Kobe International School of Planetary Sciences:
Small Bodies in Planetary Systems
6 December 2006

Dust Models and Optical Properties

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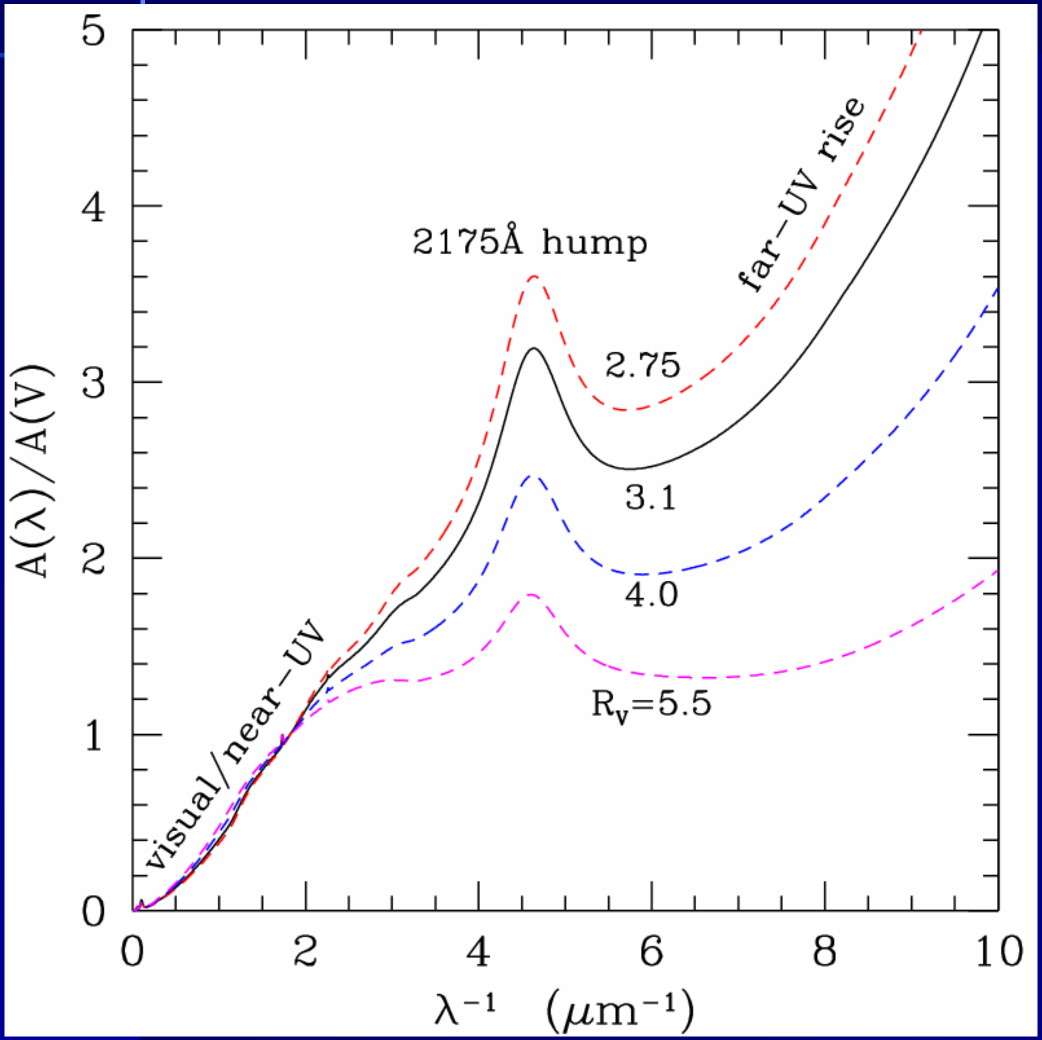
- Part I: Optics of Dust
- Part II: Interstellar Dust
- Part III: Interstellar, Cometary, Circumstellar Disk Dust Models
  - Silicate-Graphite-PAH model;
  - Core-mantle model;
  - Composite model;
  - Porous aggregate model for cometary dust;
  - Porous dust model for dust disks;

Part II: Interstellar Dust

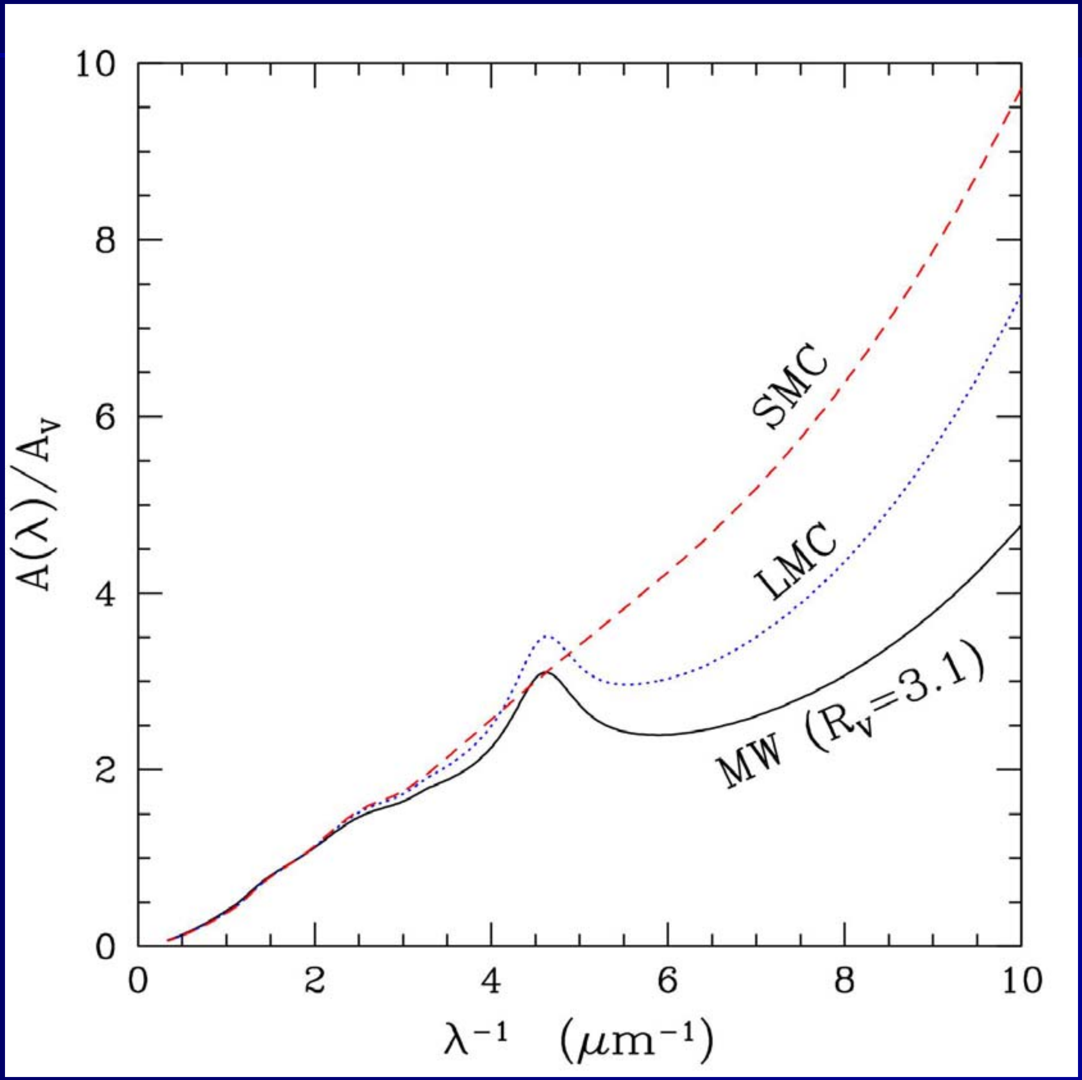
- The nature of the Milky Way interstellar dust
  - extinction ⇨ dust size;
  - spectral features ⇨ composition;
  - IR emission ⇨ dust size, composition;
  - polarization ⇨ shape: nonspherical;

Milky Way Interstellar Extinction: Grain Size

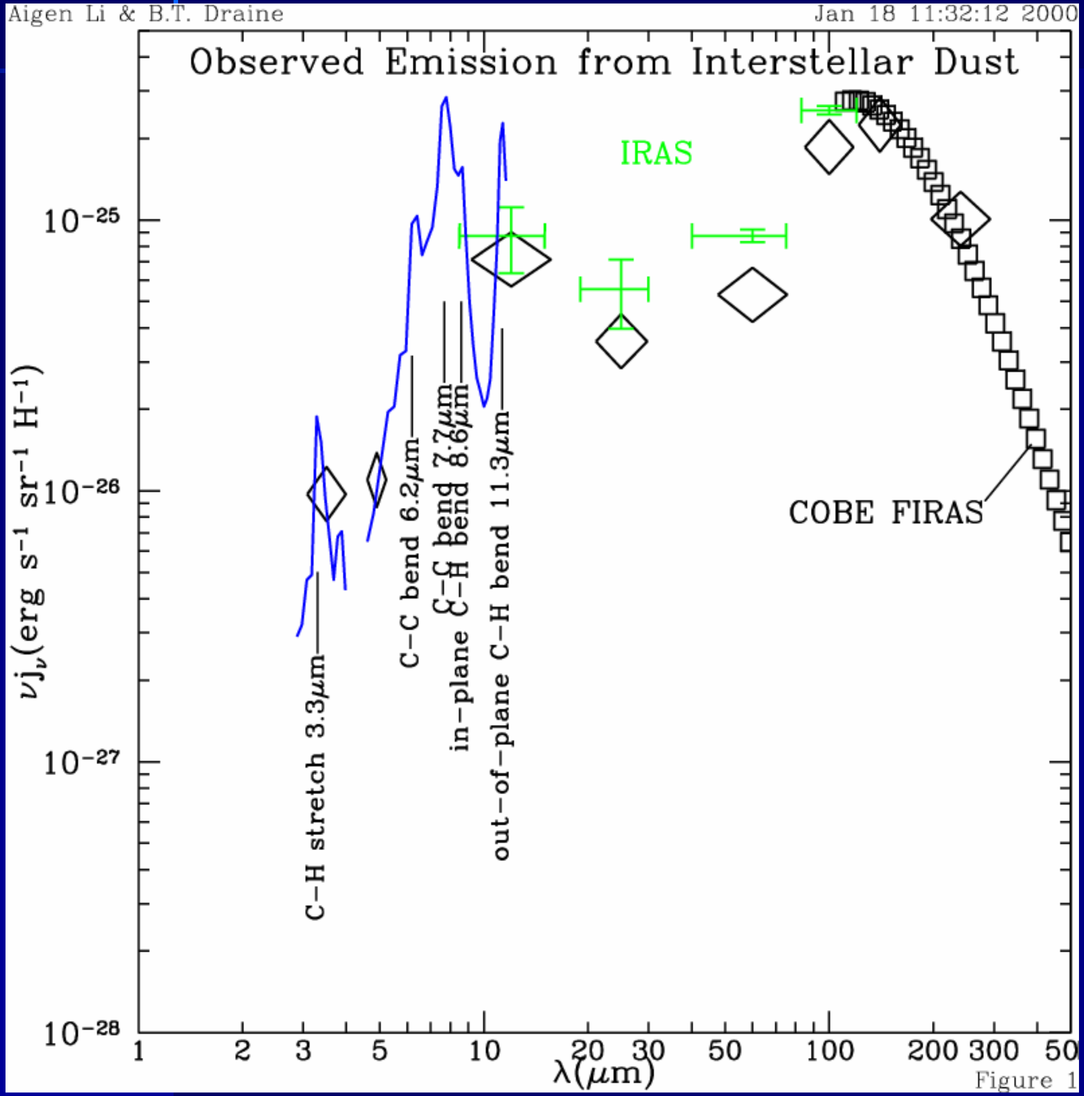


- 2 grain populations:
  - a < 100 Å;
  - a>0.1 μm;
- Characterized by $R_V = A_V / E(B-V)$;
  - dense regions: larger R_V;
  - larger $R_V \rightarrow$ larger grains;
- 2175 Å bump
  - aromatic carbon;
  - small graphitic grains or PAHs;

Interstellar Extinction:
SMC/LMC vs. MW



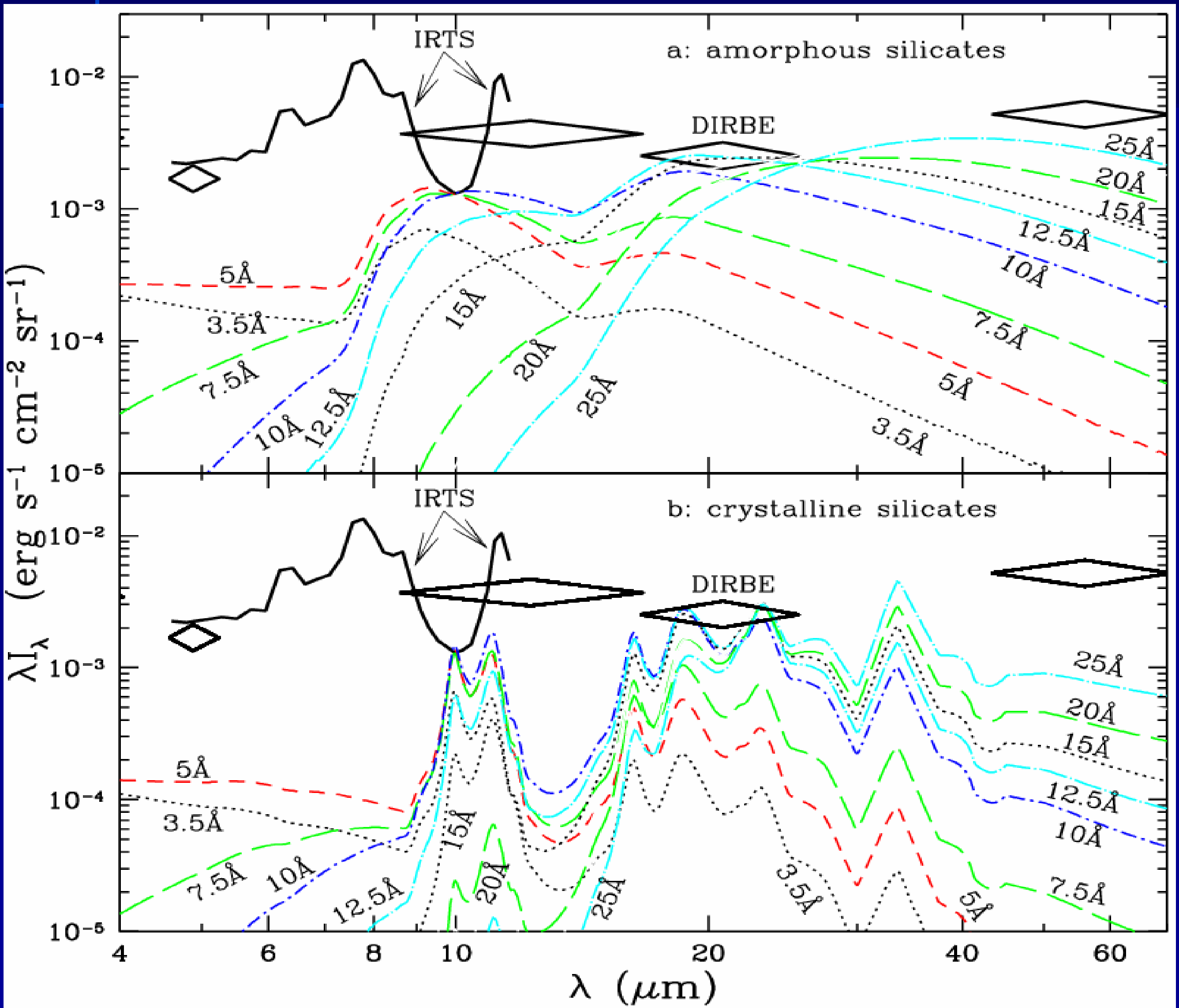
Infrared Emission: Grain Size and Composition



