Summary from Previous Lecture

- ISM is a multi-phase system:
  - Gas + solid (dust)
  - Gas can be molecular (MCs, dense), atomic (HI regions), ionized (HII regions, dense)
  - Reflection and Dark Nebulae are produced by Dust

- Where is dust produced ?
- Dust forms by nucleation and then grows by accretion
- Why is dust important ?
- It locks most heavy material: C, Si, Mg
- It shapes the emission of galaxies in the IR/mid-IR
- It is the source of extinction, re-process UV into the IR
- It is a tracer of Star formation

Interstellar Extinction

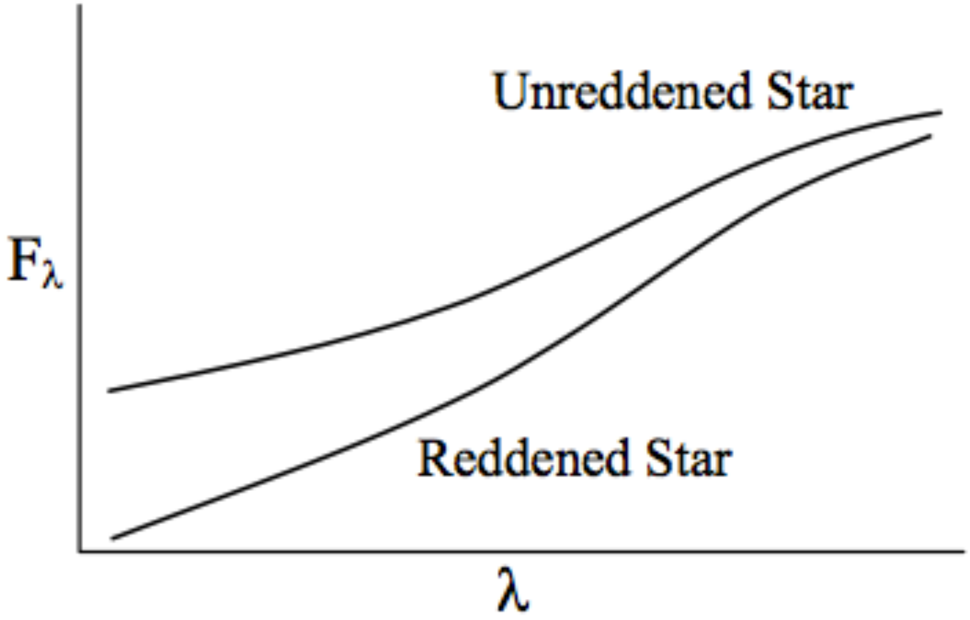
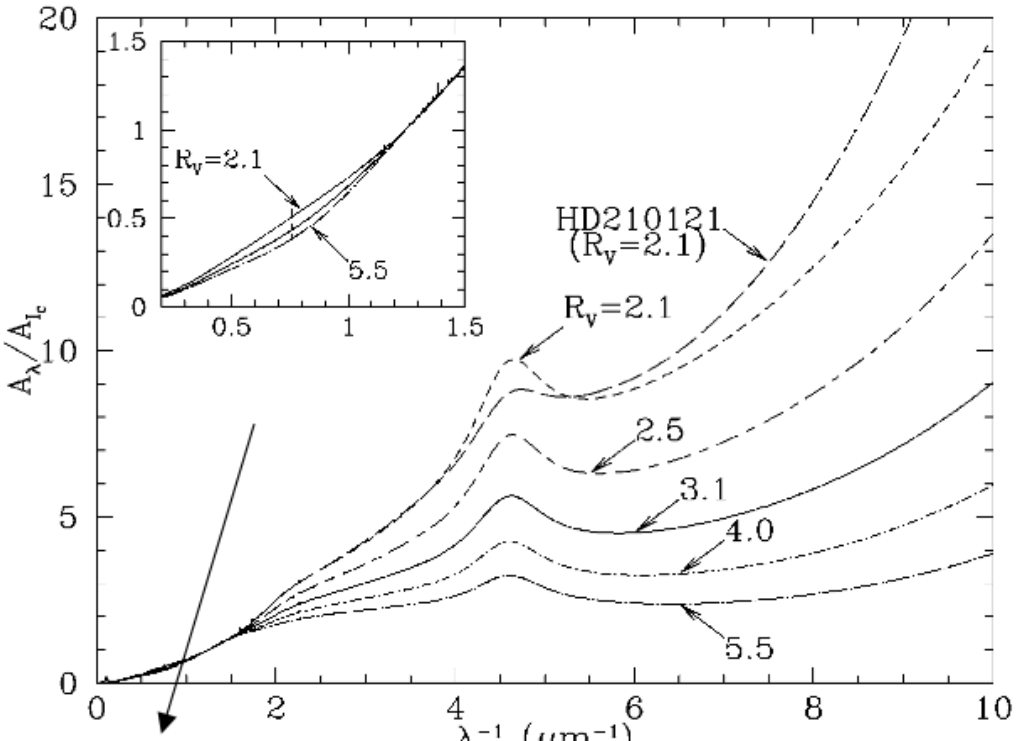


