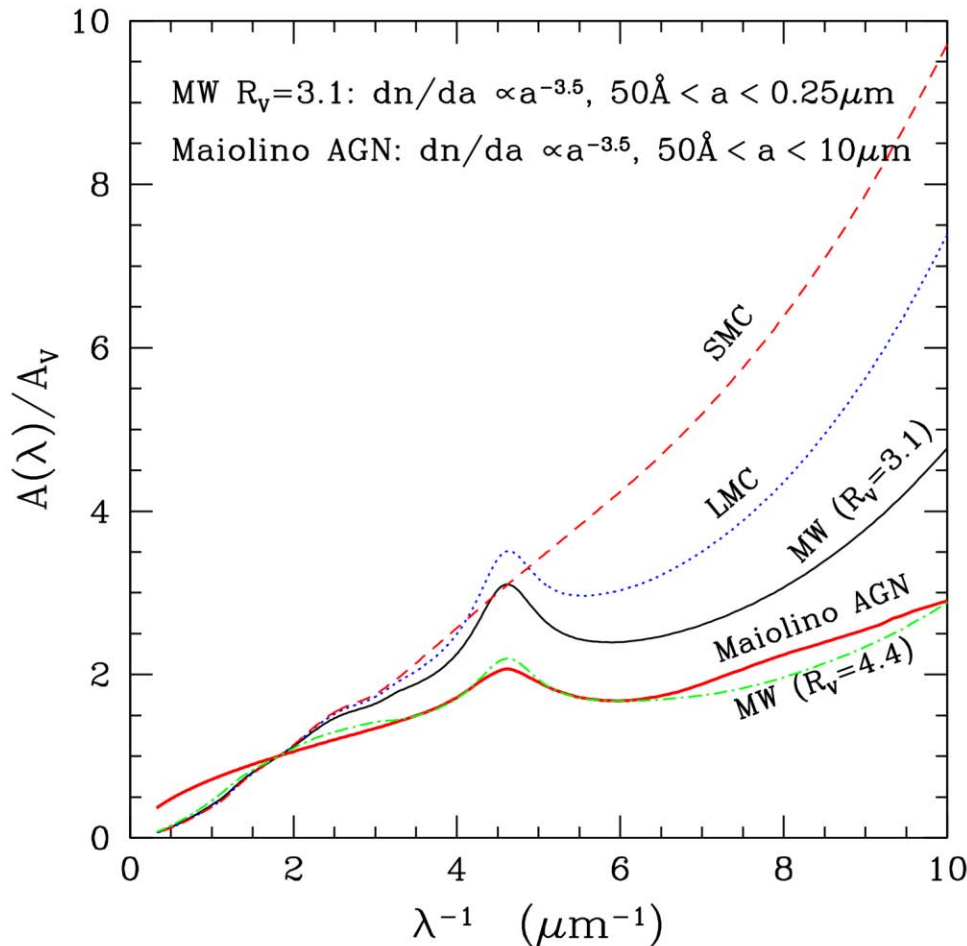


- Maiolino et al. (2001):  $E(B-V)/N_H$  for 16 AGNs smaller than the Galactic value by a factor of 3-100 → grain growth?
- optical/near-IR emission lines →  $E(B-V)$
- X-ray absorp. →  $N_H$

# AGN Dust Extinction:

**Lower  $E(B-V)/N_H$  and  $A_V/N_H$  ratios**

**⇒ large grains?**

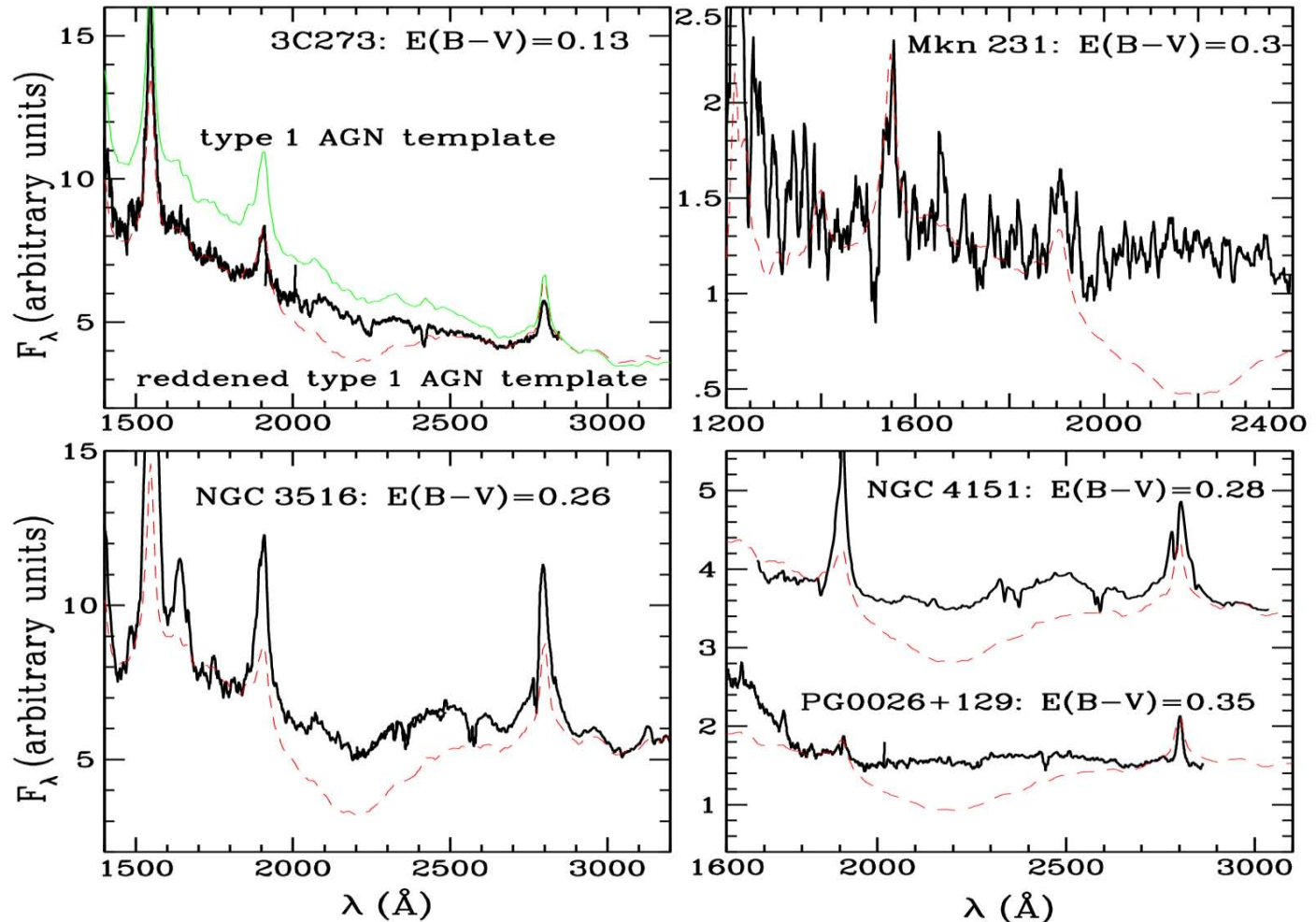


- grain growth → flat extinction, and lower  $E(B-V)/N_H$  and  $A_V/N_H$  ratios;
- circumnuclear region: high density → grain growth through coagulation can occur;
- But, Weingartner & Murray (2002): X-ray absorp. and optical extinction may occur in distinct media?

# AGN Dust: Composition

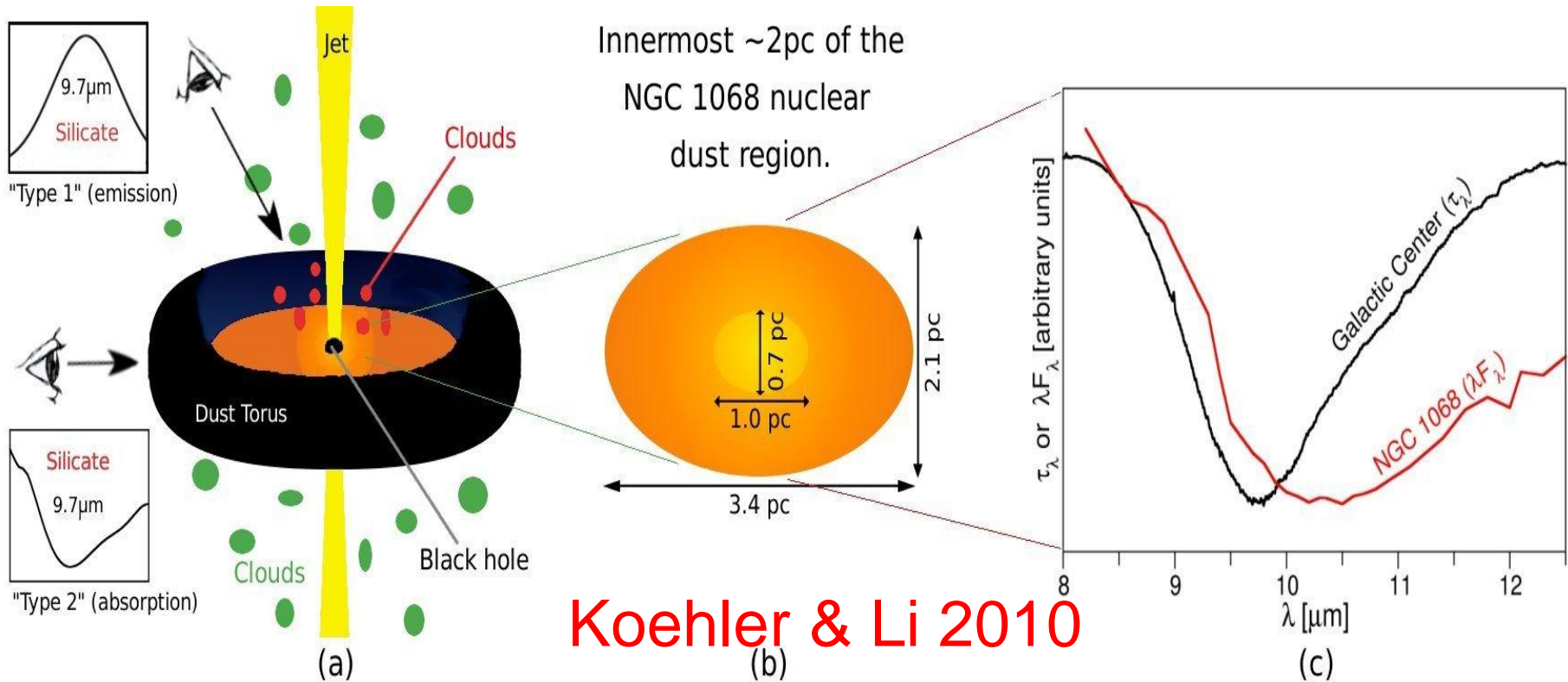
## lack of 2175 Å extinction bump

⇒ depletion of small graphitic grains/PAHs?