- Classic grains
  - 100Å <a <3000 Å;
  - T_d ~ 20K;
  - emit at λ>60 μm;
  - ~ 2/3 of total emitted power;
- Ultrasmall grains:
  - PAHs (~10% C);
  - a<100 Å;
  - emit at λ<60 μm;
  - stochastic heating;
  - ~ 1/3 of total power;

Interstellar Silicates: Amorphous

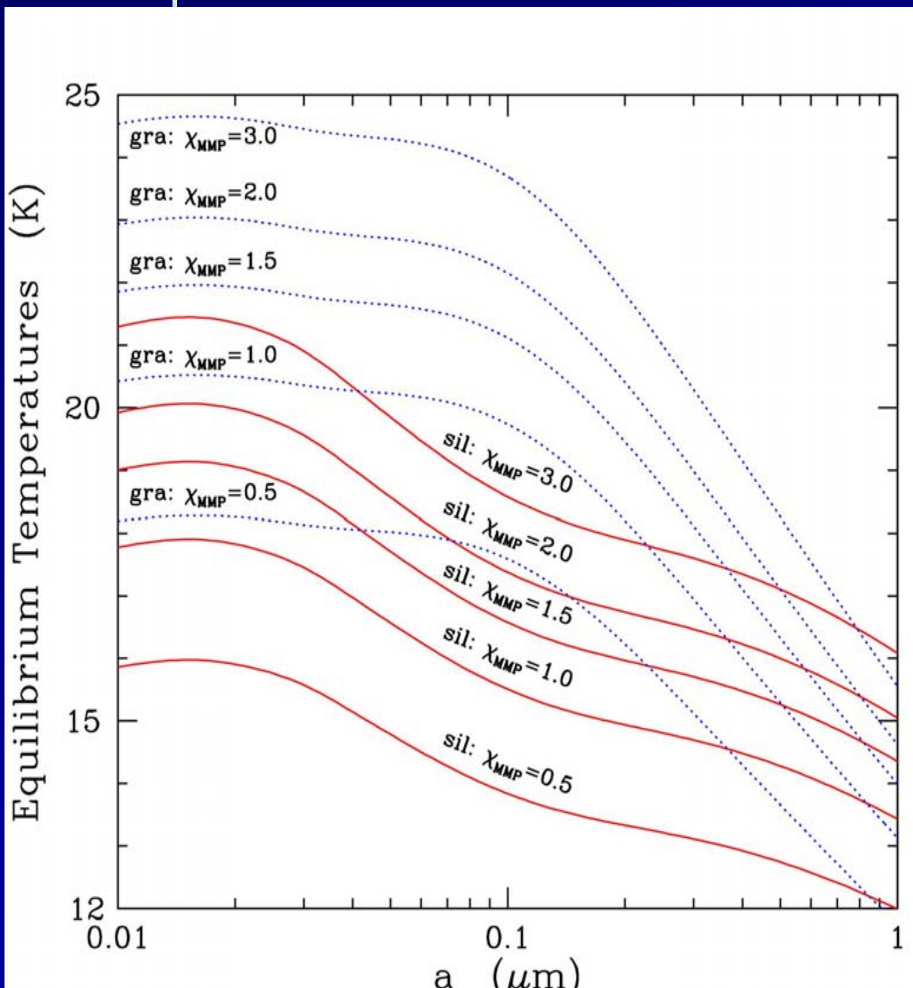
(Li & Draine 2001a)



– ultrasmall silicate grains ≤5%;

– crystalline silicate (large or small size) ≤5%;

Thermal Equilibrium Temperatures of "Classical" Grains: 15-25K (Li & Draine 2001, ApJ, 554, 778)



Energy balance between absorption and emission → **"equilibrium" temperature**:

$$\int_0^\infty C_{\rm abs}(a,\lambda) c u_\lambda d\lambda = \int_0^\infty C_{\rm abs}(a,\lambda) 4\pi B_\lambda(\bar{T}) d\lambda \quad ,$$

$C_{\rm abs}(a,\lambda)$ = absorption cross section ← determined by grain size, composition, geometry

$B_\lambda(T)$ = Planck function,

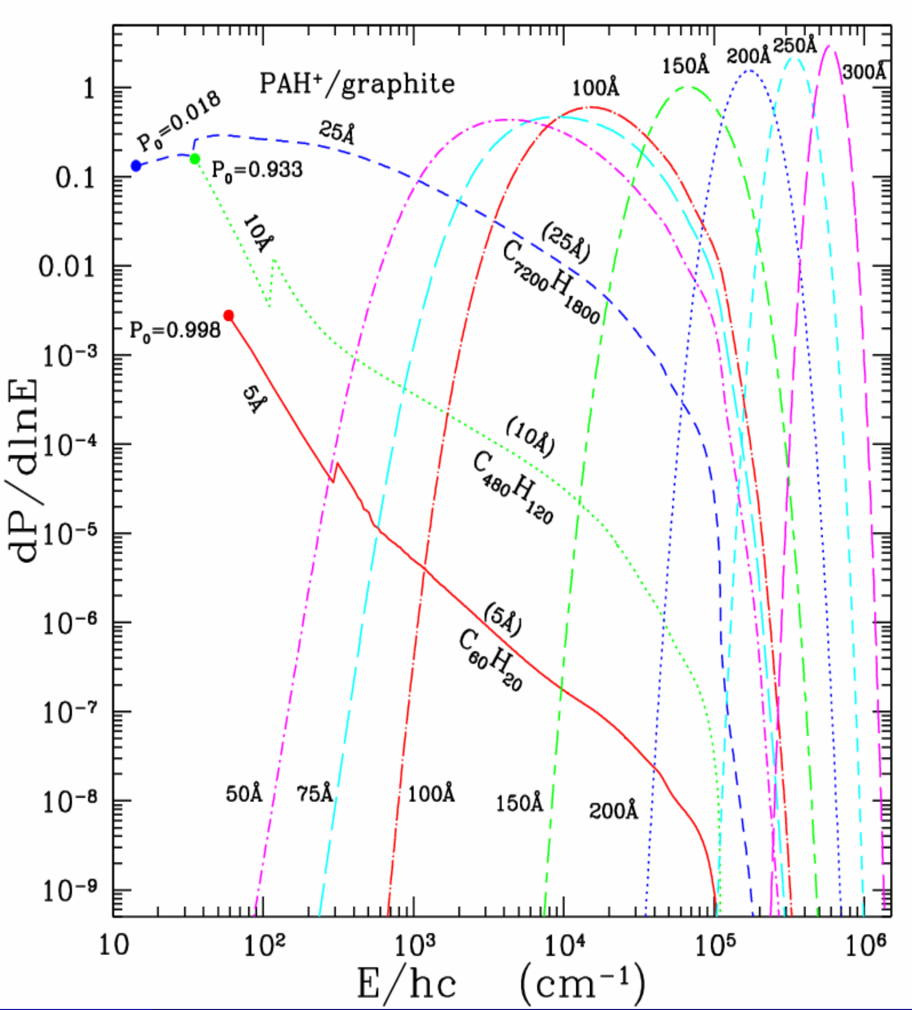
u_λ = energy density of the radiation field.

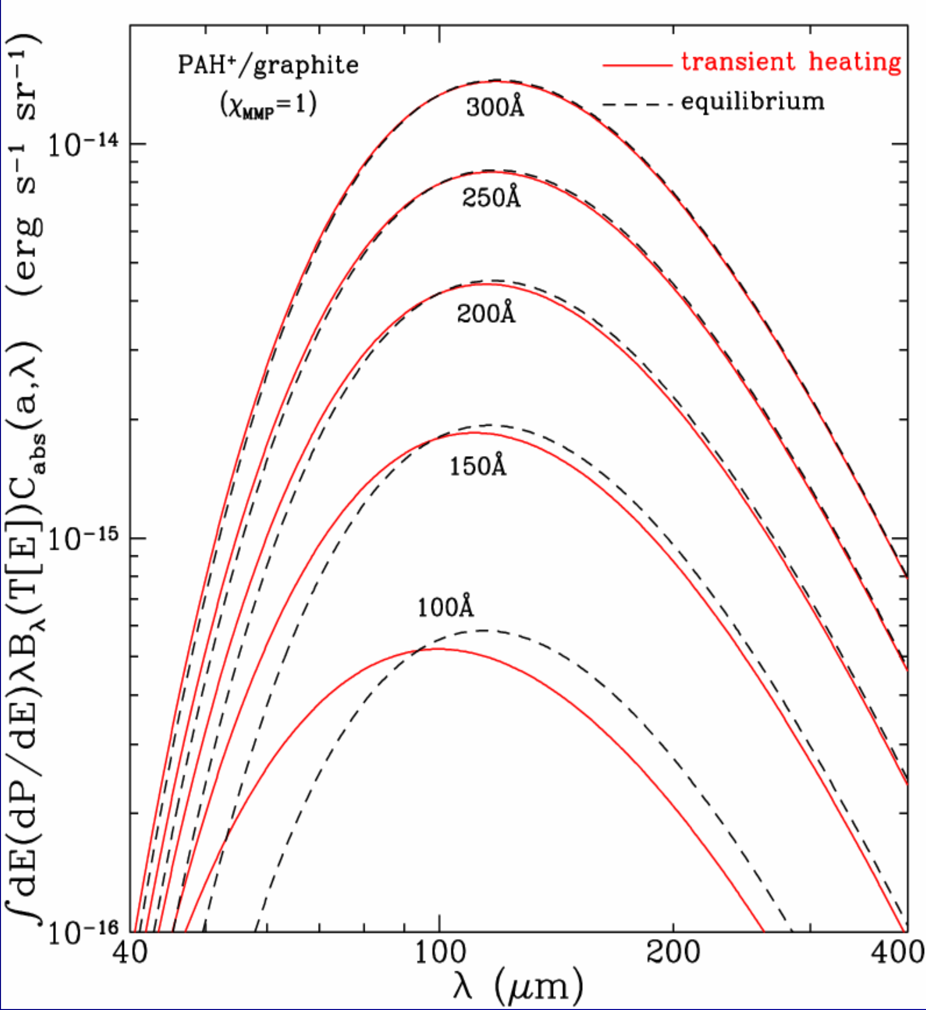
$Q_{\rm abs}(a,\lambda)$ = absorption efficiency = $C_{\rm abs}(a,\lambda)/\pi a^2$,

$\kappa_{\rm abs}(a,\lambda)$ = mass absorption coefficiency = $3Q_{\rm abs}(a,\lambda)/(4a\rho)$,

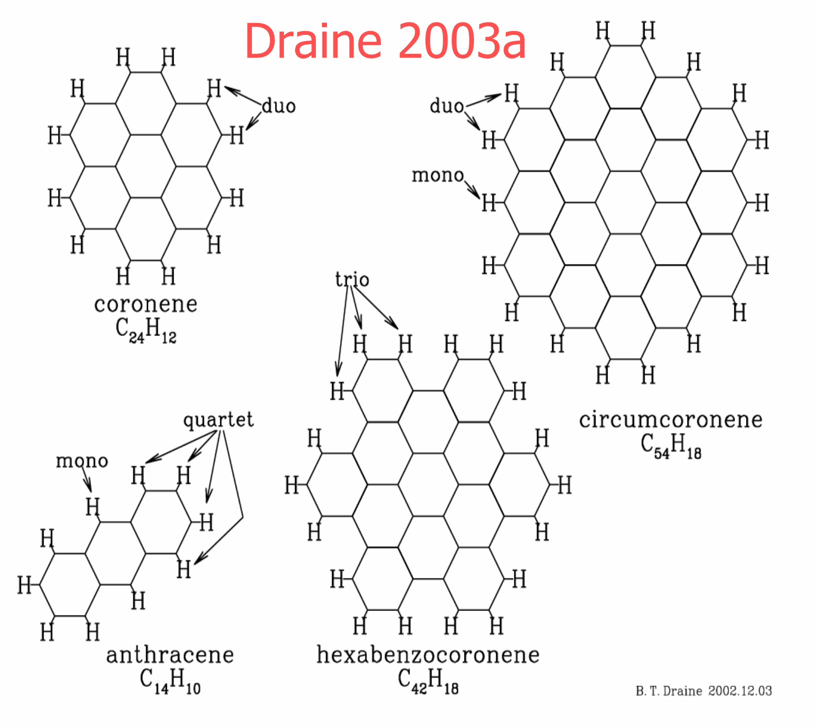
Stochastic Heating Nature of Ultrasmall Grains

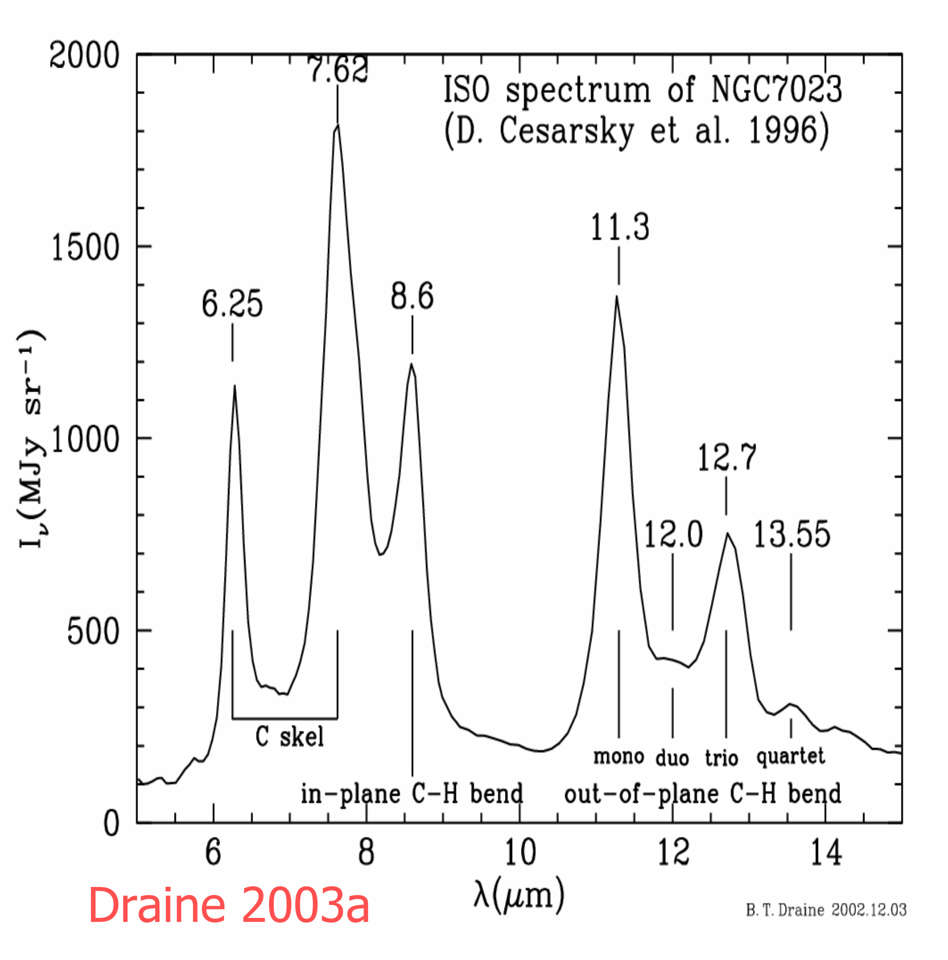
(Li & Draine, ApJ, 554, 778)





PAHs are ubiquitous in Astrophysical Environments !