Figure IV-1: Effect of extinction on a stellar spectrum. Extinction is both a total diminution of the stellar light, and is wavelength-selective, in the sense that bluer wavelengths are more extinguished than red wavelengths.

$$\tau_\lambda = const \times f(\lambda)$$

It was recognized that the optical depth depends on the distance from the source (e.g. total column density) and on a universal extinction function

Empirical Extinction Curves



Based on extinction measurements from the UV to NIR, c.f. Fitzpatrick, PASP 111 63 1999 & Draine, ARAA 41 241 2003

- R_v depends on the material along the l.o.s
  - For the diffuse ISM R_V~3.1
  - For dense MC R_V~4-6
- Bump at 2175 Å is due to particles rich in C, graphite or amorphous carbon grains
- The shape of the interstellar extinction curve contains information about the size and chemical composition of interstellar dust grains (MW curve best interpreted as mixture of silicates & graphites)

Optical Property of Dust Grains

For simplicity, we consider homogeneous spherical dust particles of radius *a* and introduce the ***cross section for extinction***

$$\sigma(\lambda) = \pi a^2 Q_{ext}(\lambda),$$

where $Q_{ext}(\lambda)$ is the ***efficiency factor for extinction***. The optical depth along a line sight with volumetric dust density n_d is then

$$\tau_\lambda^{ext} = \int n_{dust} \sigma_\lambda^{ext} ds = \sigma_\lambda^{ext} \int n_{dust} = \pi a^2 Q_{ext}(\lambda)\, N_{dust}$$

- ***Extinction in magnitudes*** A_λ is defined in terms of the reduction in the intensity cause by the presence of the dust :
- $$I(\lambda) = I_0(\lambda) \exp\left[-\tau_\lambda^{ext}\right],$$

$$A_\lambda = -2.5 \log_{10}\left[I(\lambda)/I_0(\lambda)\right] = 2.5 \log_{10}(e)\ \tau_\lambda^{ext} = 1.086\, \tau_\lambda^{ext}$$

E-M scattering by small particles

A. N. Mie (Ann Phys 25 377 1908) solved Maxwell's Equations for scattering by a uniform sphere of radius *a* and a general index of refraction

$$\boldsymbol{m = n - i\,k} \quad \text{with} \quad \boldsymbol{m = m\,(\lambda)},$$

The mathematical basis is a *multipole expansion* of the scattered wave in terms of (vector) spherical harmonics times, each multiplied by a radial Bessel function, plus the application of appropriate boundary conditions at the surface of the sphere. The classic reference is:

H.C. van de Hulst, "Light Scattering from Small Particles"

The basic parameter, measuring radius in terms of wavelength is: $x = 2\pi a/\lambda$

- **$x \ll 1$:** long wavelength *diffraction limit* - need only a few terms
- **$x \gg 1$:** short wavelengths *geometrical optics limit* -need many terms