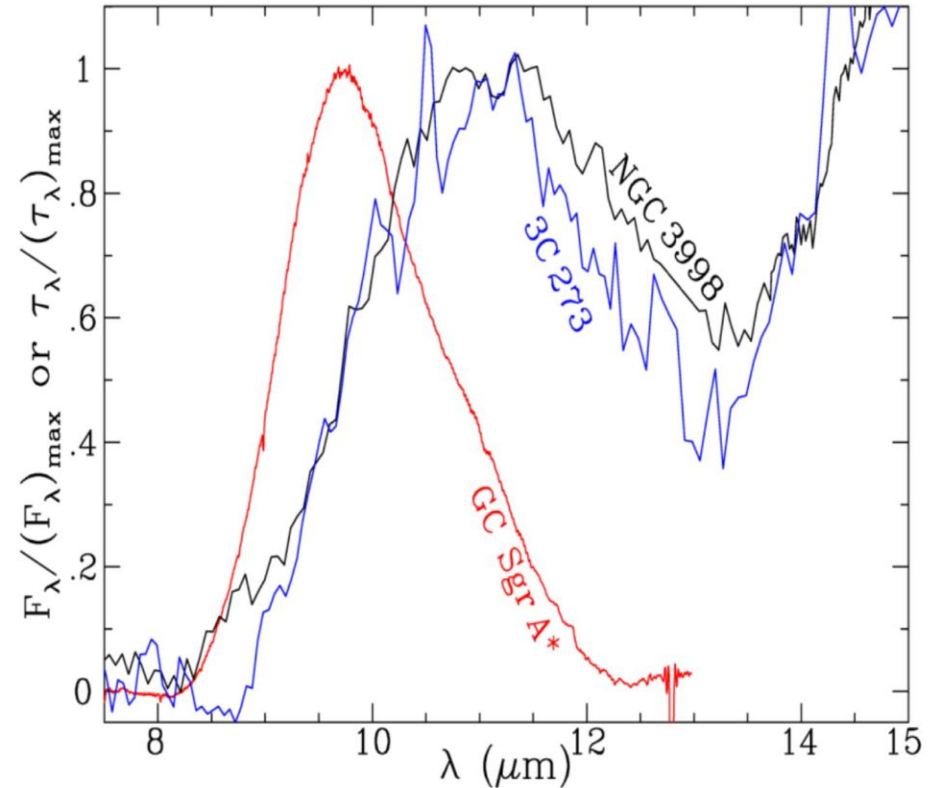
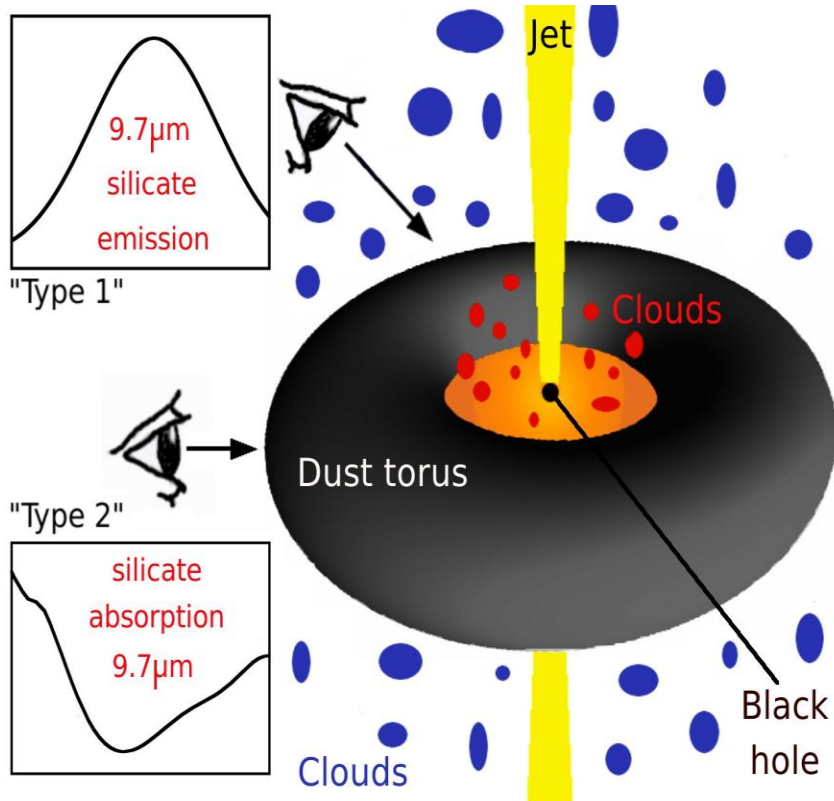
# AGN silicates differ from Milky Way ISM?



Koehler & Li 2010

**non-olivine  $\text{MgFeSiO}_4$  composition ? calcium aluminium silicate  $\text{Ca}_2\text{Al}_2\text{SiO}_7$  ? (Jaffe et al. 2004)**

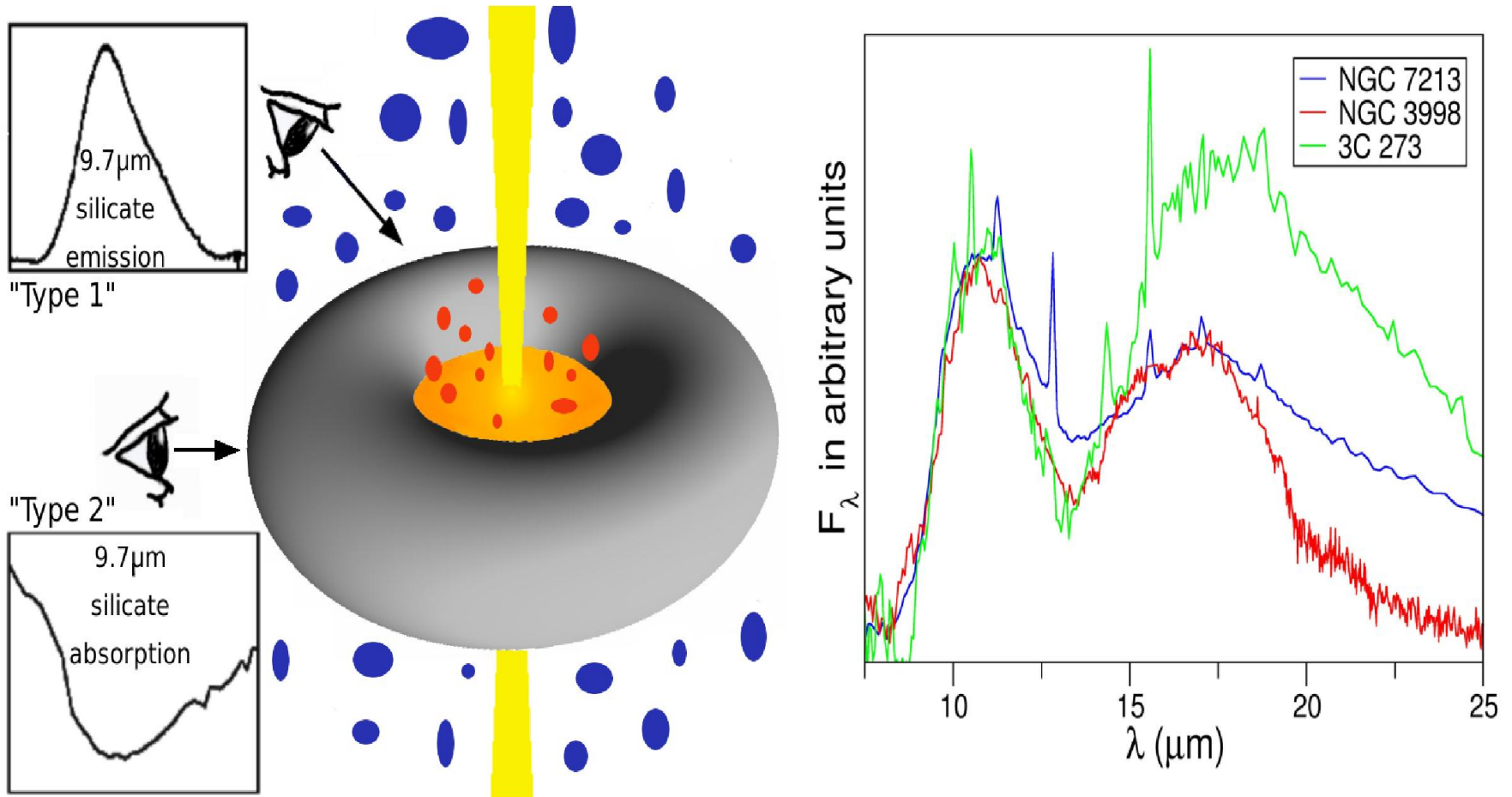
# AGN silicates differ from Milky Way ISM?