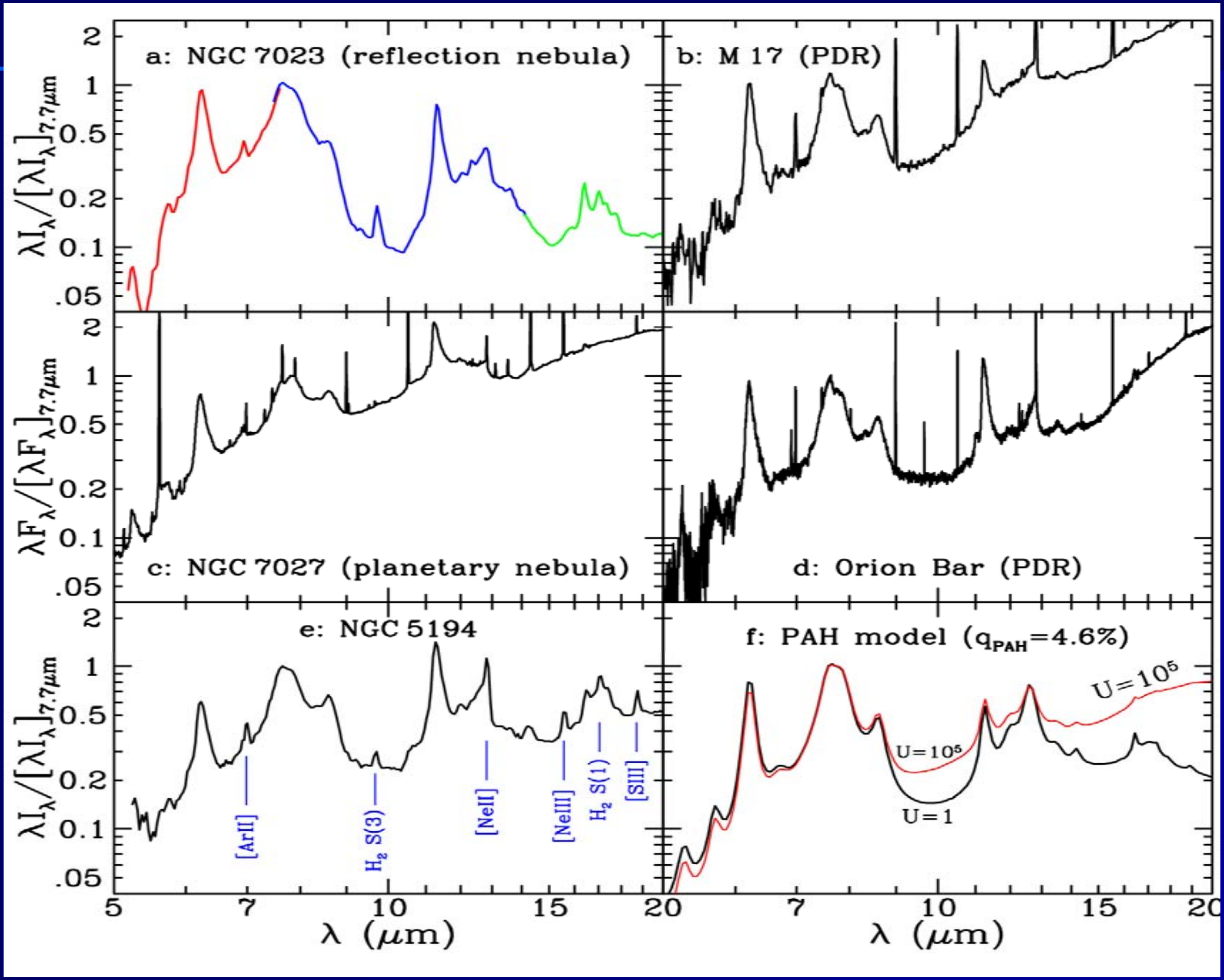


PAHs are ubiquitous in the interstellar medium

- "Unidentified Infrared" (UIR) bands at 3.3, 6.2, 7.7, 8.6, 11.3μm are ubiquitously seen in interstellar space;
- → They are generally attributed to PAHs:
  - 3.3μm: C-H stretching mode;
  - 6.2, 7.7μm: C-C stretching modes;
  - 8.6μm: C-H in-plane bending mode;
  - 11.3, 12.7μm: C-H out-of-plane bending modes;
  - They require [C/H] ~ 60ppm (Li & Draine 2001b);

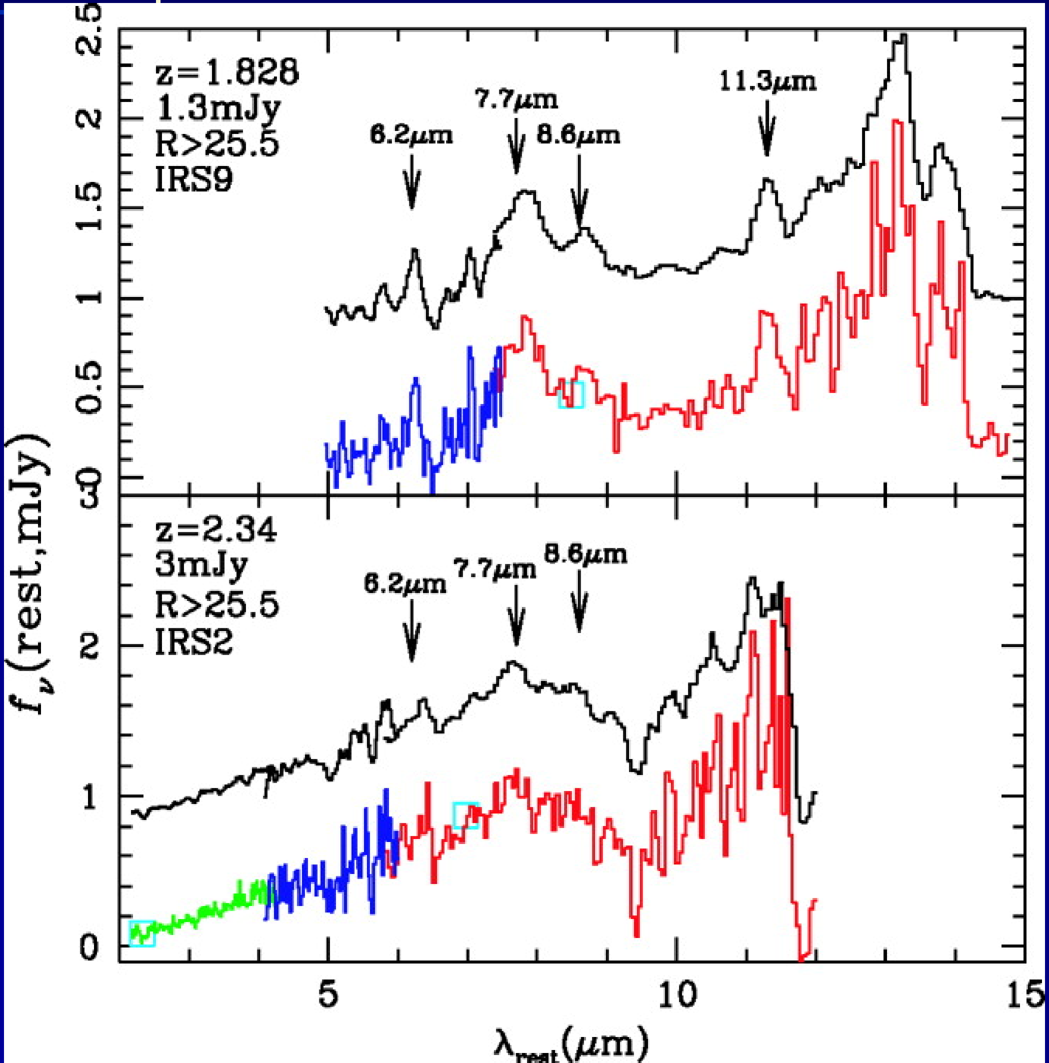
PAHs are ubiquitous in space

(Draine & Li 2006, ApJ, in press)

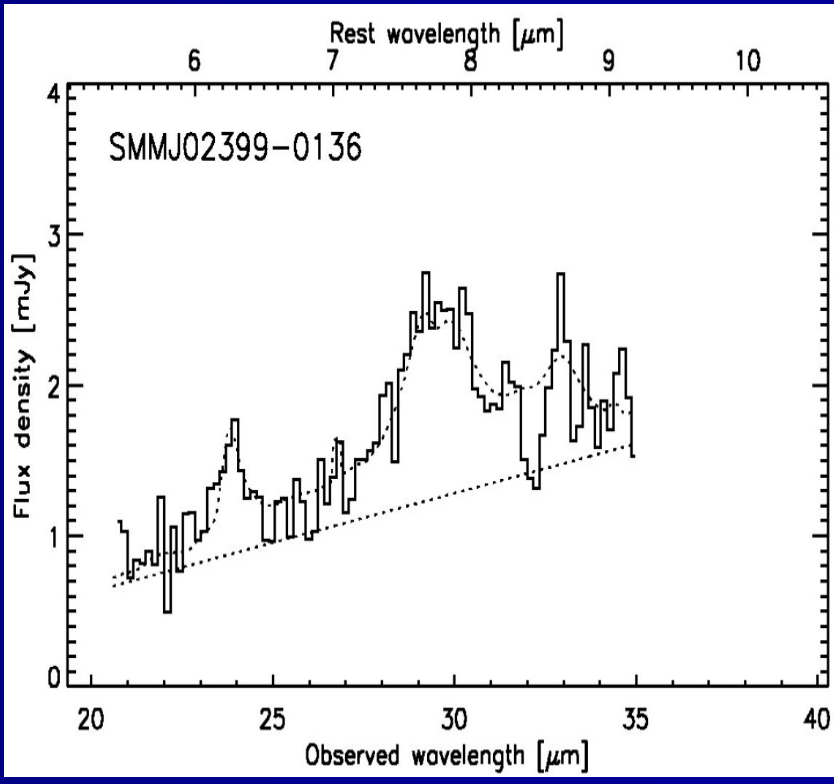


PAHs in high-redshift galaxies

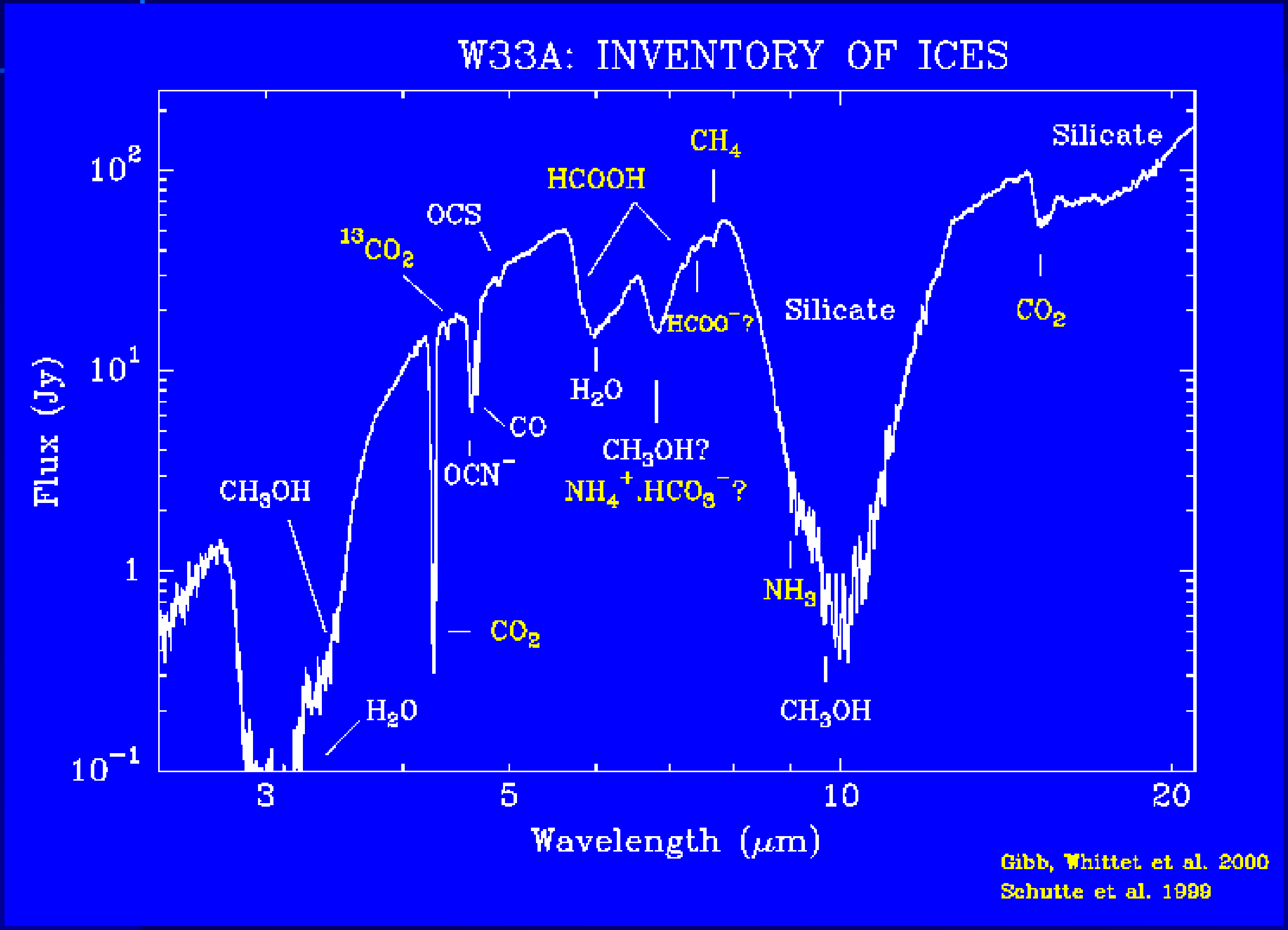
ULIRGs (Yan et al. 2005)