Asymptotic Mie Formulae For $x = 2\pi a/\lambda \ll 1$

$$Q_{abs} = -4x\,\mathrm{Im}\left(\frac{m^2-1}{m^2+2}\right) \propto \lambda^{-1}$$

$$Q_{sca} = \frac{8}{3}x^4\,\mathrm{Re}\left\{\left(\frac{m^2-1}{m^2+2}\right)^2\right\} \propto \lambda^{-4}$$

In this long wavelength or Rayleigh limit, the absorption cross section depends only on the mass of the grain:

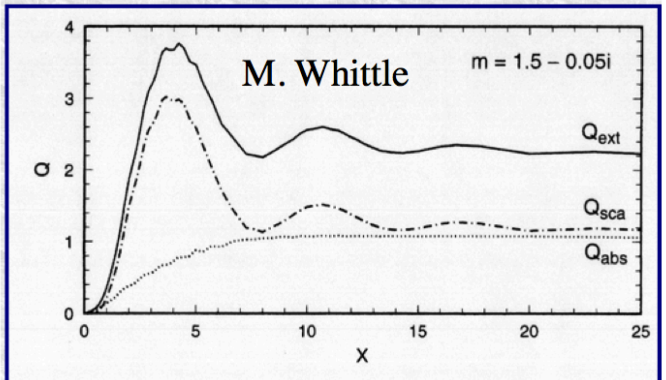


Figure 3.1. Results of Mie theory calculations for spherical grains of refractive index $m = 1.5 - 0.05i$. Efficiency factors Q_{ext}, Q_{sca} and Q_{abs} are plotted against the dimensionless size parameter $X = 2\pi a/\lambda$.

$$\sigma_{abs} = Q_{abs}\pi a^2 \propto a^3 \propto m_{dust}$$

Note:

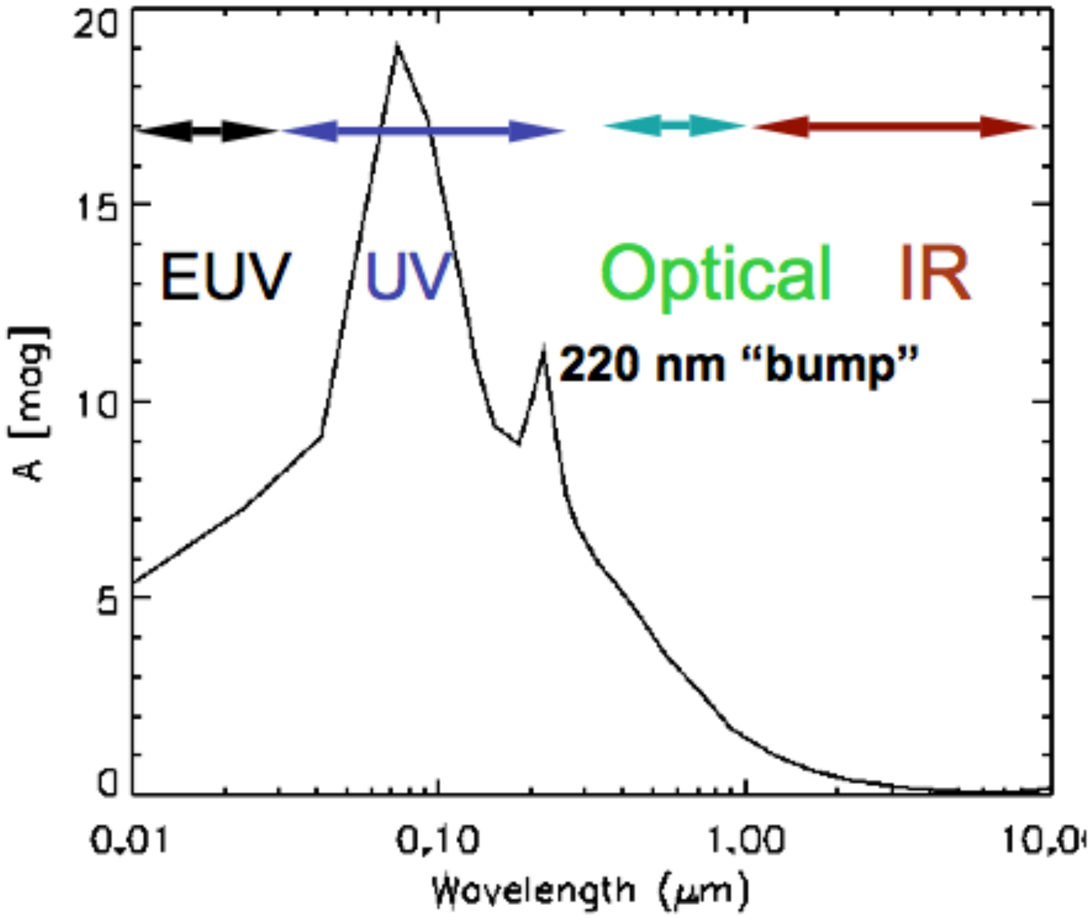
1. The λ^{-1} behavior explains the extinction curve
2. The λ^{-4} behavior explains why scattering is more effective on blue wavelengths