**9.7  $\mu\text{m}$  silicate feature: “red”** shifted and broadened (Hao et al. 2005, Sturm et al. 2005)

⇒ Large grains? elongated grains? different composition?  
Rad.transf. effects? (Henning 2008)

# AGN silicates differ from Milky Way ISM?



**18  $\mu\text{m}$  silicate feature: large diversity!**

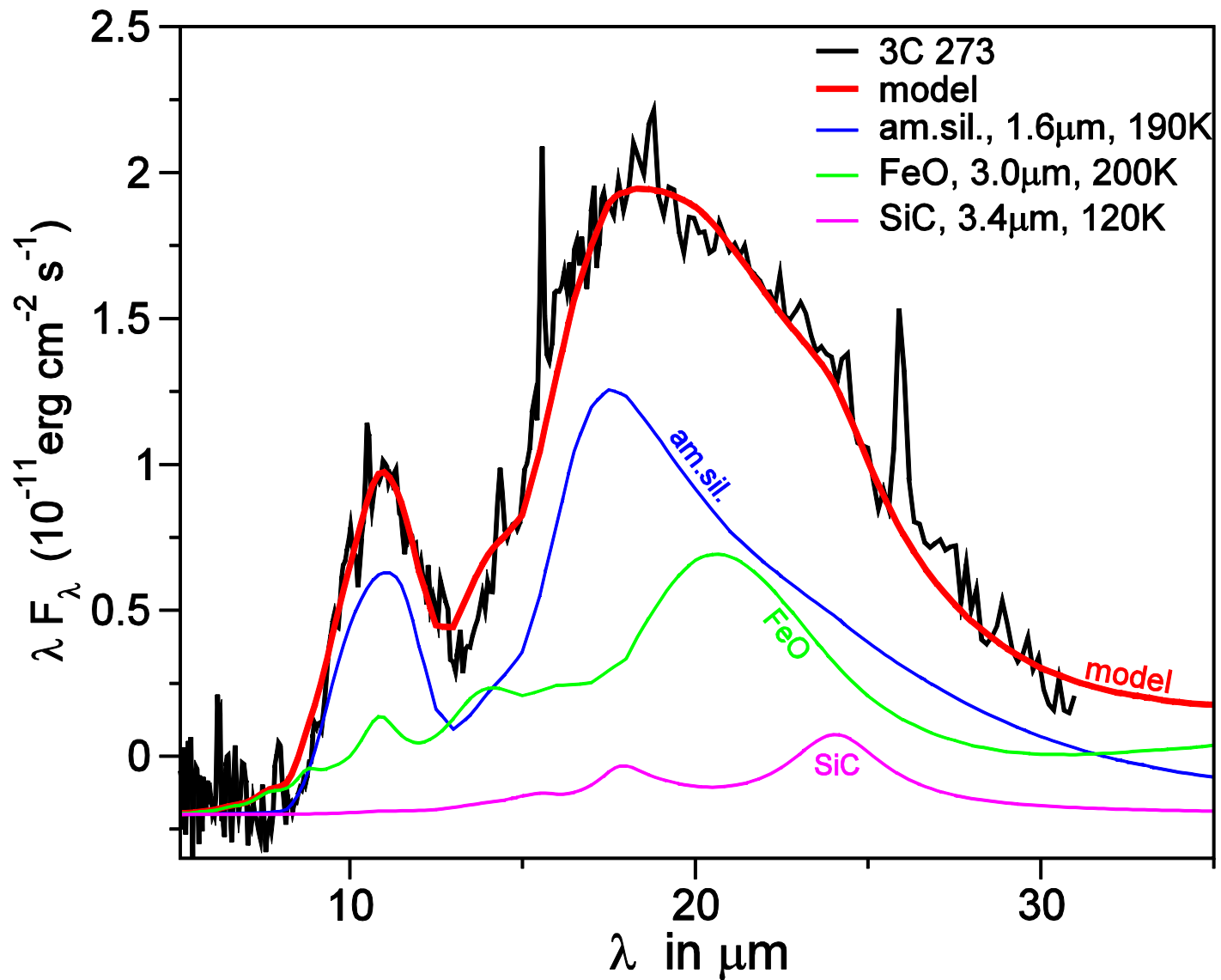
## **Li et al. (2008)**

**Porous structure ? Large grain size?** ⇒ “red-shifting” and broadening the silicate feature.

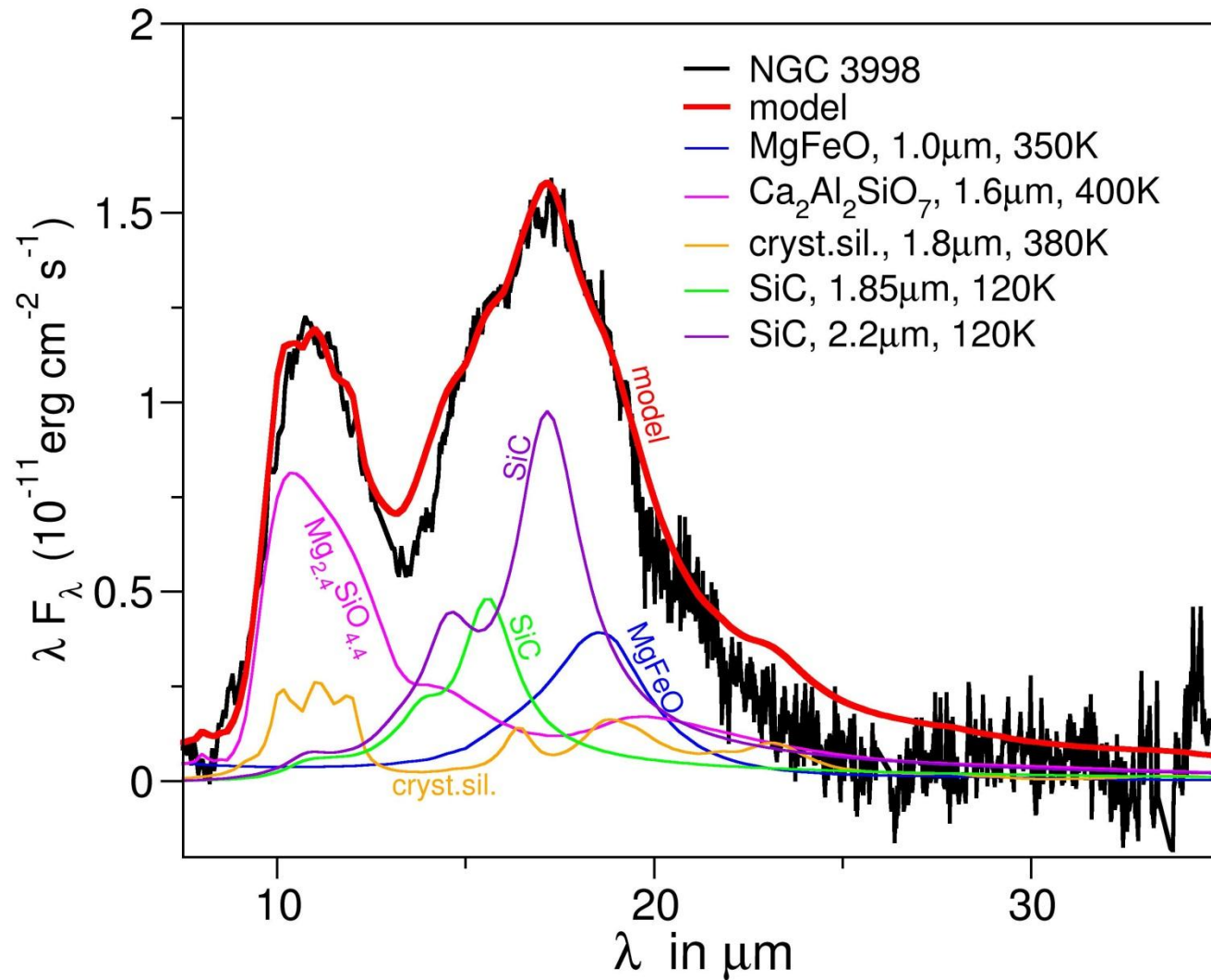
**Are All AGNs Born Equal?**

(Koelher & Li 2011)

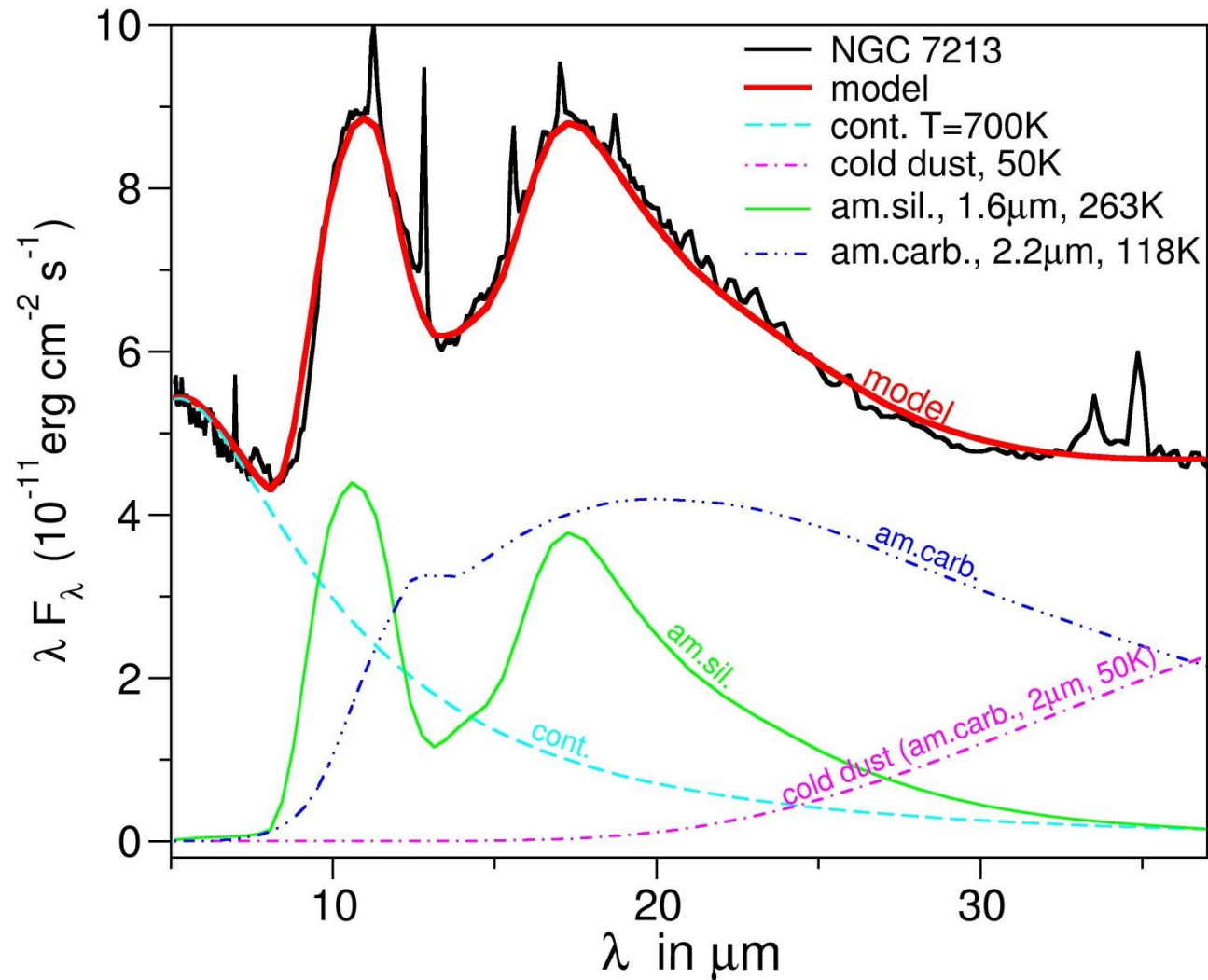
# 3C 273: Koehler & Li (2010)