Luminous submm galaxy z~ 2.8 (Lutz et al. 2005)

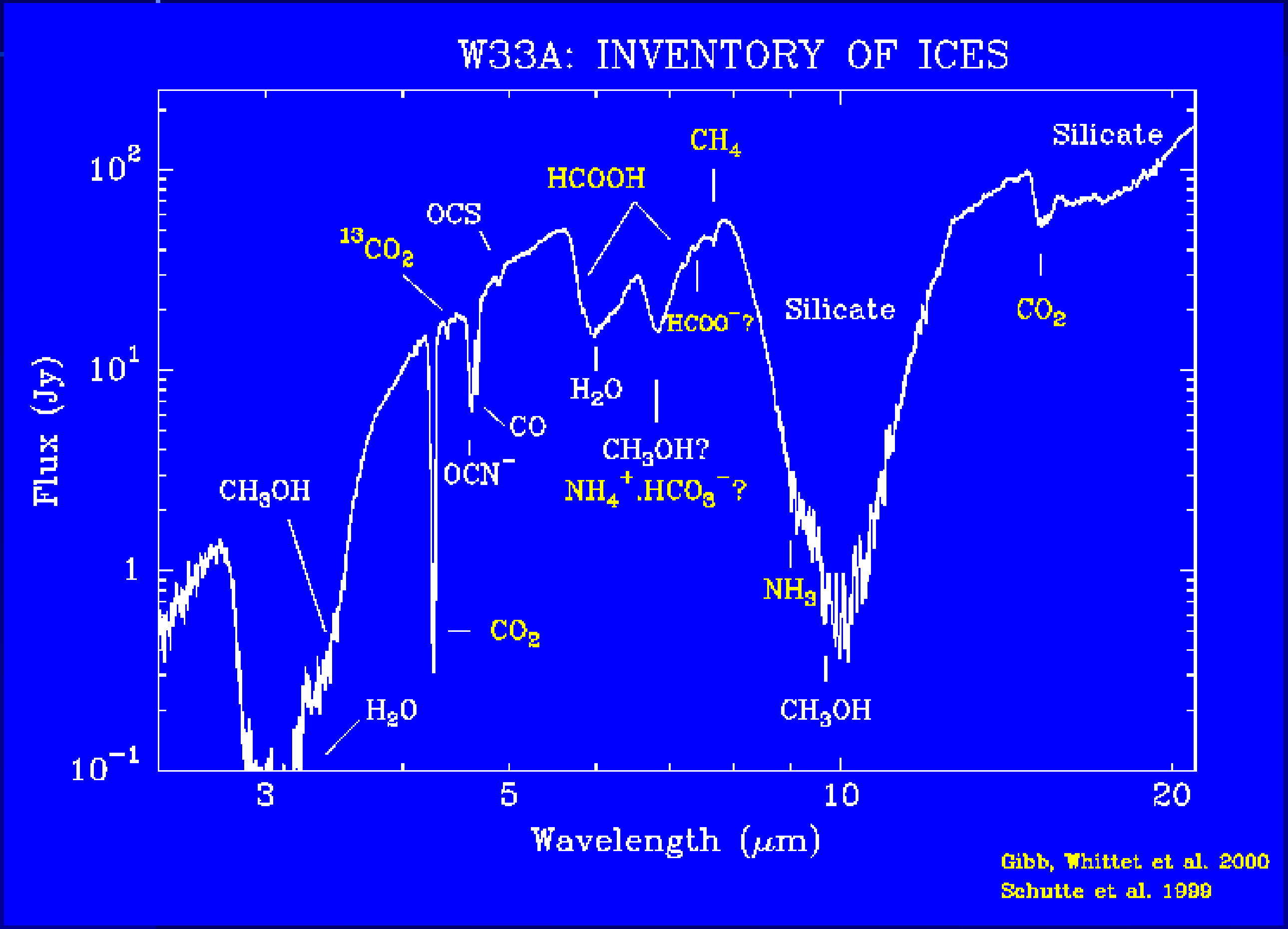


Absorption Features: Grain Composition



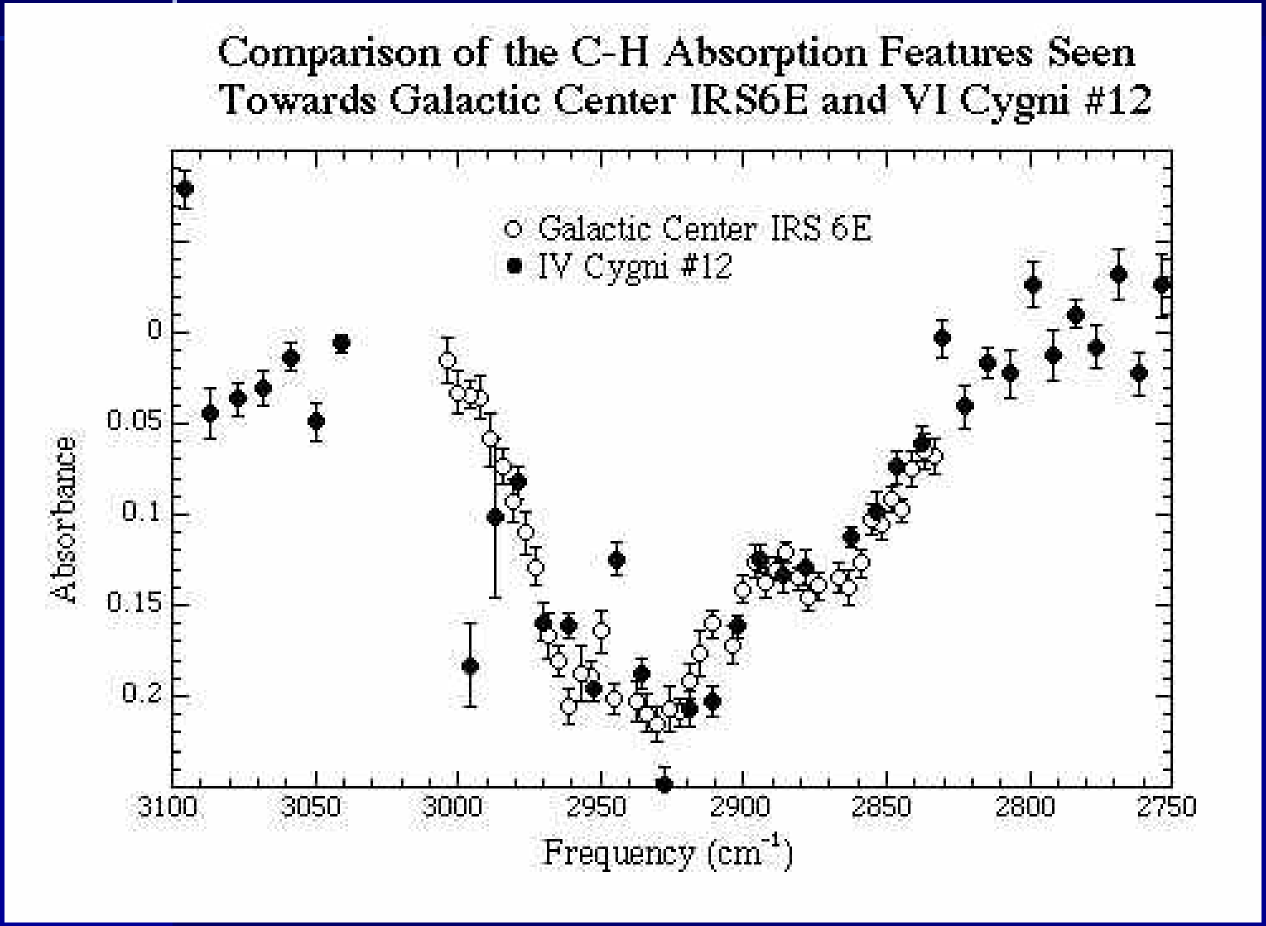
- Silicate dust
  - 9.7 μm: Si-O stretching;
  - 18 μm: O-Si-O bending;
  - Amorphous;

Absorption Features: Grain Composition



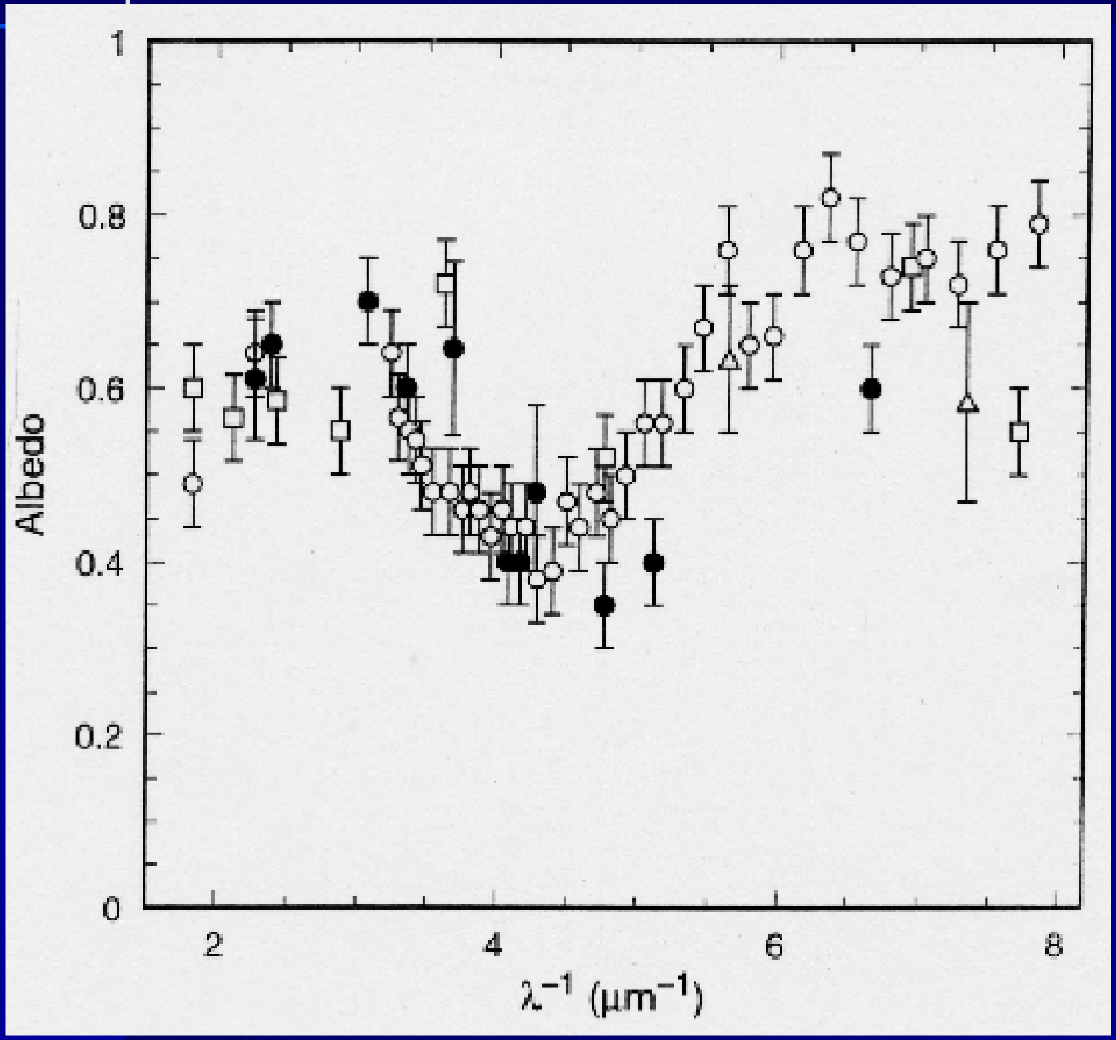
- Ices
  - dense regions (A_v>3 mag);
  - H_2O 3.1, 6.0μm;
  - CO 4.68μm;
  - CO_2 4.28, 15.2μm;
  - CH_3OH 3.54, 9.75μm;
  - H_2CO 5.81μm;
  - CH_4 7.68μm;
  - NH_3 2.97μm;