Schematic plot of extinction

General Properties

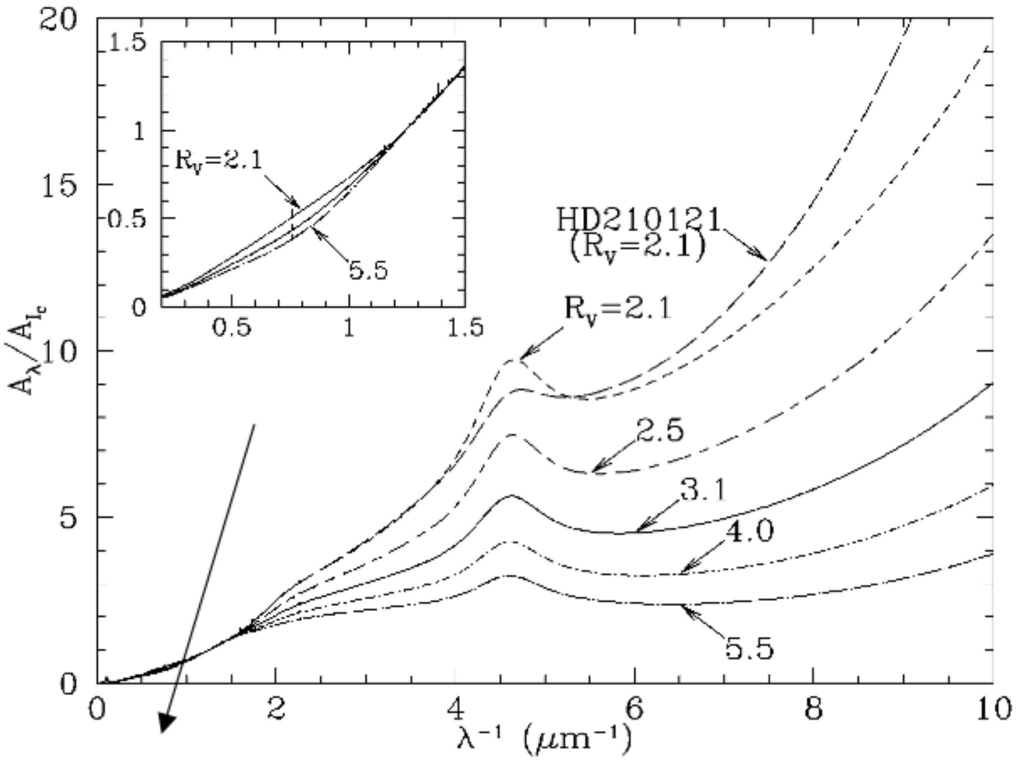
1. $\lambda^{-1.5}$ trend in the optical/NIR
3. steep UV rise with peak at ~ 800 Å
4. strong features:
   λ = 220 nm, $\Delta\lambda$ = 47 nm
   λ = 9.7 μm, $\Delta\lambda$ ~ 2-3 μm
   (not visible on this plot)