# NGC 3998: Koehler & Li (2010)

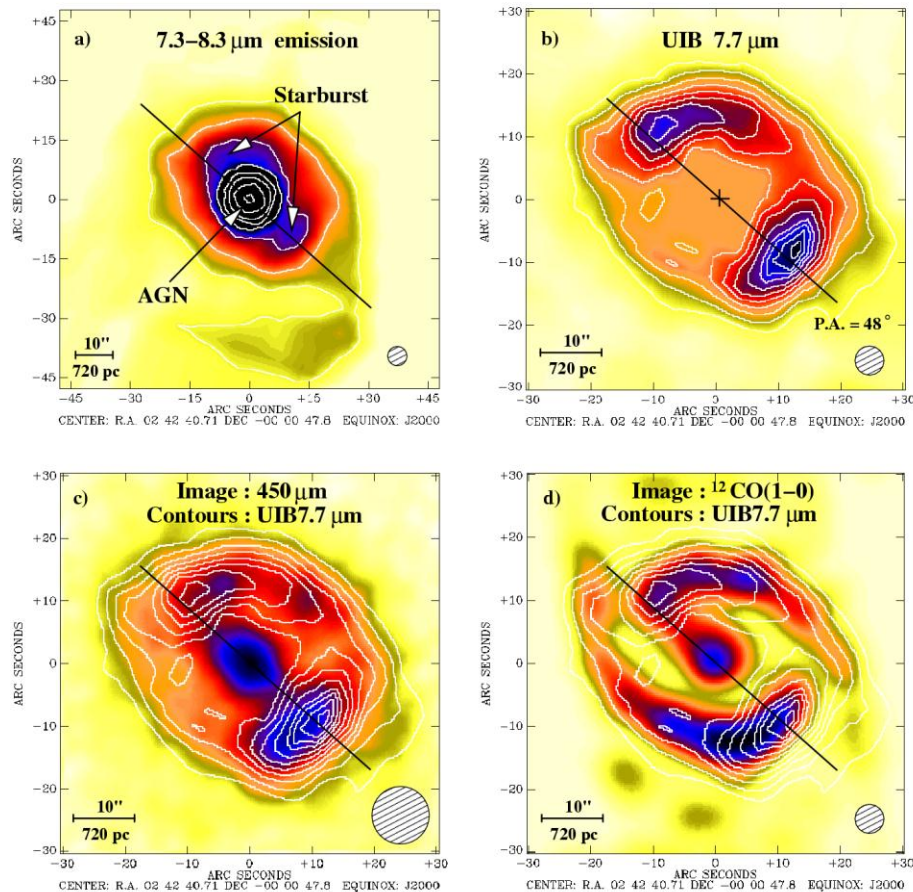


# NGC 7213: Koehler & Li (2010)

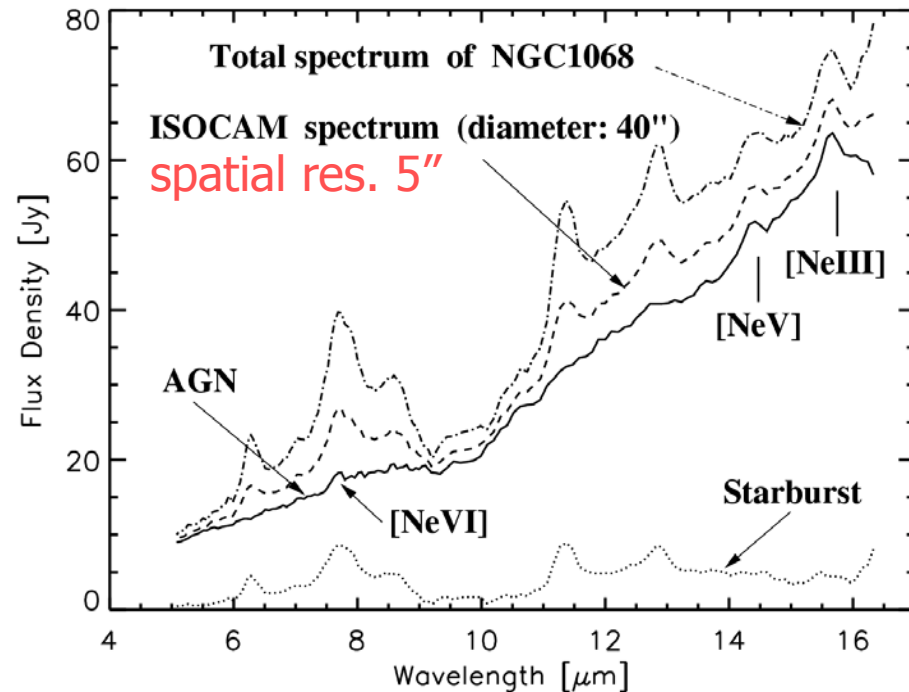


# In some Seyfert 2, PAHs are detected

⇒ PAHs are from the **circumnuclear star-forming region, not from AGN!**



NGC 1068 (Le Floc'h et al. 2001)  
 Starburst ring ( $r \sim 1.5$  kpc)



# Dust in the High-Redshift Universe

- Dust is seen in (almost) all high- $z$  sources: quasars, GRBs, submm galaxies, DLAs ...
  - Reddening and obscuration
  - IR to mm emission
  - Depletion of heavy elements
- Whether the dust properties vary with  $z$ ?

# The Sources of Dust

- $z < 5$  (age  $> 1$  Gyr): AGB Stars

At local universe, the major source of dust are the envelopes of AGB stars, which require about 1 Gyr to evolve.

- $z > 5$  (age  $< 1$  Gyr): SNe  
Supernova origin for dust  
in **high-z quasar**

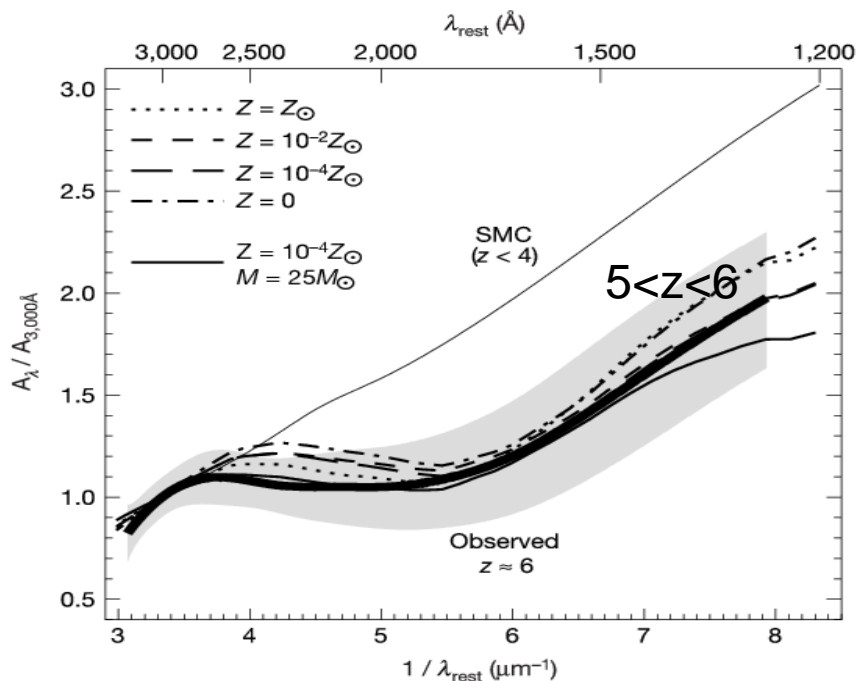
(Maiolino et al. 2004, Nature)



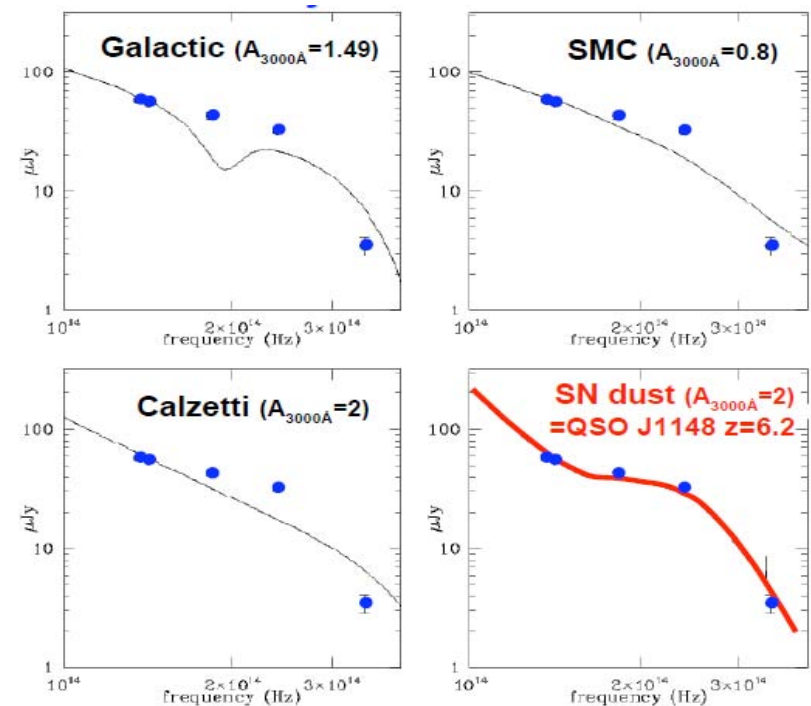
Supernova also origin for  
dust in high-z GRBs (?)