Absorption Features: Grain Composition



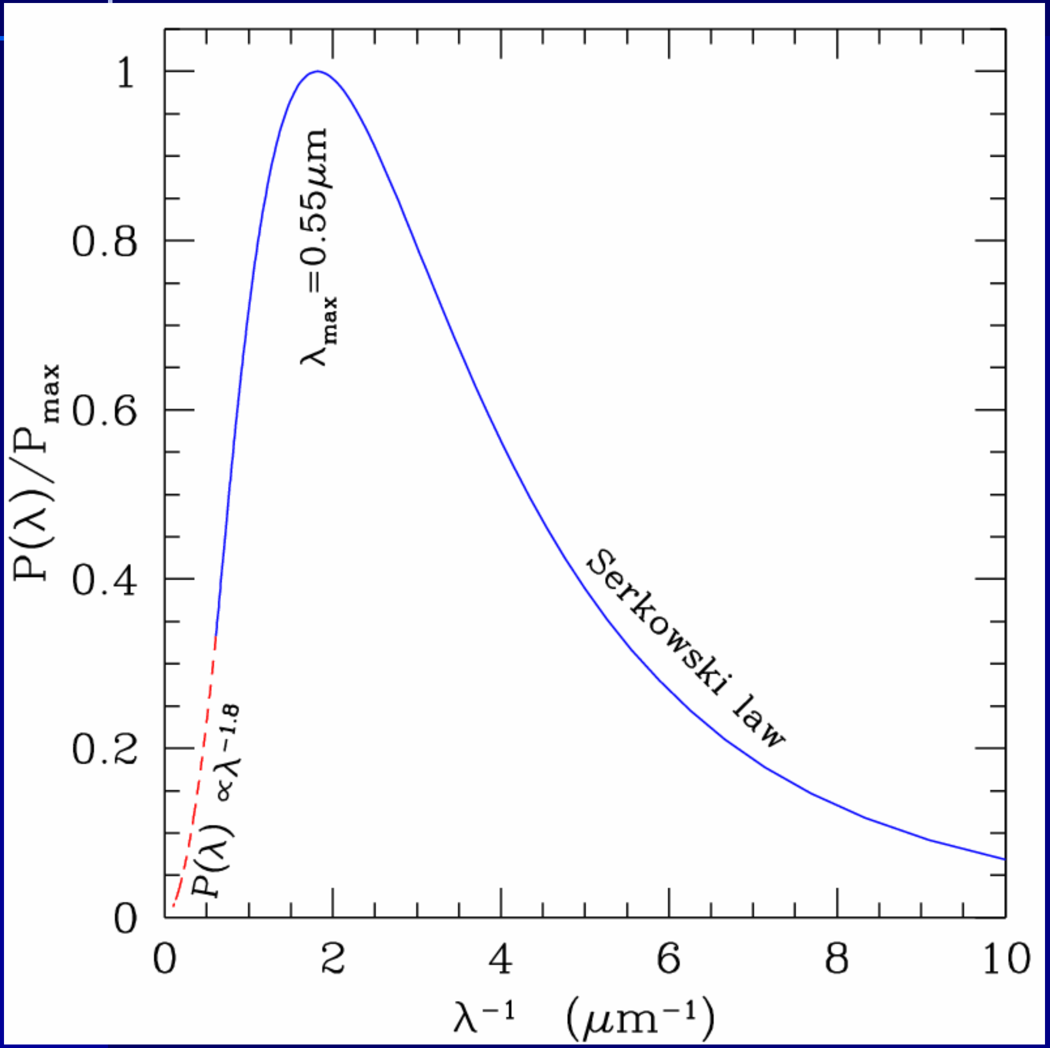
- Aliphatic hydrocarbon
  - 3.4 µm C-H stretching band;
  - diffuse ISM;
  - PPN CRL 618;
  - other galaxies;

Interstellar Scattering



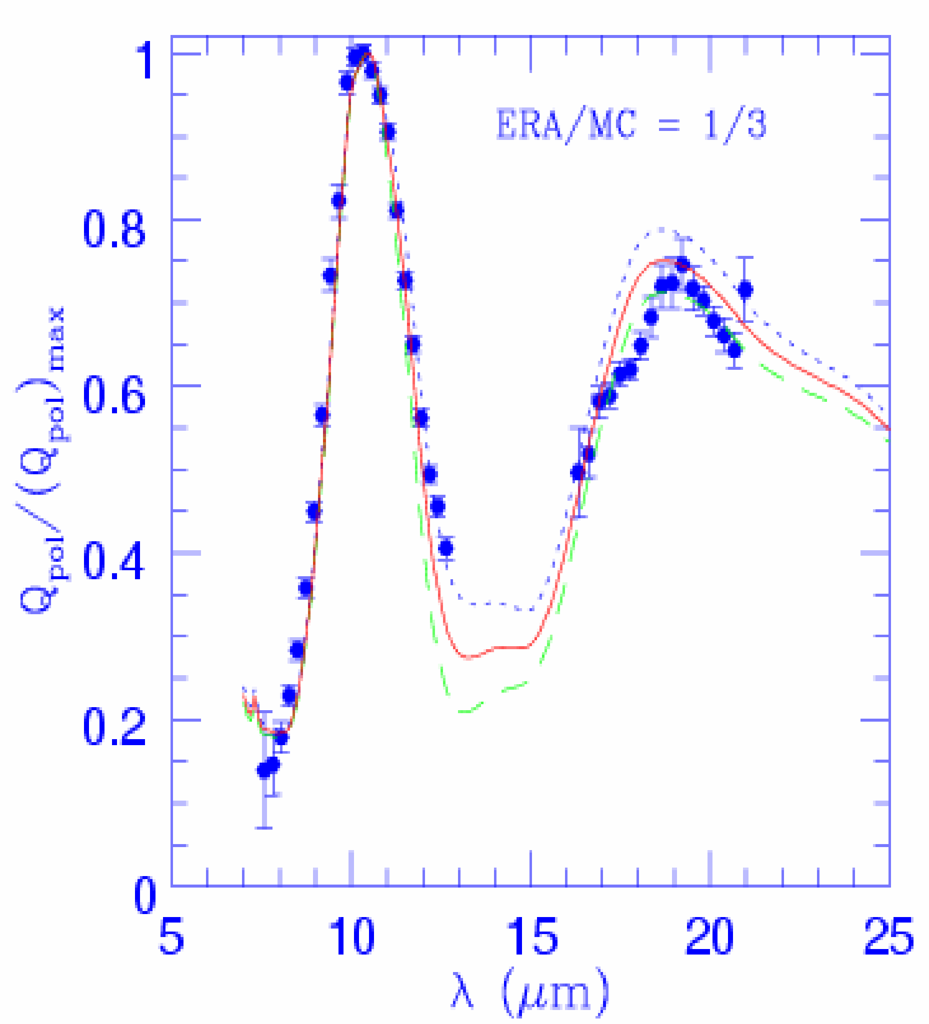
- Albedo α≈0.6;
- Asymmetry factor g≈0.6-0.8;
- 2175 Å hump:
  - no Scattering;

Interstellar Polarization



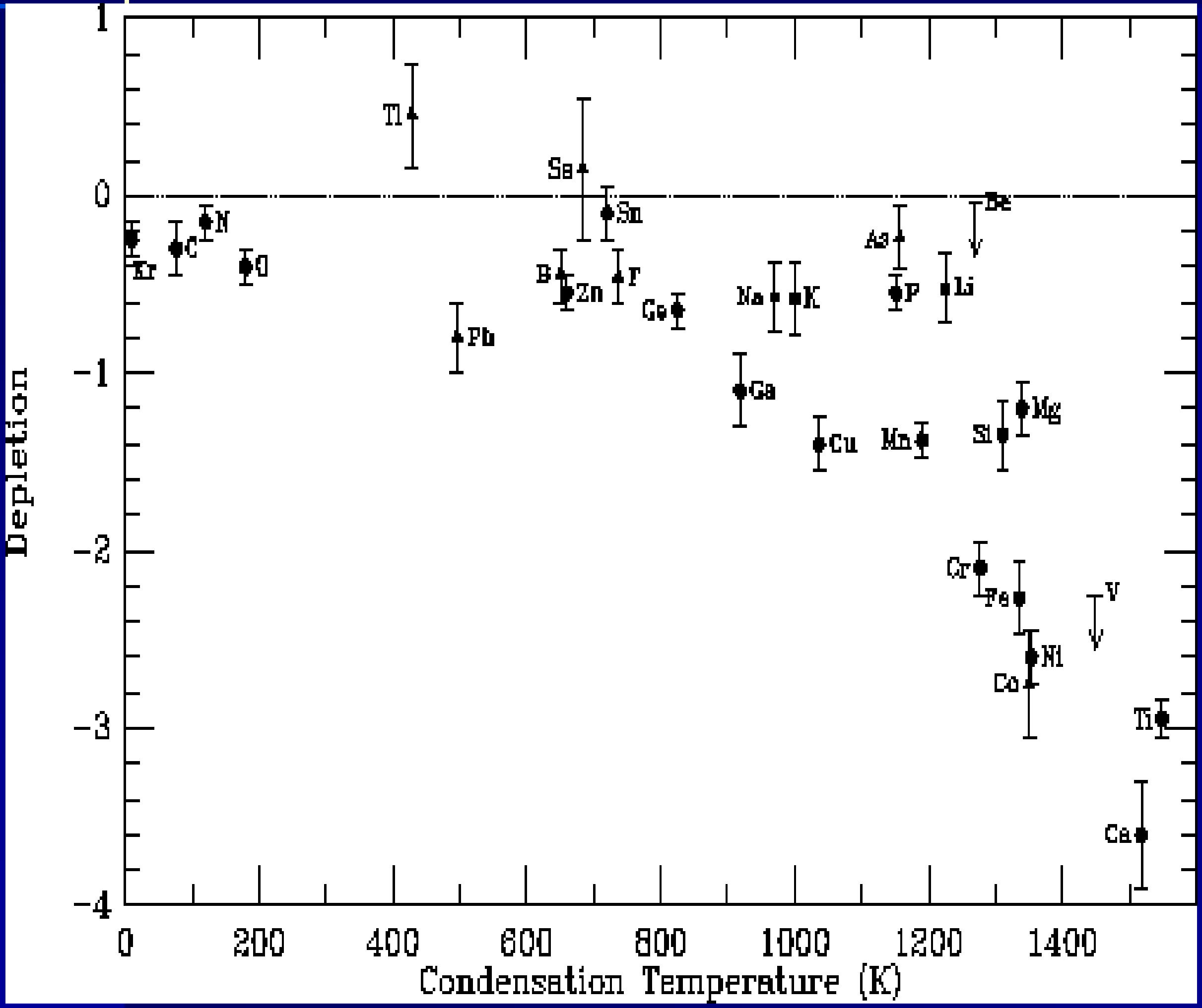
- Large grains
  - nonspherical and
  - aligned
- Small grains
  - spherical and/or
  - not aligned;

Interstellar Polarization Features



- 9.7,18μm silicate: polariz.
  - Becklin-Neugebauer object;
  - Aitken et al. (1989);
  - Greenberg & Li (1996);
- 3.4μm hydrocarbon:
  - Unpolarized (Adamson et al. 1999, Chiar et al. 2006);
- PAHs bands: unpolariz.;
- Far-IR emission: polariz.;
- Ice bands: polarized;
  - 3.1μm H_2O;
  - 4.67μm CO;
  - 4.62μm XCN^-;

Elemental Depletions



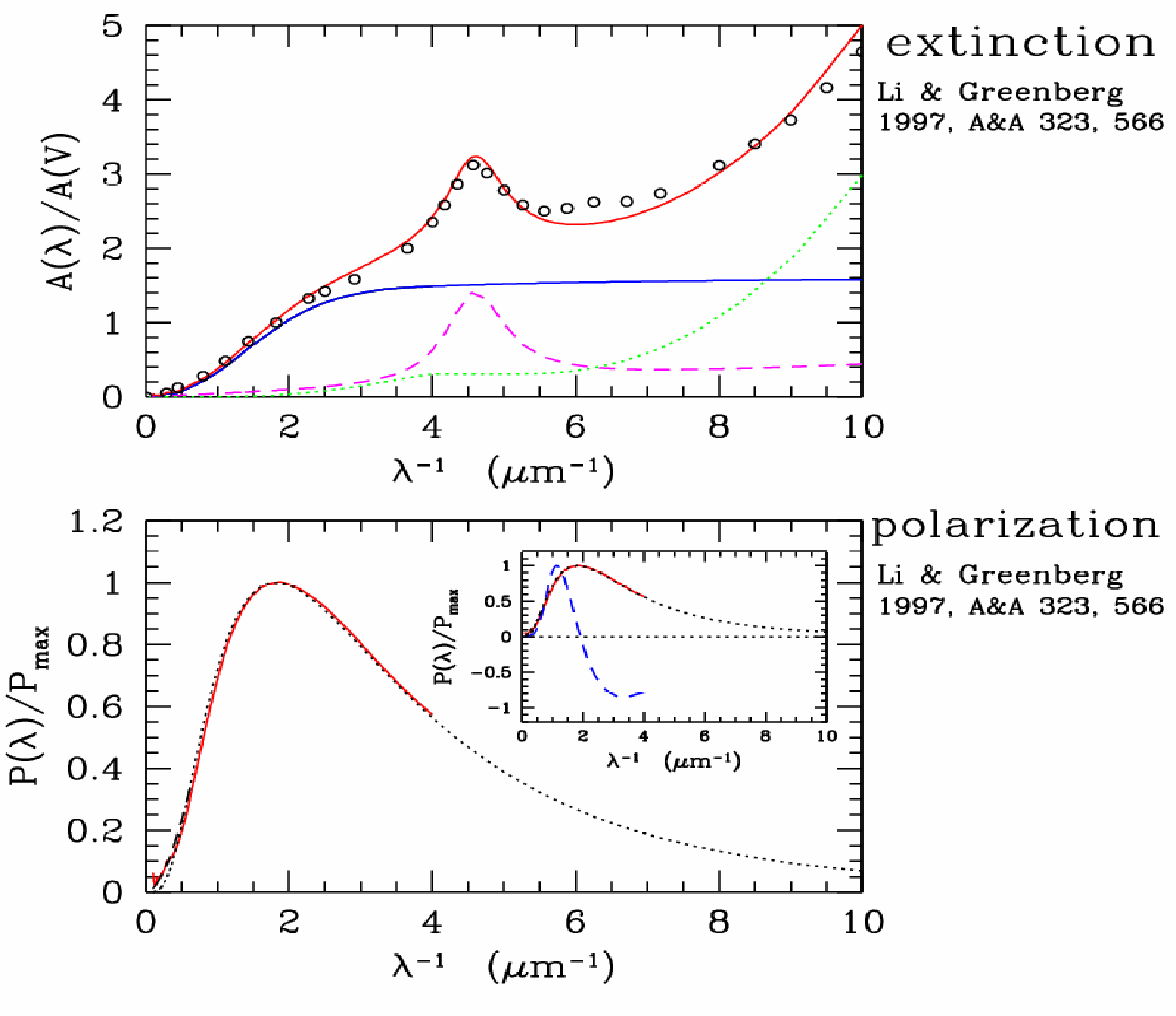
- $[X/H]_{gas} < [X/H]_{\odot}$;
- ≥90% of Si, Mg, Fe and ≥60% of C, O are locked up in dust;
- Dust composition:

Silicate, carbon

Part III:
(1) Interstellar Dust Models

- Observational constraints
  - wavelength dependent extinction;
  - wavelength dependent polarization;
  - absorption and emission spectra;
  - cosmic abundance (depletion);
- 3 key models
  - core-mantle model;
  - composite dust model;
  - silicate-graphite-PAH model;