Remember, grain sizes: 5 --3000Å (e.g. <0.3 μm)



Magnitudes of extinction vs, wavelength (schematic)

Empirical Extinction Curves



Based on extinction measurements from the UV to NIR, c.f. Fitzpatrick, PASP 111 63 1999 & Draine, ARAA 41 241 2003

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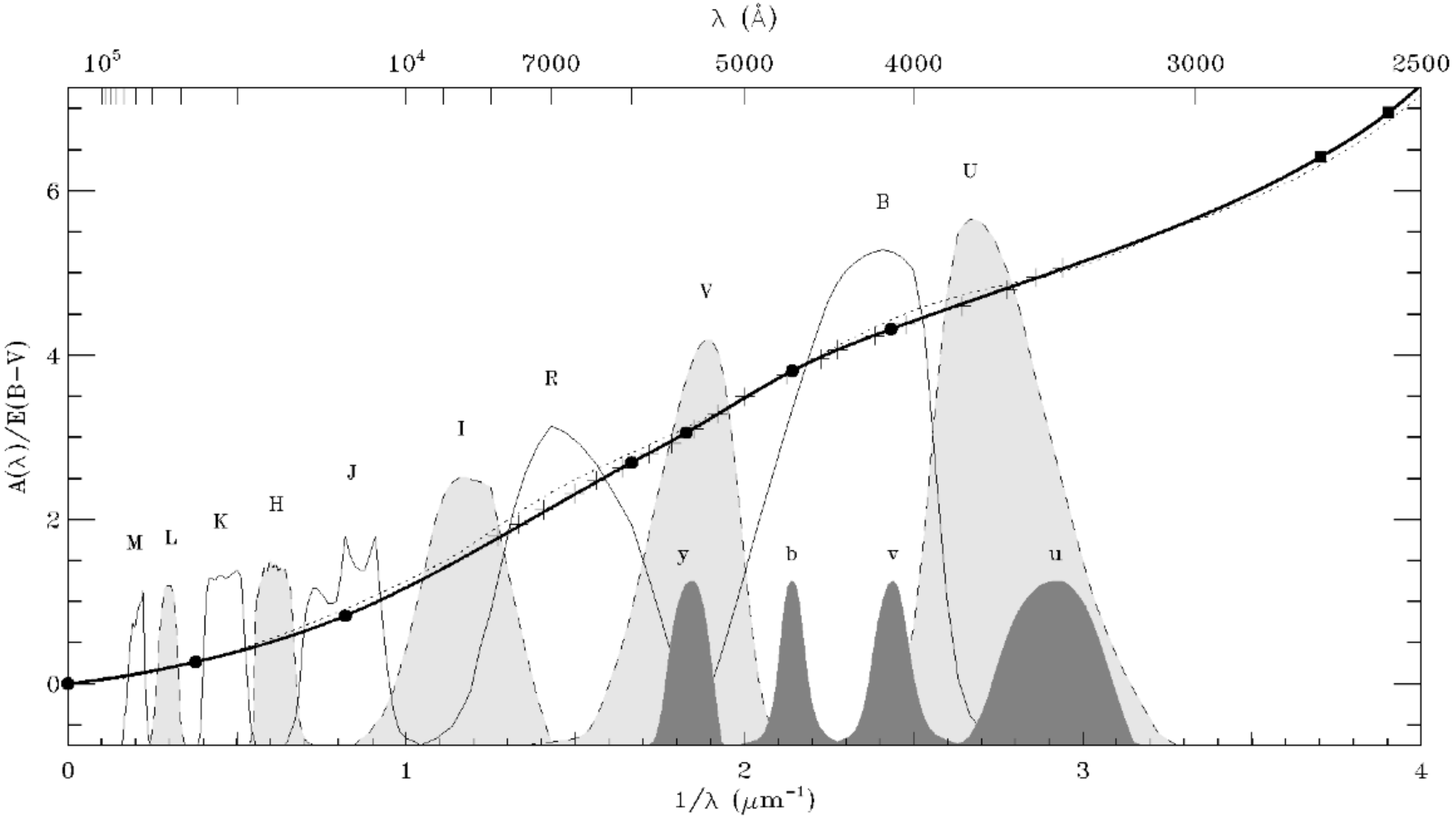
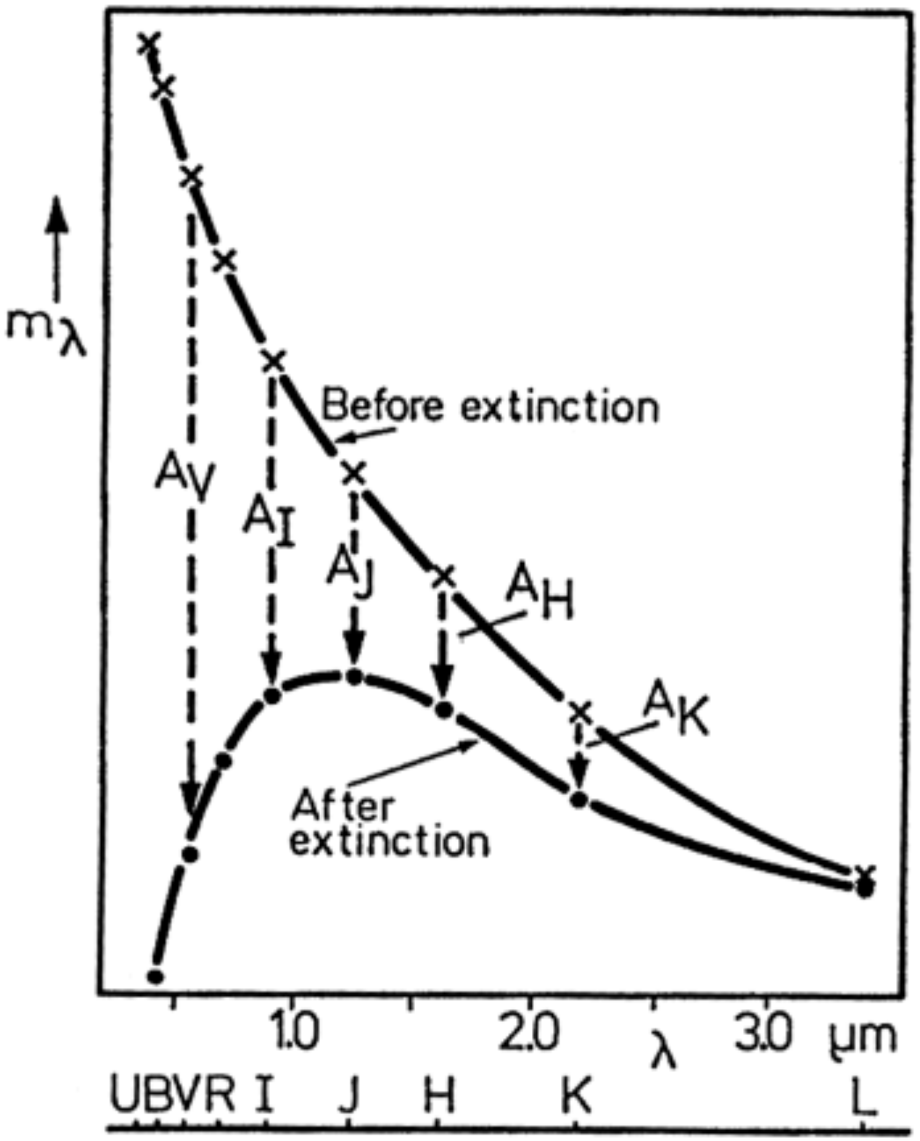