# Dust properties vary with redshift $z$ ?

- Maiolino et al. (2004): dust at  $z=6.2$  quasar differs substantially from the SMC, LMC, MW extinction law
- Stratta et al. (2007): dust of GRB 050904 at  $z=6.29$  like  $z=6.2$  quasar ?



(Maiolino et al. 2004)

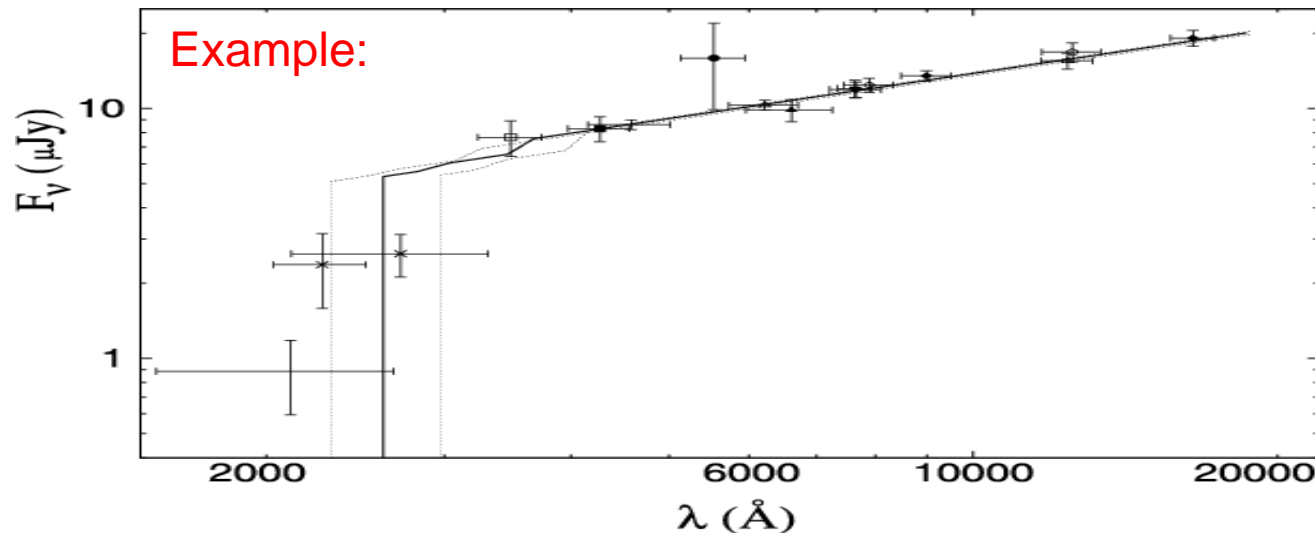


(Stratta et al. 2007)

# Determining dust extinction of GRB host galaxies from **afterglow** spectral energy distributions

$$F_\nu = F_o (\nu / \text{Hz})^{-\beta} \exp \left[ - \frac{A_{V_r}}{1.086} \frac{A_{(1+z)\nu}}{A_{V_r}} \right]$$

Compared with observed afterglow SEDs



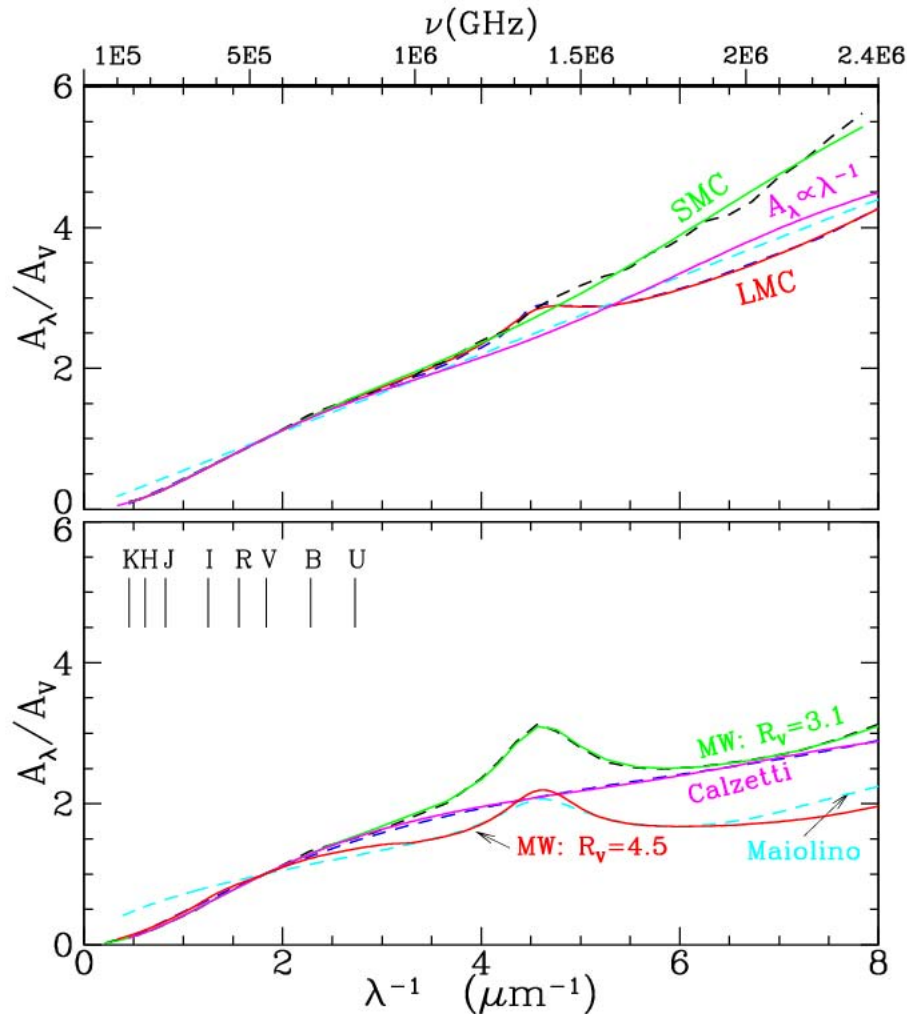
## Dust extinction model:

$$F_\nu = F_o (\nu / Hz)^{-\beta} \exp \left[ - \frac{A_{V_r}}{1.086} \frac{A_{(1+z)\nu}}{A_{V_r}} \right]$$

Our approach: “*Drude*” model: (Li, Liang, Wei 2008)

$$\begin{aligned} A_\lambda / A_V &= \frac{c_1}{(\lambda / 0.08)^{c_2} + (0.08 / \lambda)^{c_2} + c_3} \\ &+ \frac{233[1 - c_1 / (6.88^{c_2} + 0.145^{c_2} + c_3) - c_4 / 4.60]}{(\lambda / 0.046)^2 + (0.046 / \lambda)^2 + 90} \\ &+ \frac{c_4}{(\lambda / 0.2175)^2 + (0.2175 / \lambda)^2 - 1.95} \end{aligned}$$