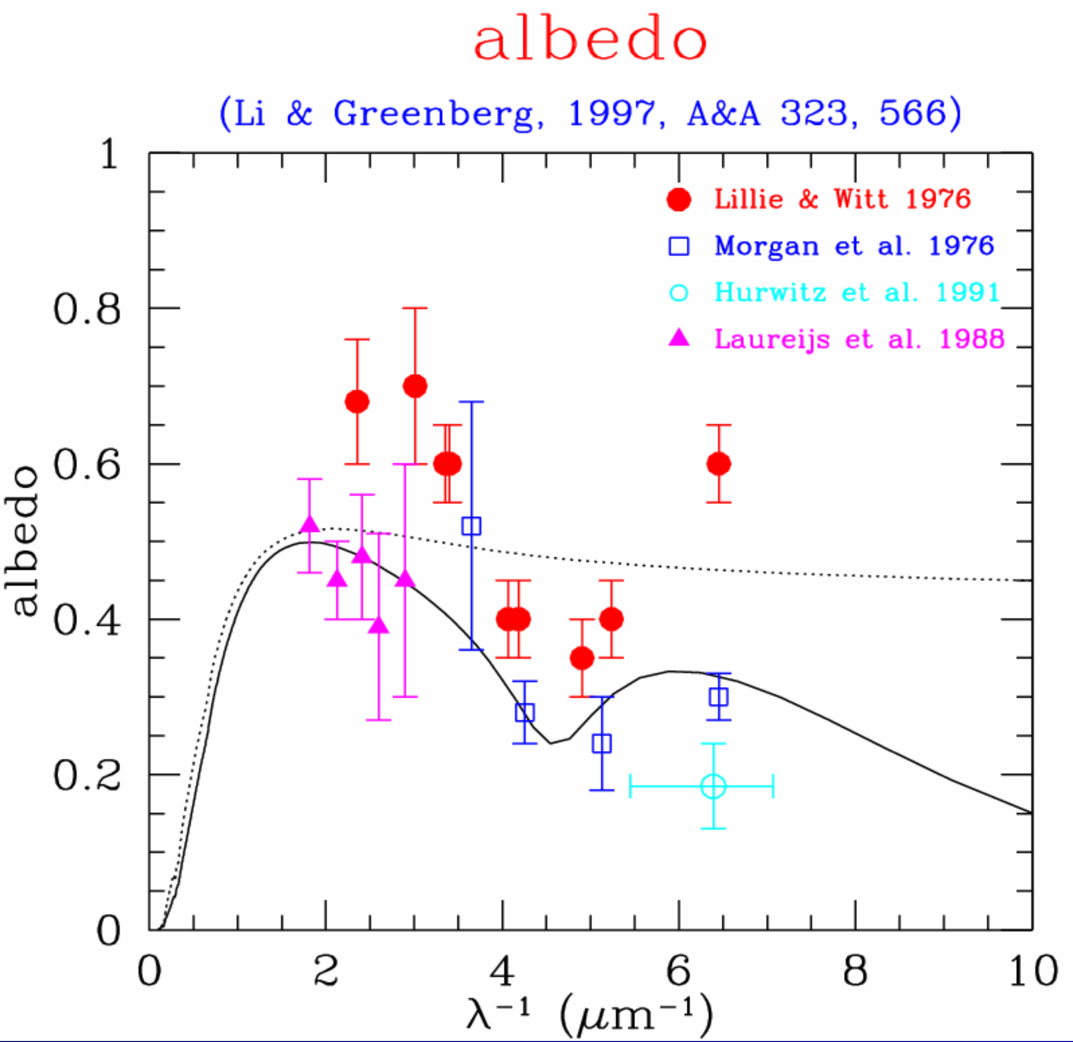
Core-Mantle Model



- Li & Greenberg (1997)
  - silicate core;
  - carbon mantle;
  - PAHs + small graphitic grains;
- dust destruction $\tau_{des} \approx 1\text{-}5\ 10^8 yrs$;
- dust injection $\tau_{pro} \approx 2.5\ 10^9 yrs$;
- mantle (accretion; protection);

Core-Mantle Model

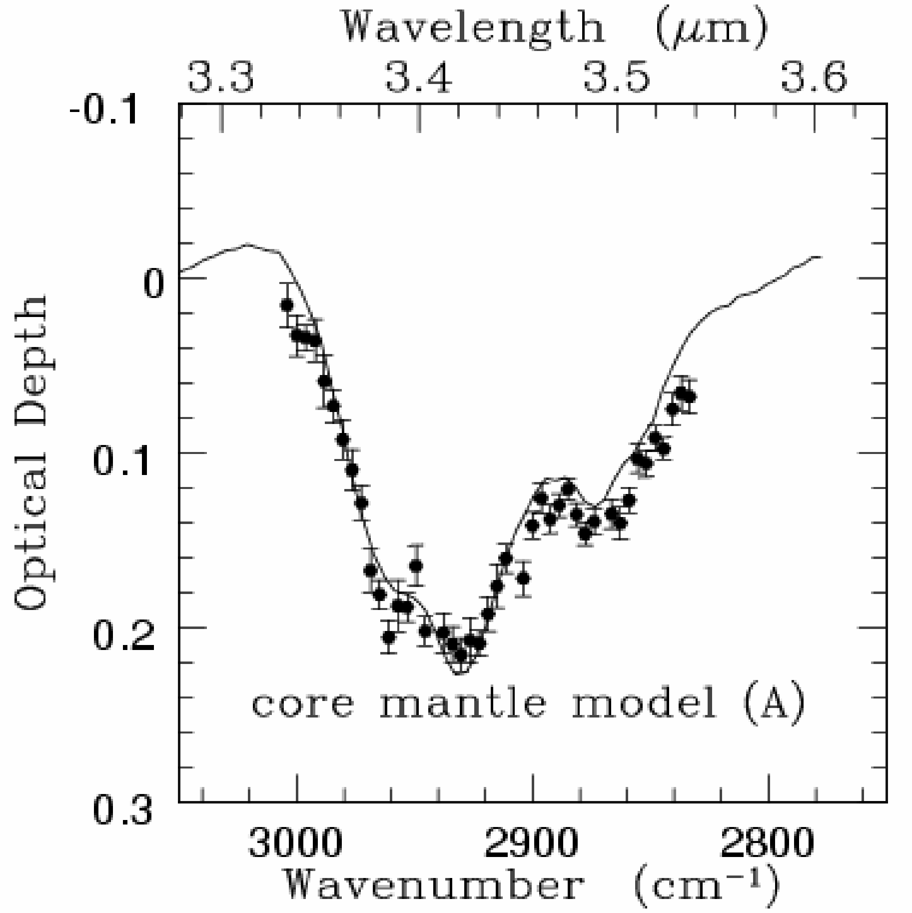
albedo (Li & Greenberg 1997)

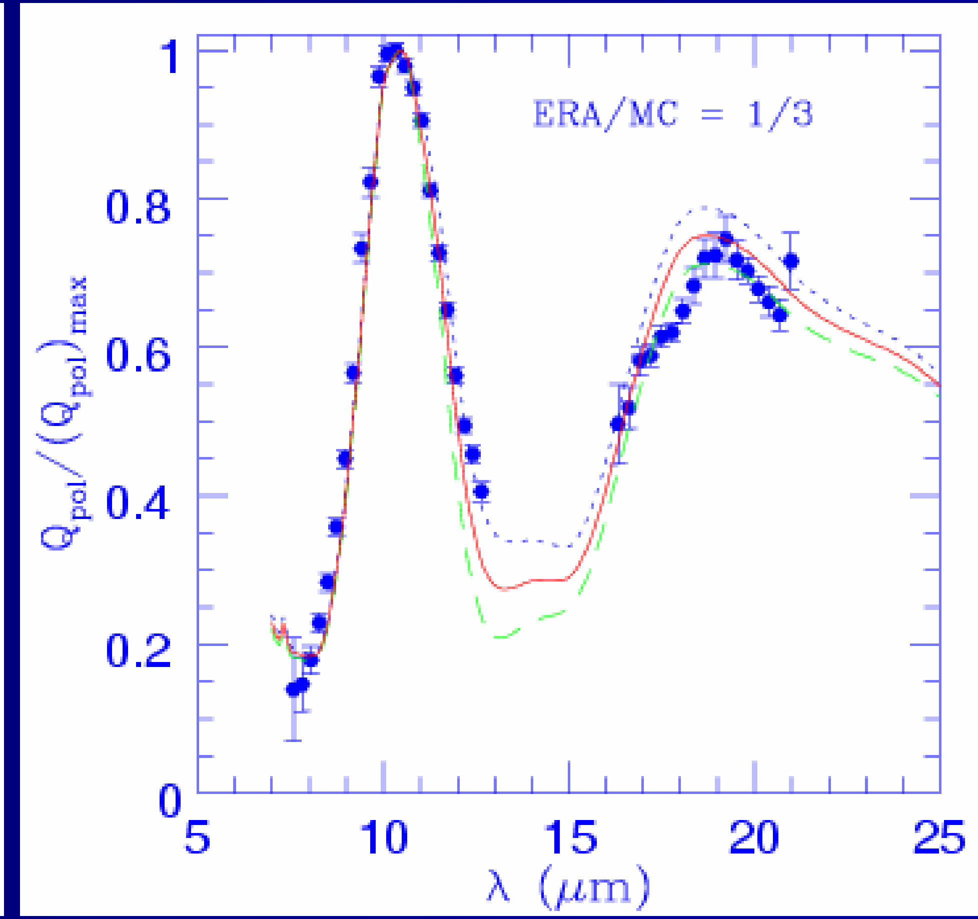


Core-Mantle Model

3.4μm C-H carbon
(Greenberg, Li, et al. 1995)

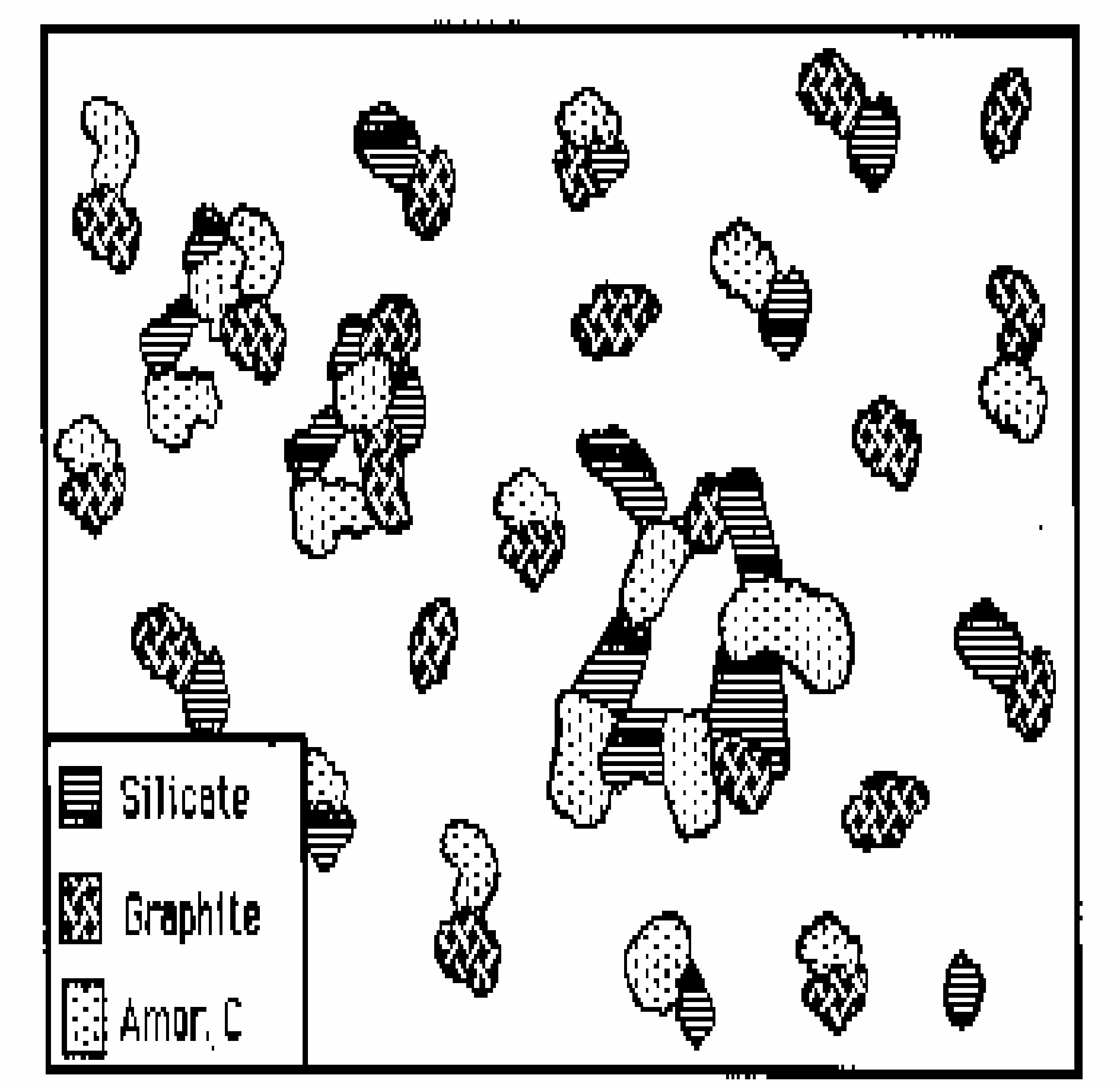
- 9.7,18μm silicate polarizat.
(Greenberg & Li 1996)