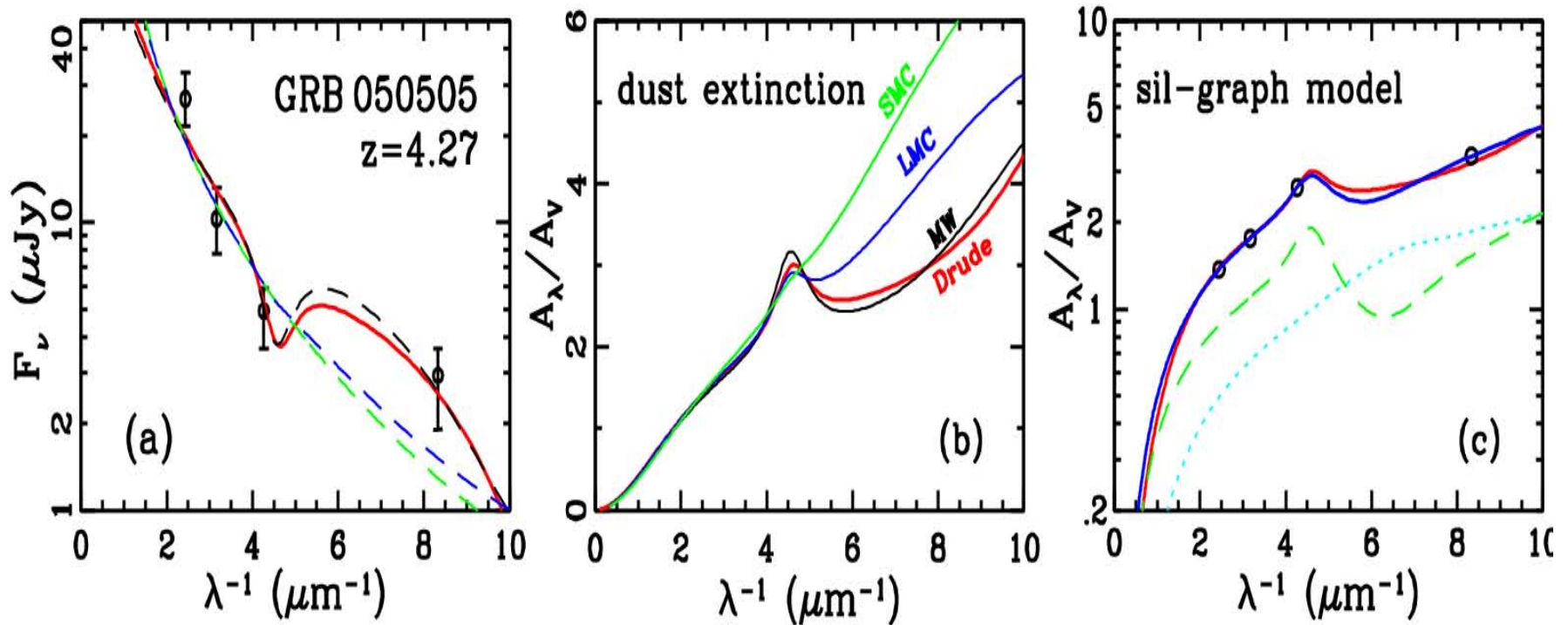
# Advantages of Drude Model



(1) Eliminates the need for a priori assumption of template laws

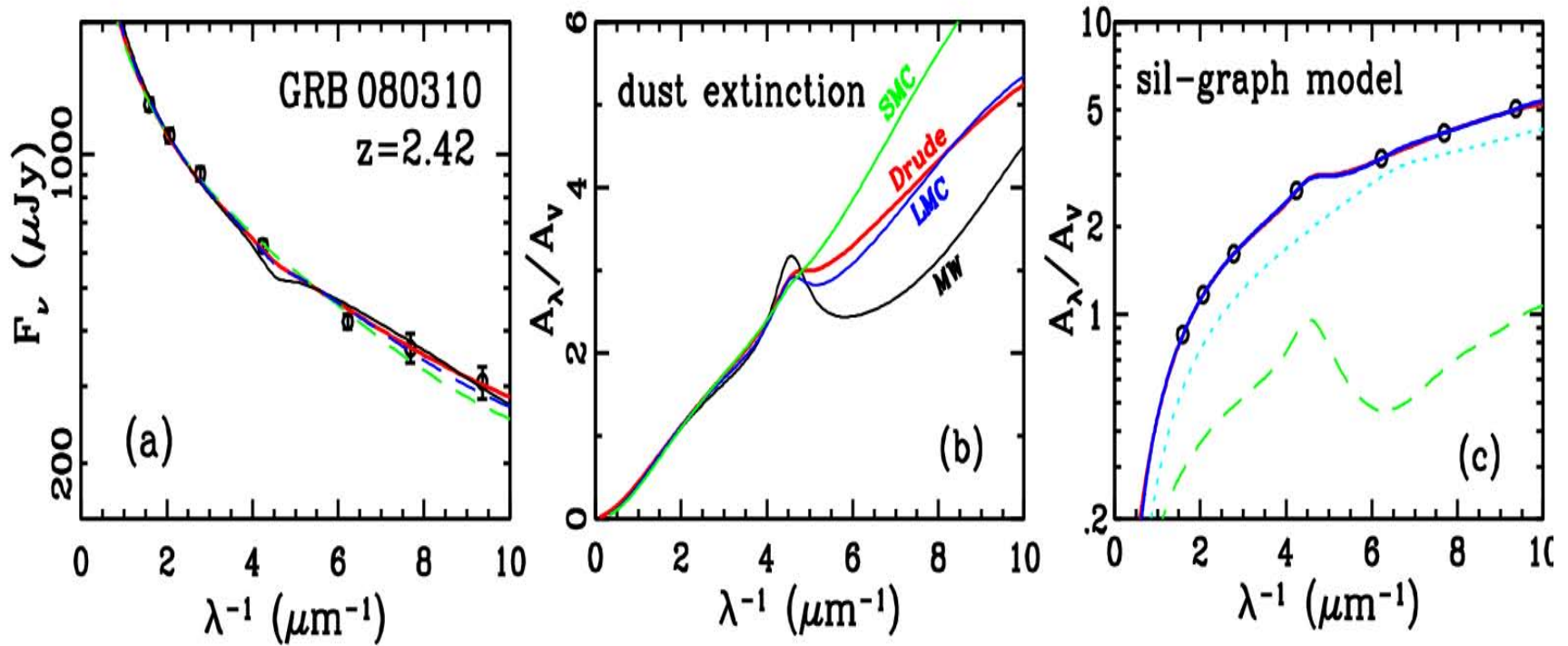
(2) Restores the widely adopted MW, SMC, LMC and “Calzetti” template dust extinction model

# Milky Way-type extinction law

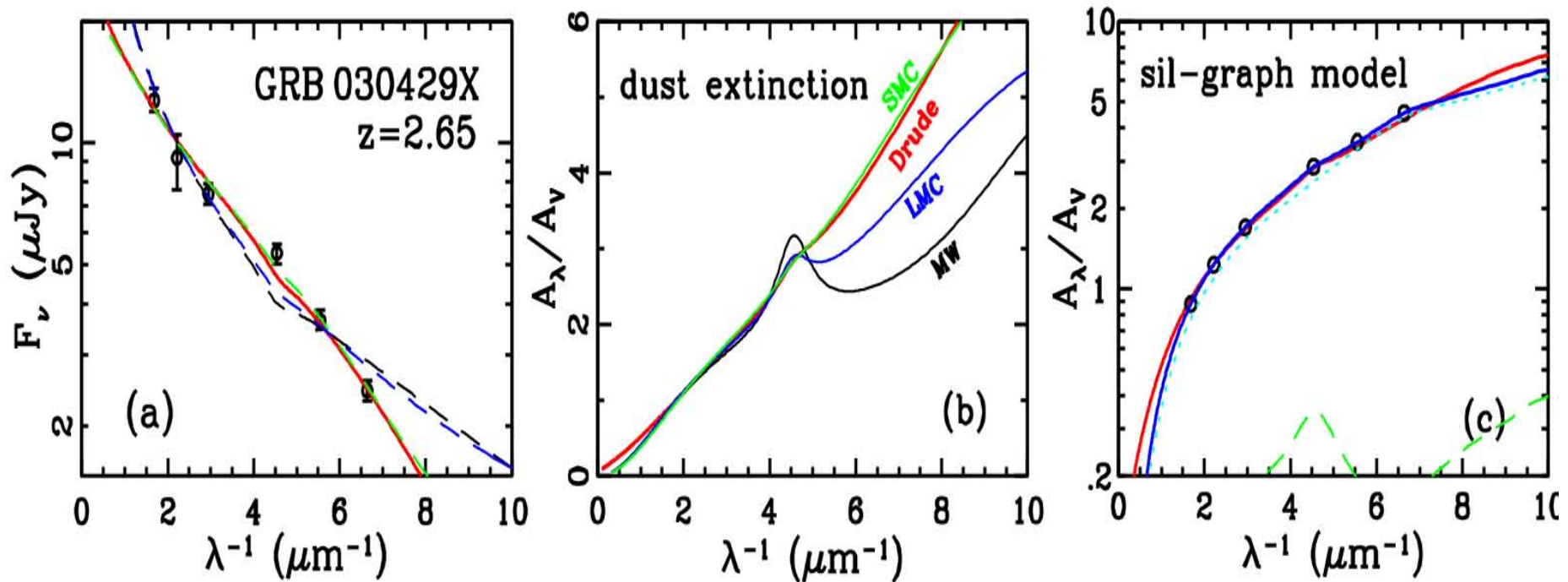


(Liang & Li 2010, 2011)