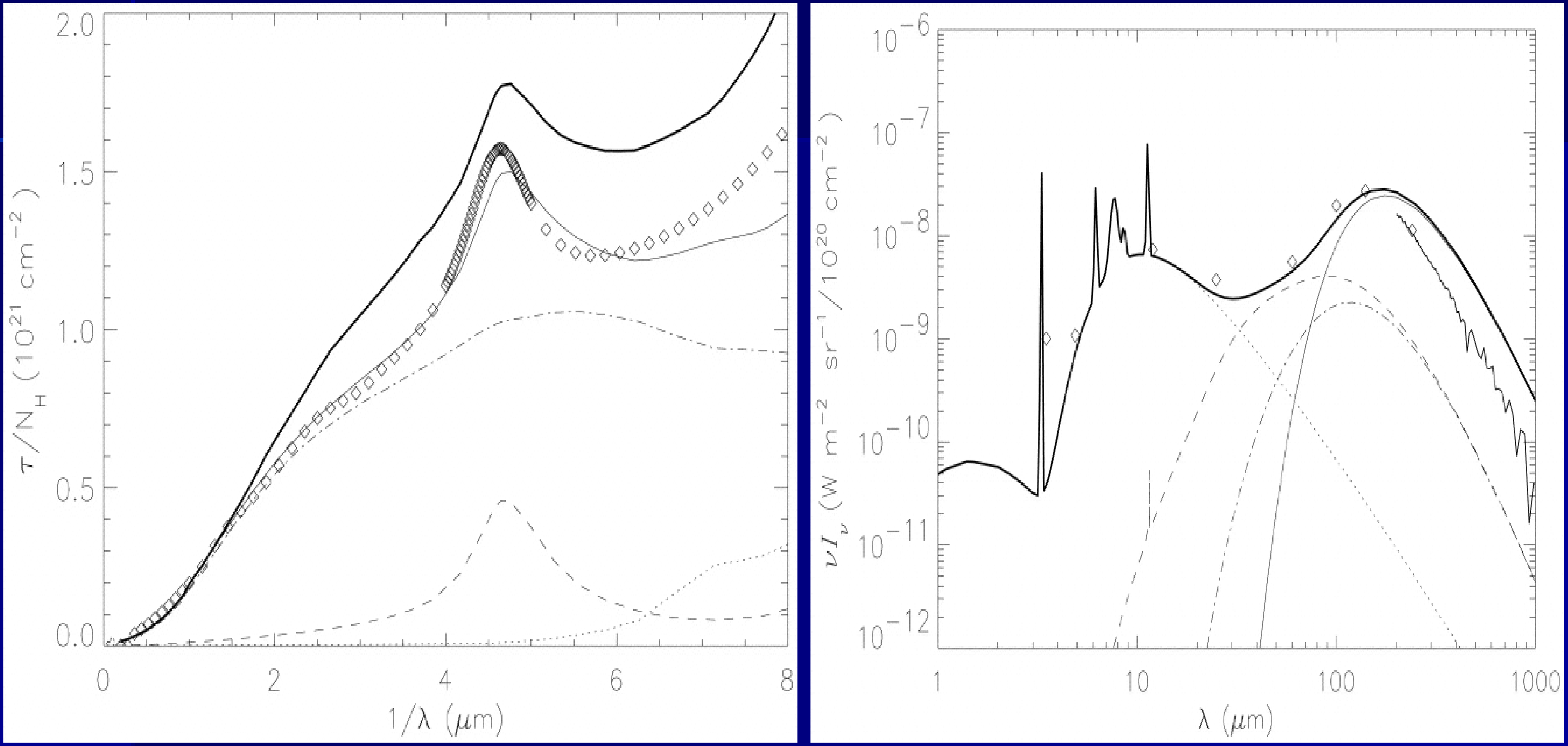
Composite Dust Model

(Mathis & Whiffen 1989, Mathis 1996)



- composite collections of
  - small silicates;
  - small graphite, amorphous carbon, HAC;
  - Vacuum (45%);

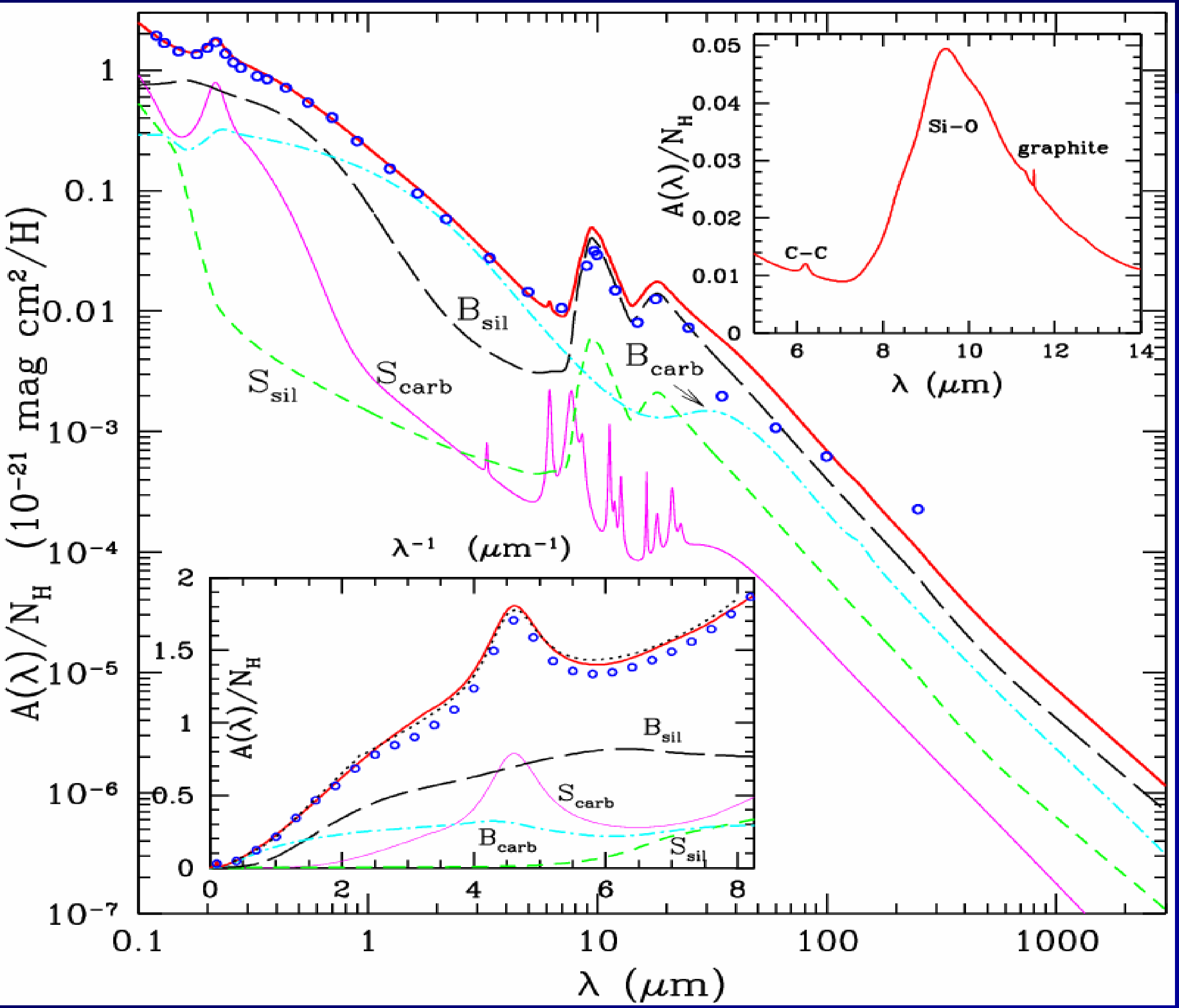
Composite Dust Model



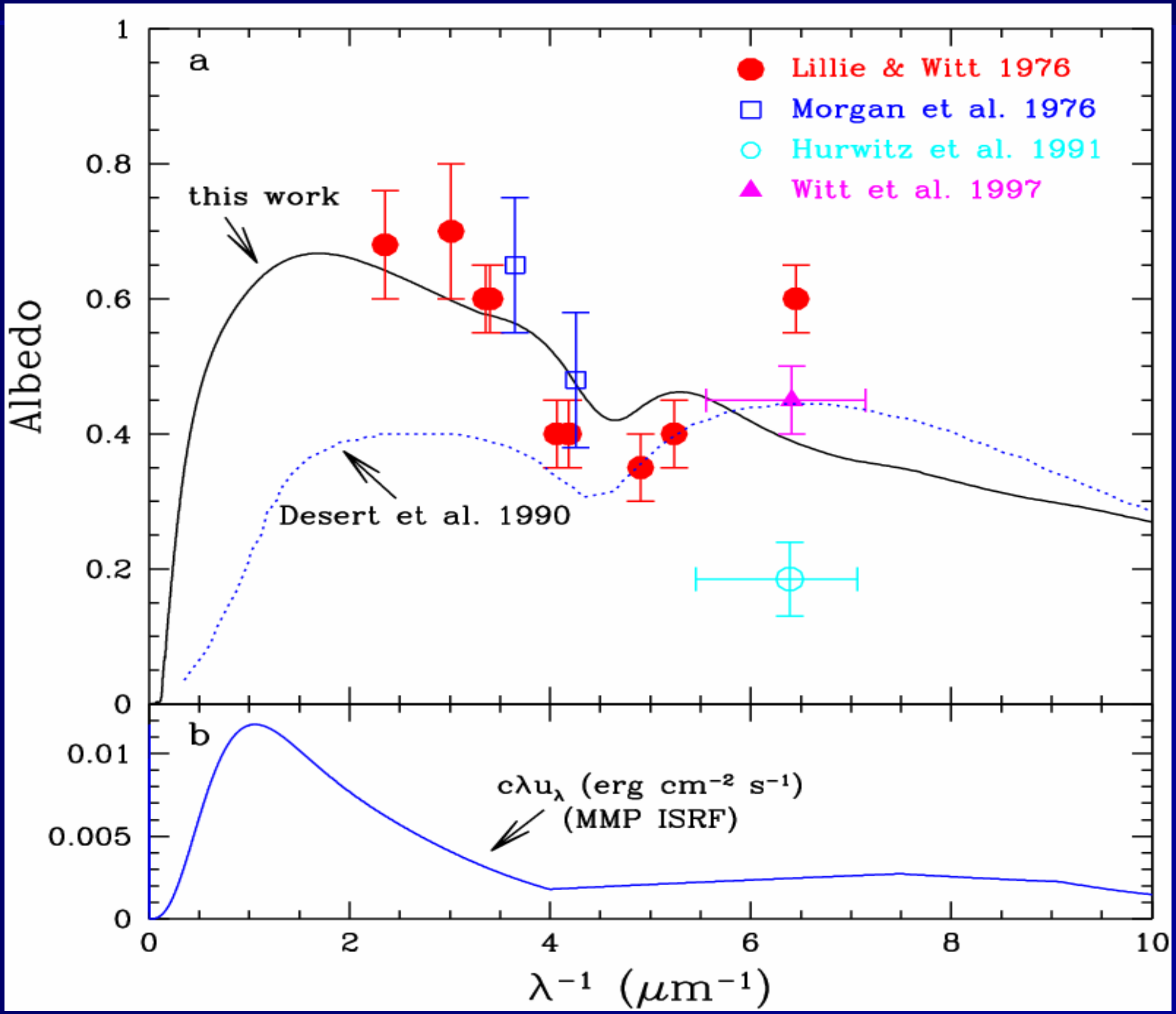
- with PAHs included (to explain PAH emission features)
  → too much far-UV extinction;
- emit too much at λ>100 μm (Dwek 1997);

Silicate-Graphite-PAH Model

(Li & Draine 2001b, Weingartner & Draine 2001)



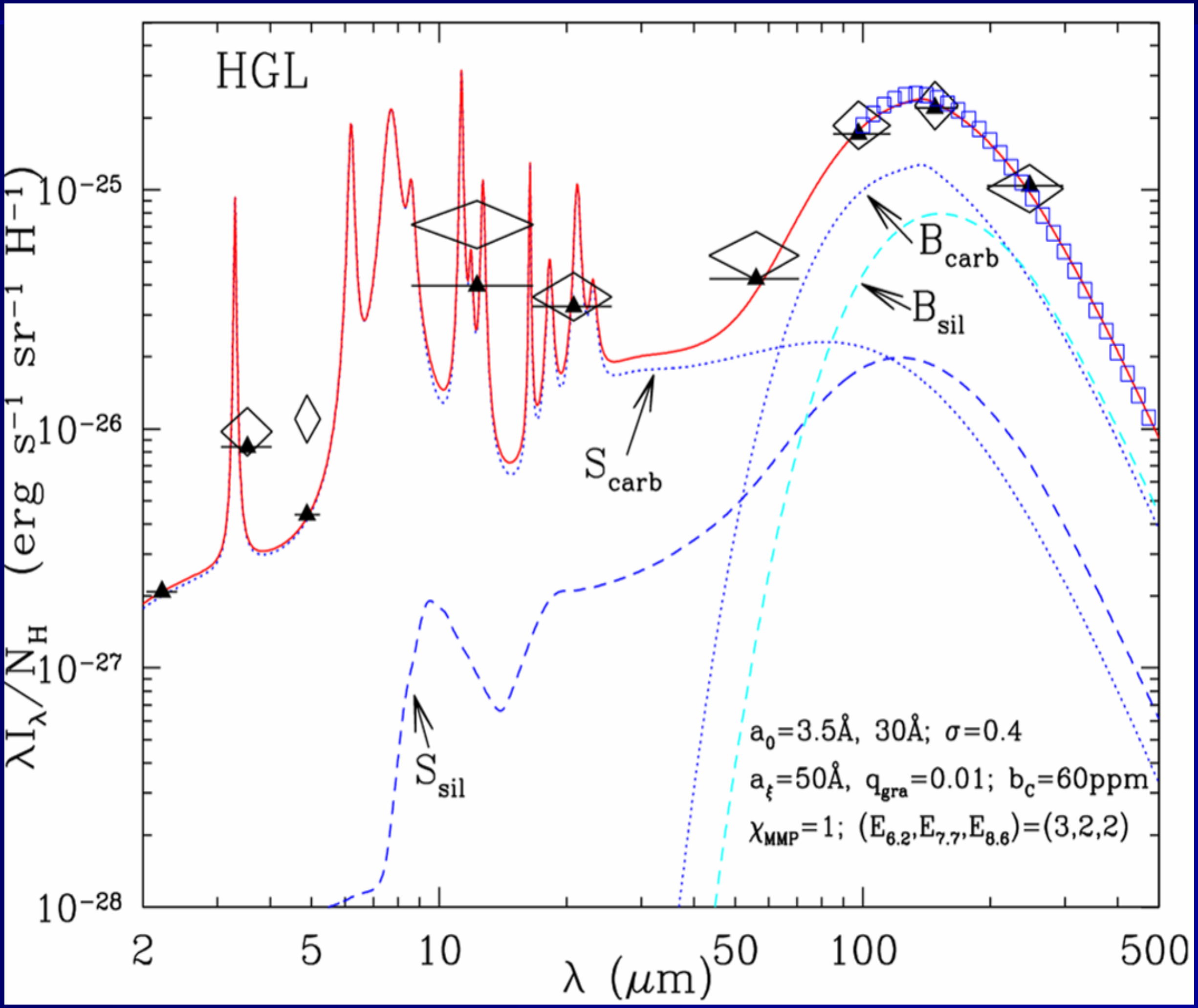
Silicate-Graphite-PAH Model
albedo (Li & Draine 2001b)