# LMC-type extinction law

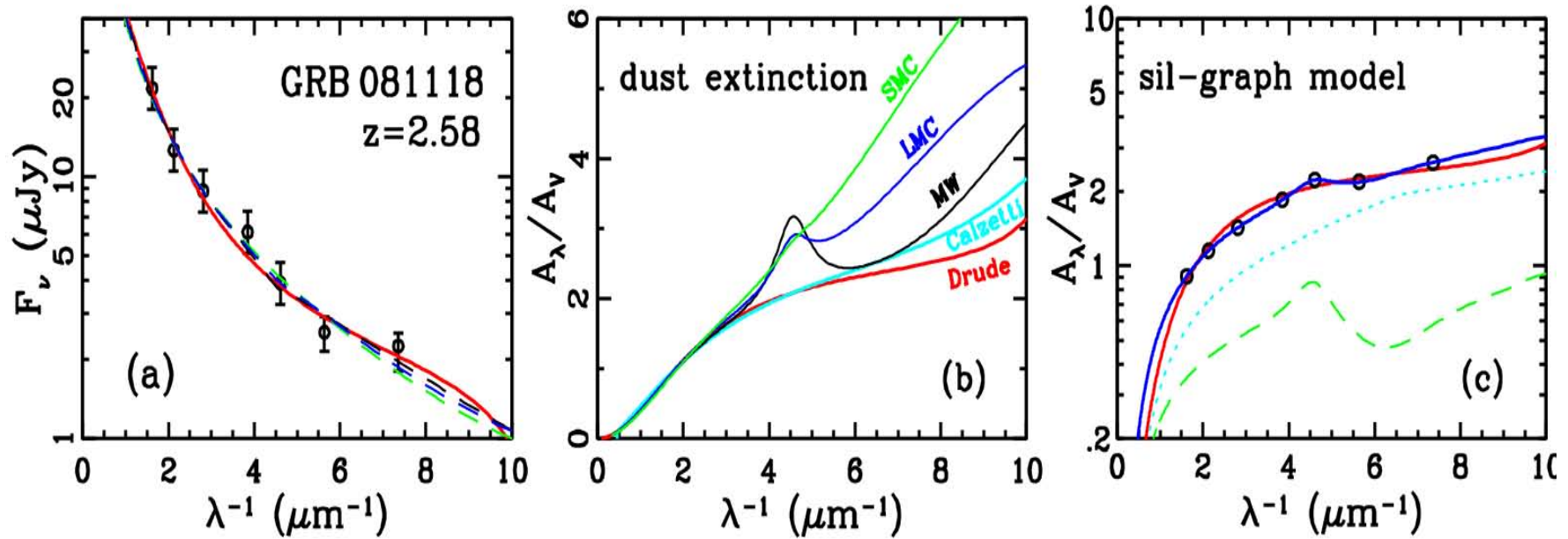


# SMC-type extinction law



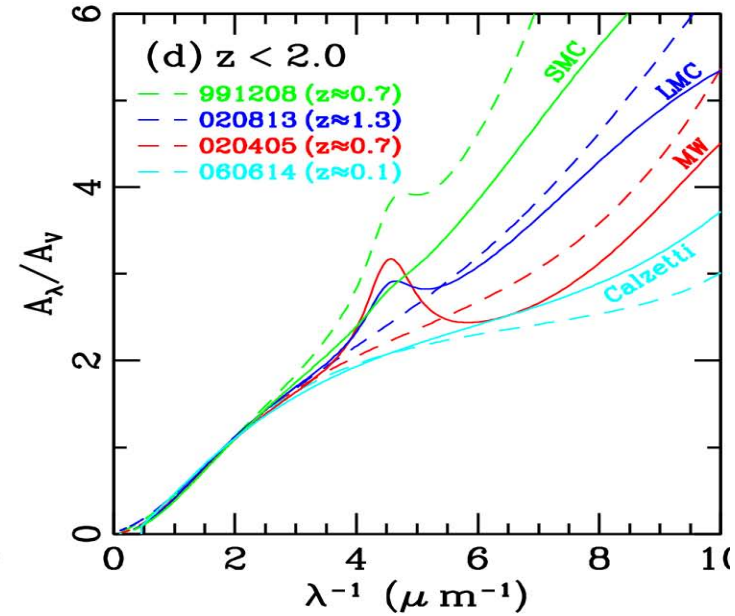
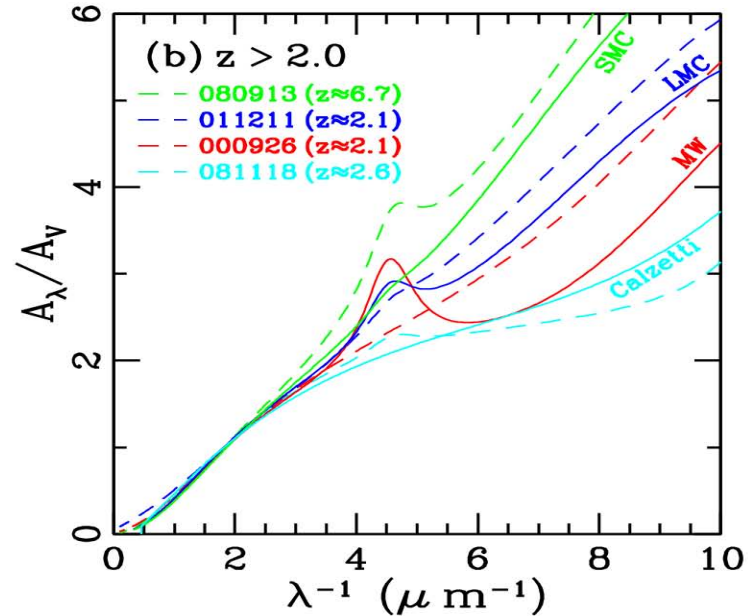
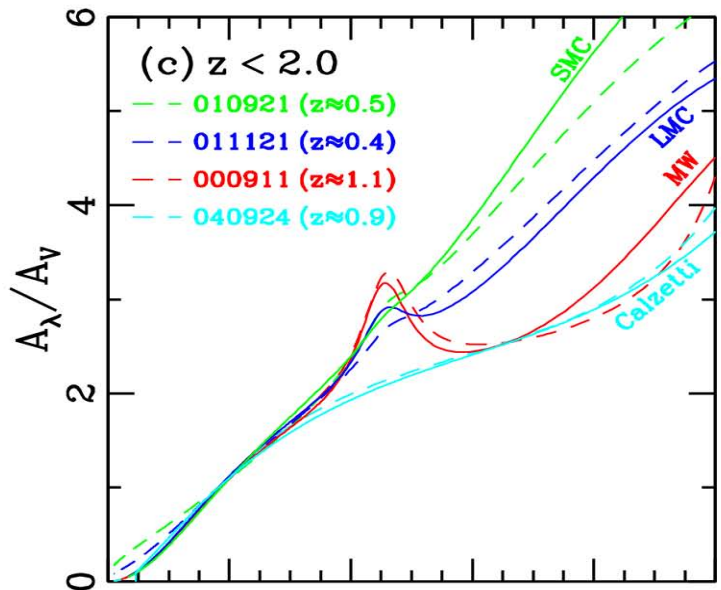
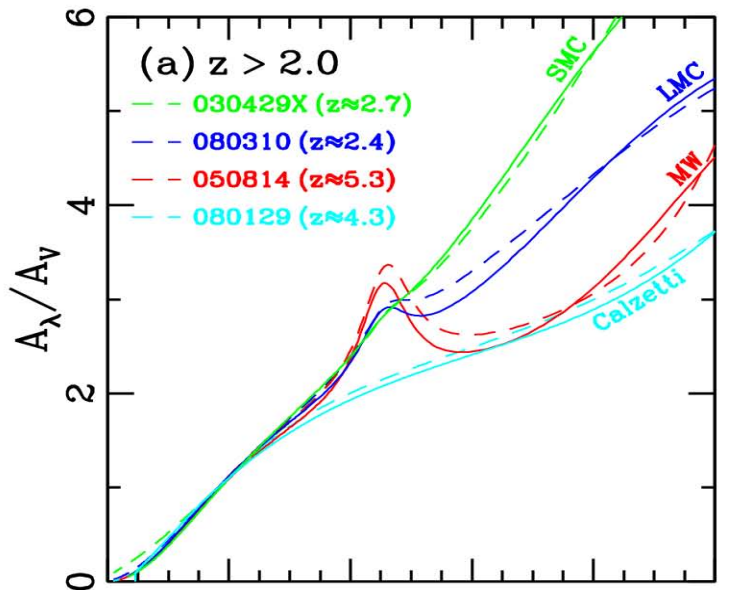
(Liang & Li 2010, 2011)

# Starburst galaxy-type extinction law



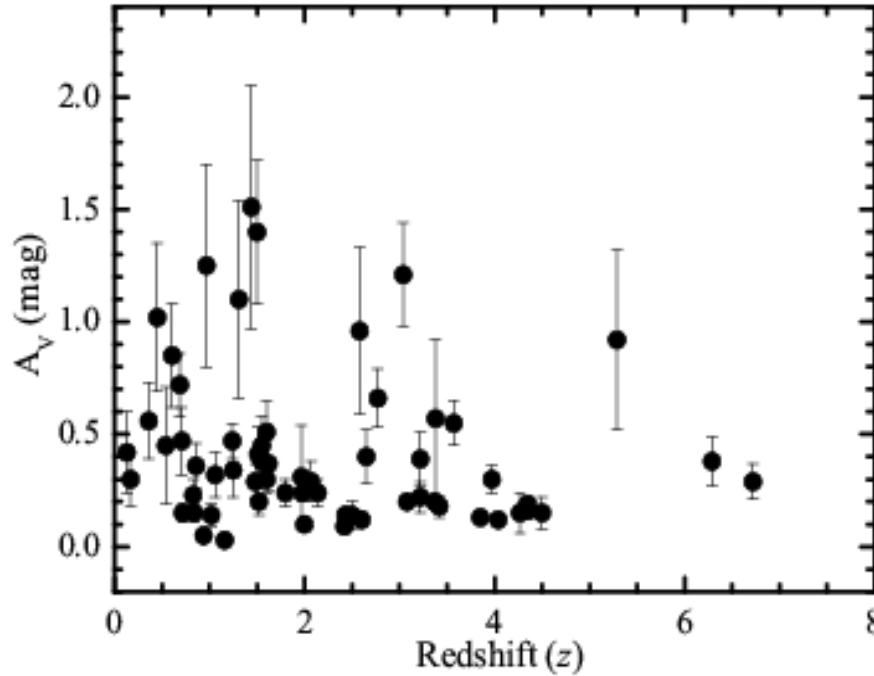
(Liang & Li 2010, 2011)

# GRB Host Extinction Curves



# Extragalactic dust through GRBs

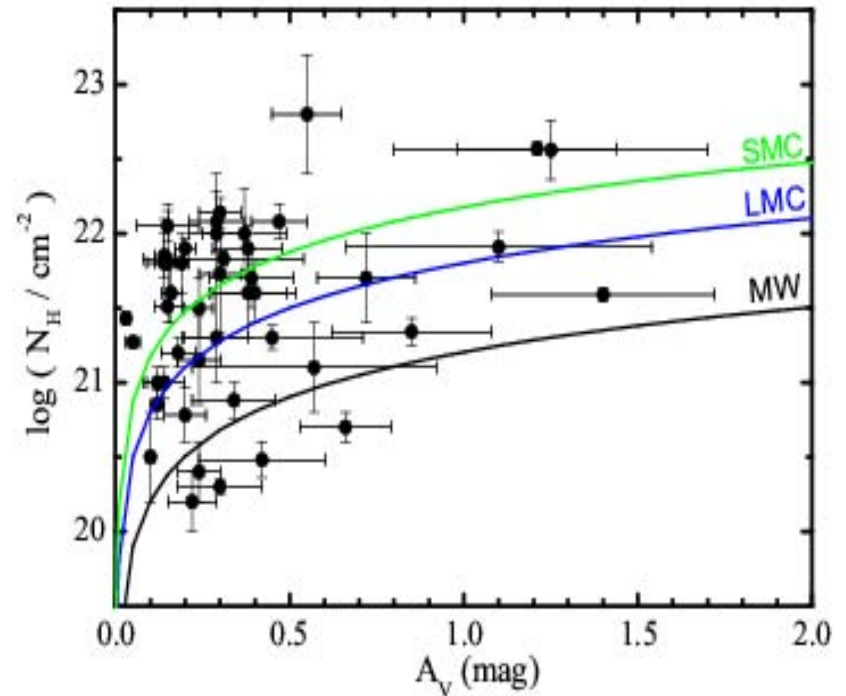
--- 67 GRBs at  $0 < z < 7.0$



extinction  $A_V$  vs.  $z$

No strong evidence for the dependence of  $A_V$  on  $z$ .