Silicate-Graphite-PAH Model

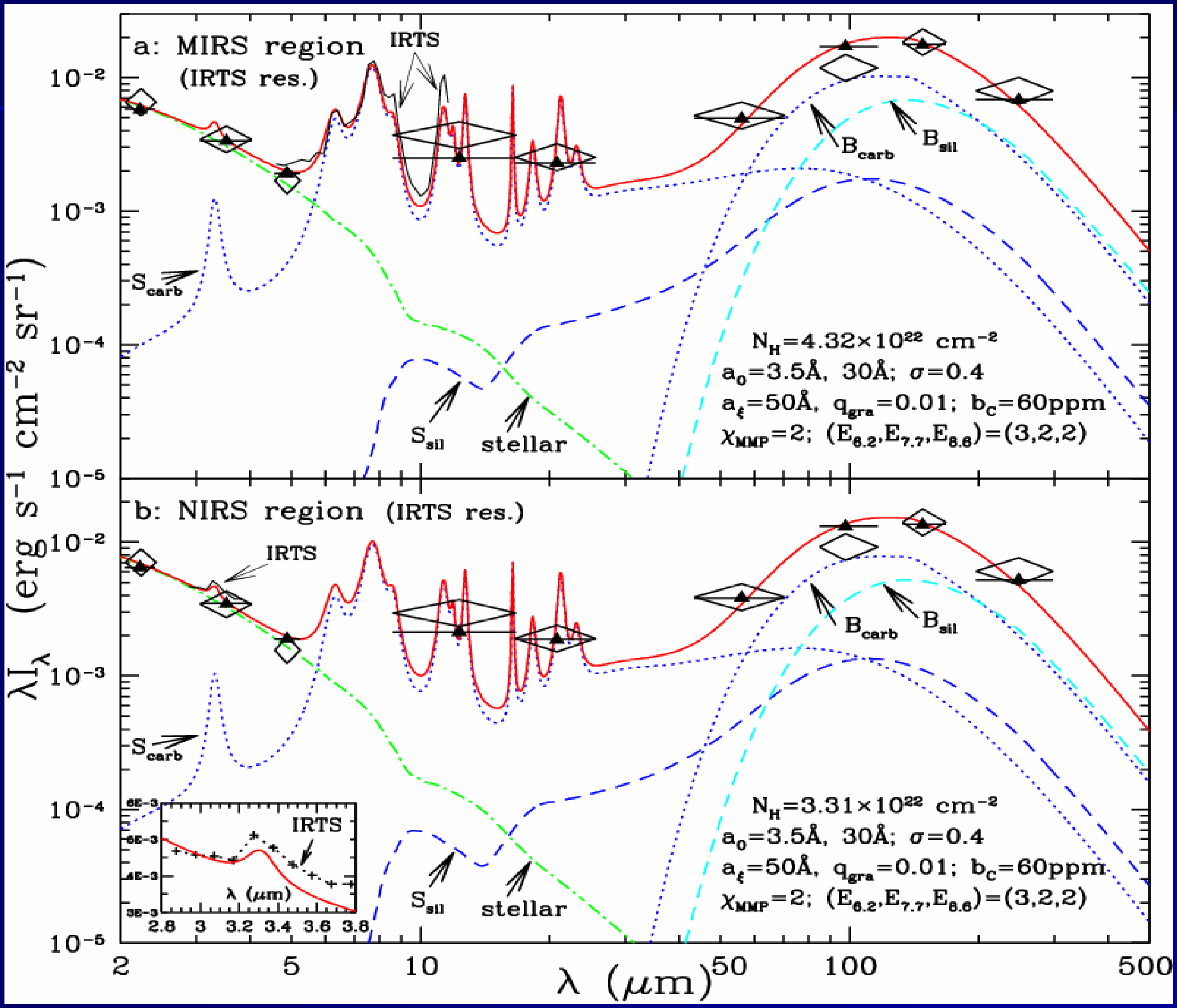
High Galactic Latitude region

(Li & Draine 2001b)



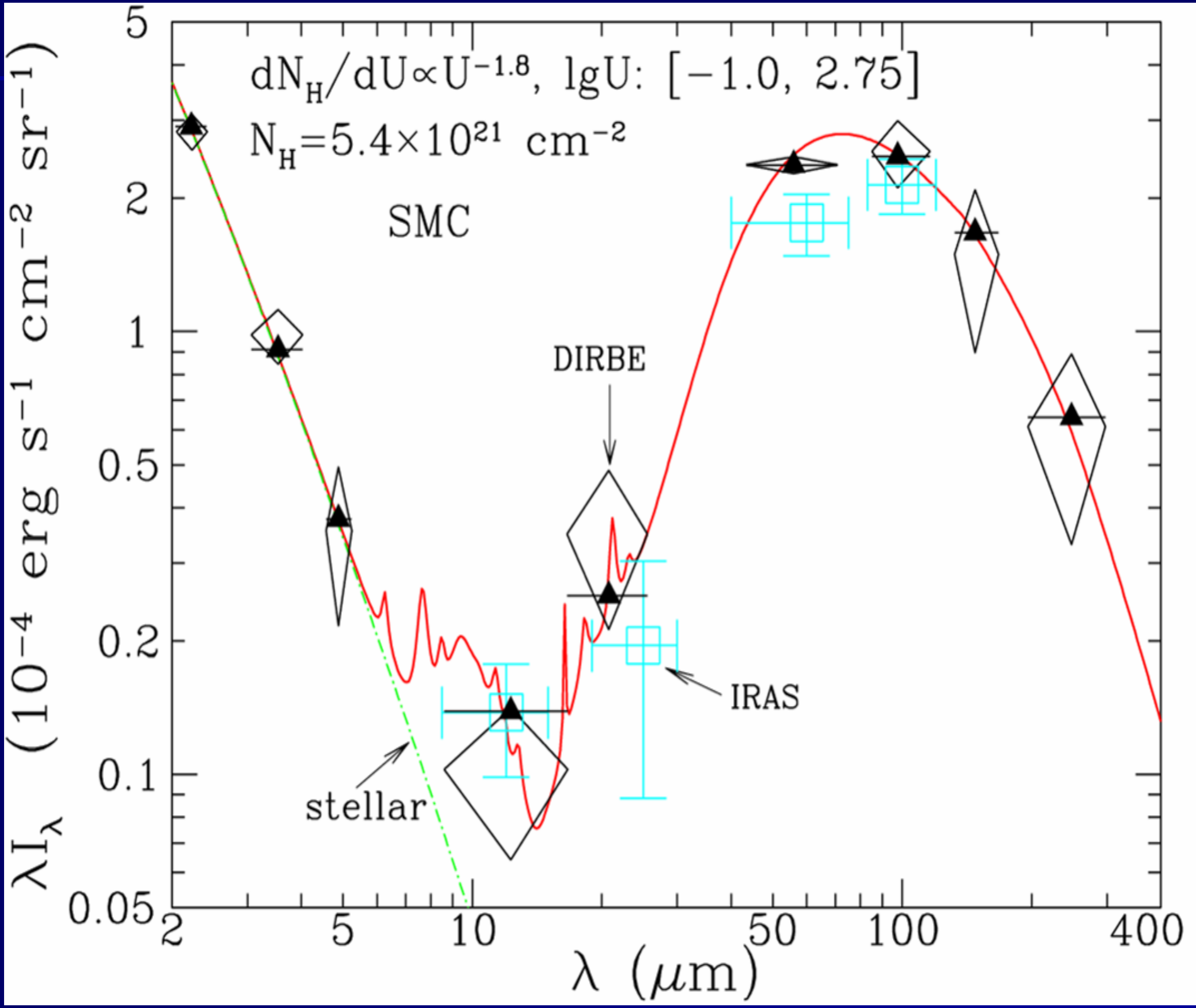
Silicate-Graphite-PAH Model

2 Galactic plane regions (Li & Draine 2001b)

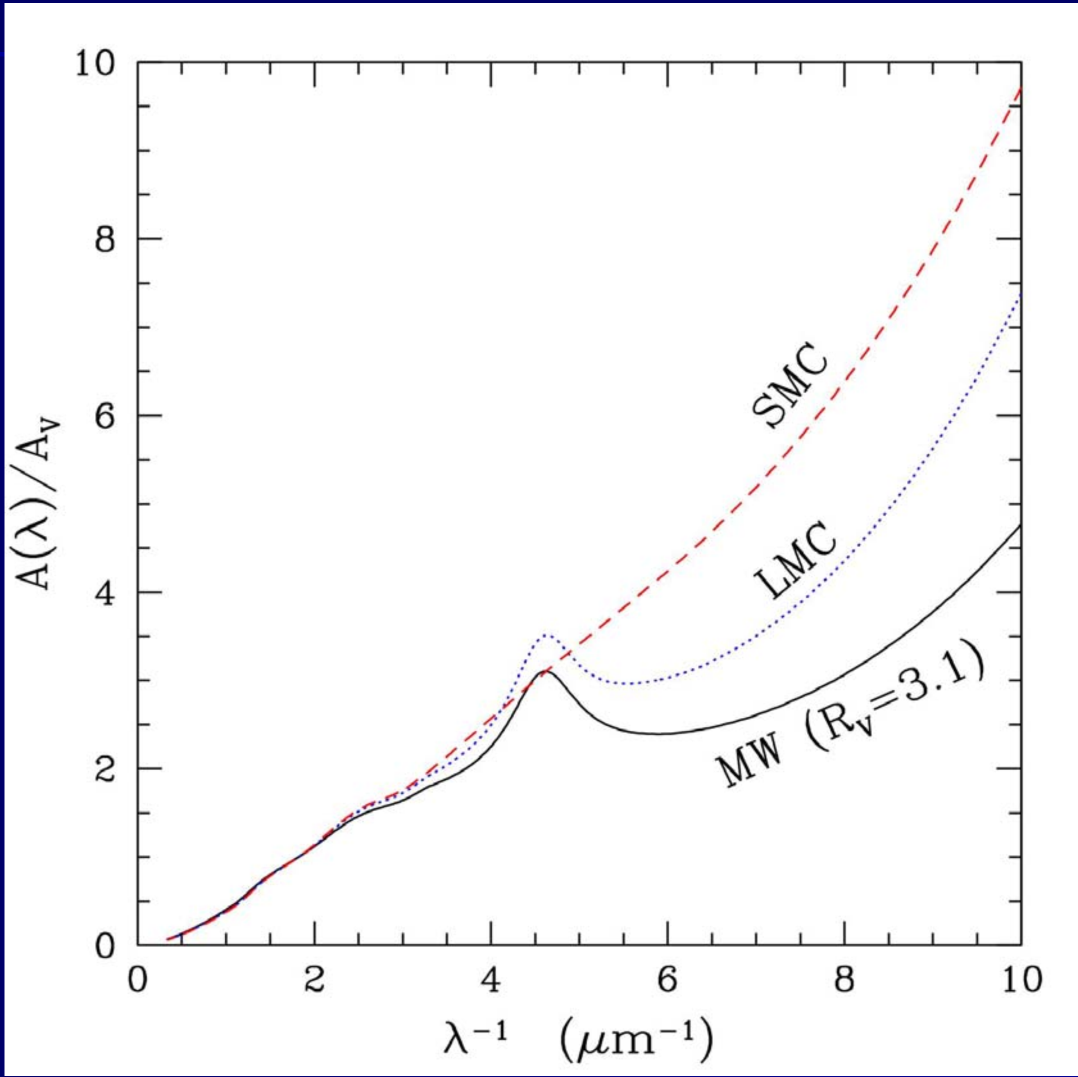


Silicate-Graphite-PAH Model

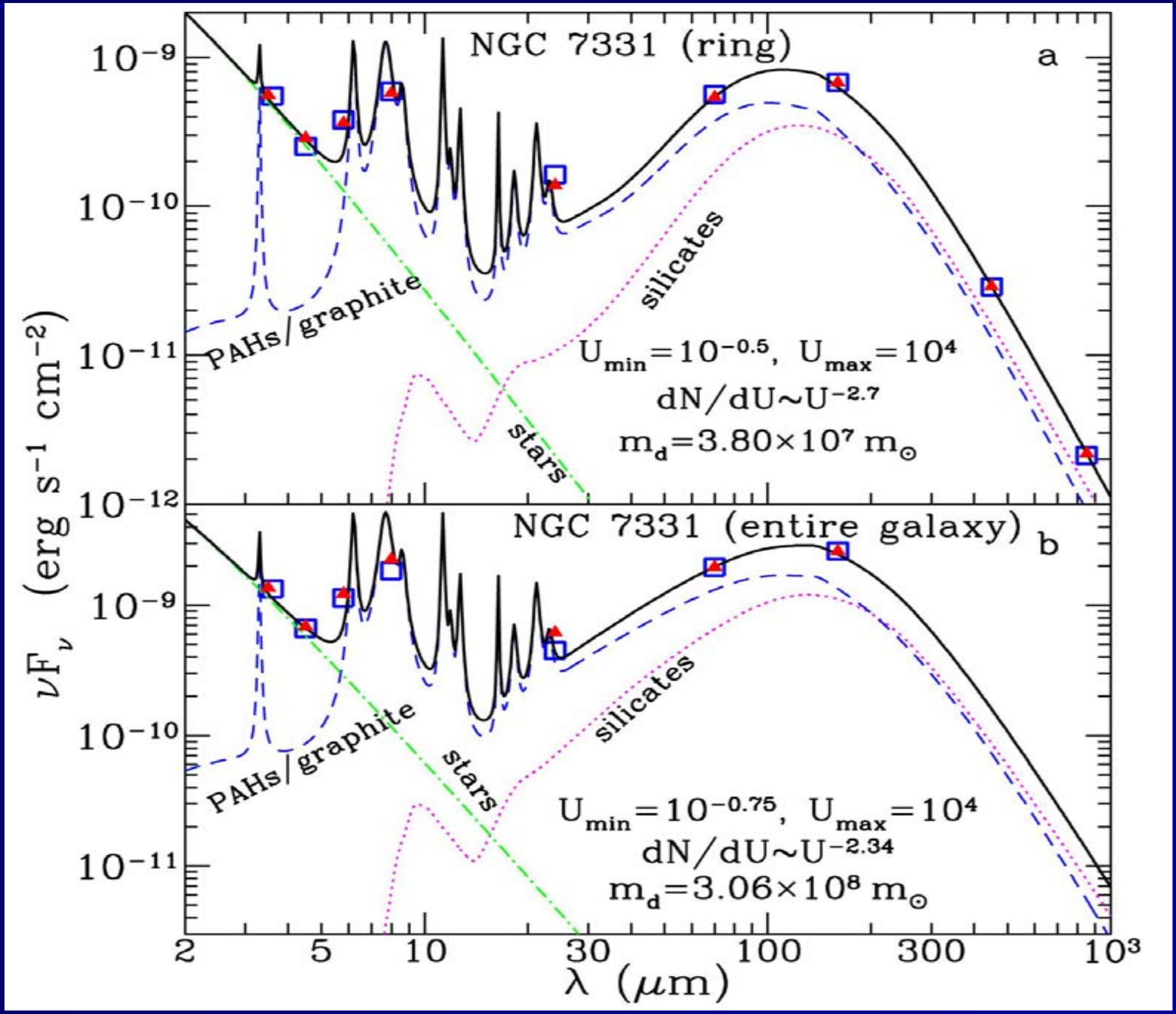
SMC Bar (Li & Draine 2002c)



Interstellar Extinction:
SMC/LMC vs. MW



Silicate-Graphite-PAH Model:
NGC 7331
(Regan et al. 2004, ApJ, Spitzer Special issue)



Silicate-Graphite-PAH Model:
NGC 7331
(Smith et al. 2004, ApJ, Spitzer Special issue)