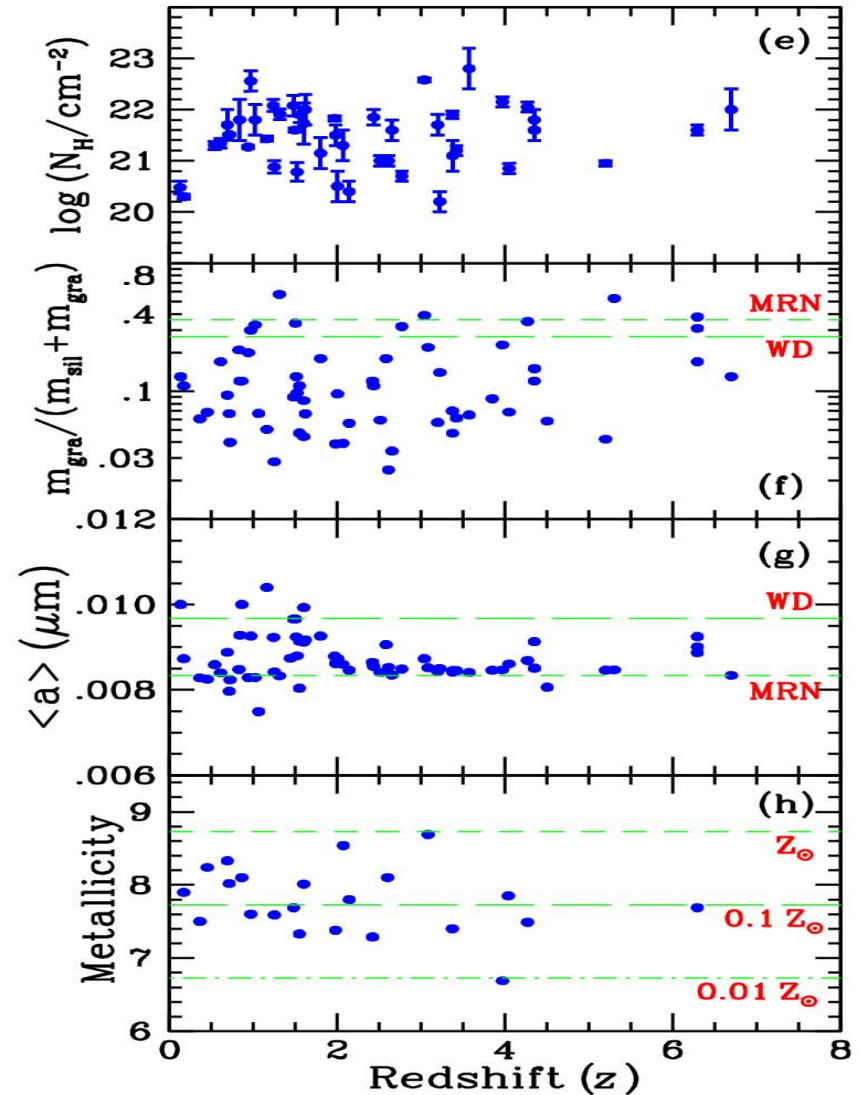
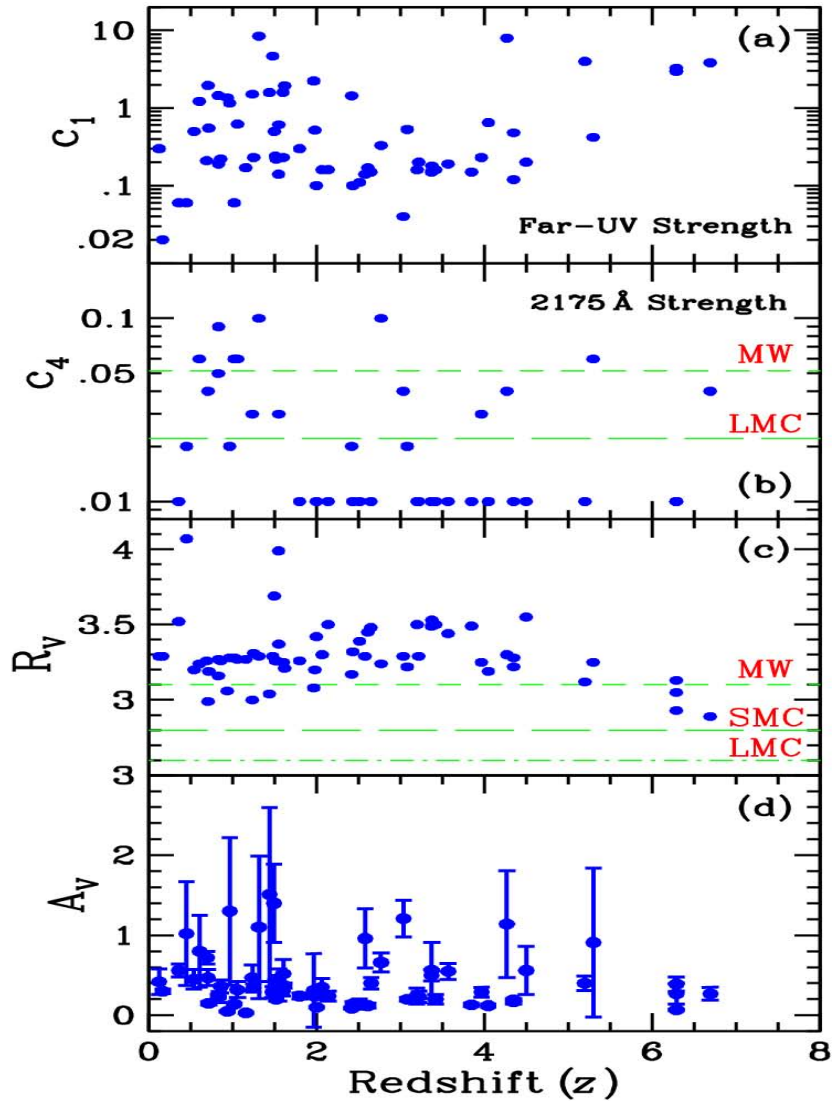
## Dust-to-gas ratios



Liang & Li 2011

# Extragalactic dust through GRBs

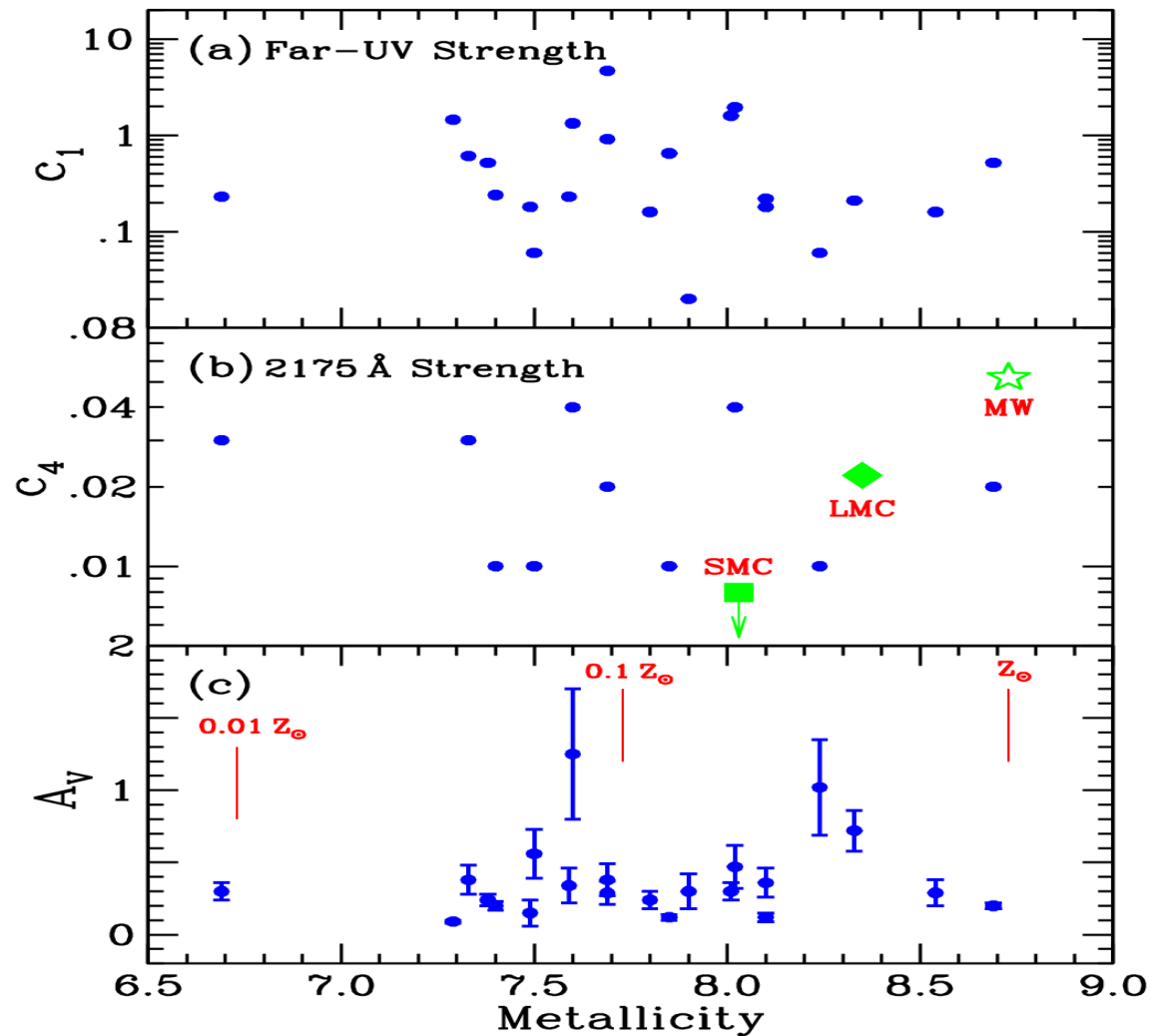
--- 67 GRBs at  $0 < z < 7.0$  (Liang & Li 2011)



# Extragalactic dust through GRBs

--- 67 GRBs at  $0 < z < 7.0$

(Liang & Li 2011)



# Final Reminder

- Caution should be taken in using the CCM formula to calculate external extinction.
- The dust composition (particularly silicates) in AGNs differs from that of the Galaxy.
- The extinction curves of AGNs and GRB host galaxies can differ substantially from the known MW/LMC/SMC extinction laws.
- The 2175 Å extinction feature appears to be present at all redshifts.
- There does not appear to show any evidence for a dependence of dust extinction on redshifts, although the extinction curve does vary from one burst to another.
- No obvious evidence to show dust properties are different between  $z < 5$  and  $z > 5$ .