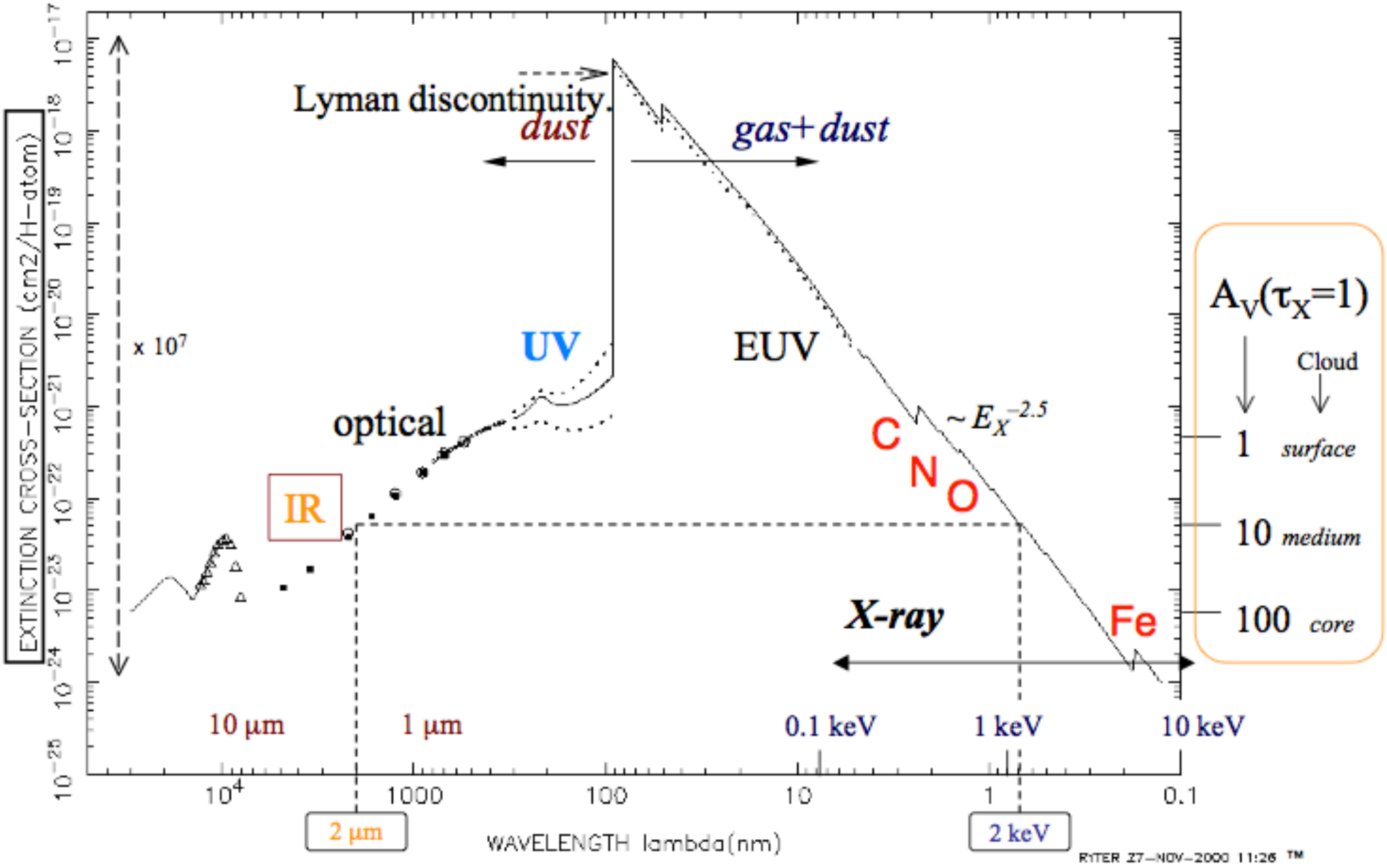
Fitzpatrick et al 1999



Filter	A_λ/A_V
U	1.531
B	1.324
V	1.000
R	0.748
I	0.482
J	0.282
H	0.175
K	0.112
L	0.058
M	0.023
N	0.052

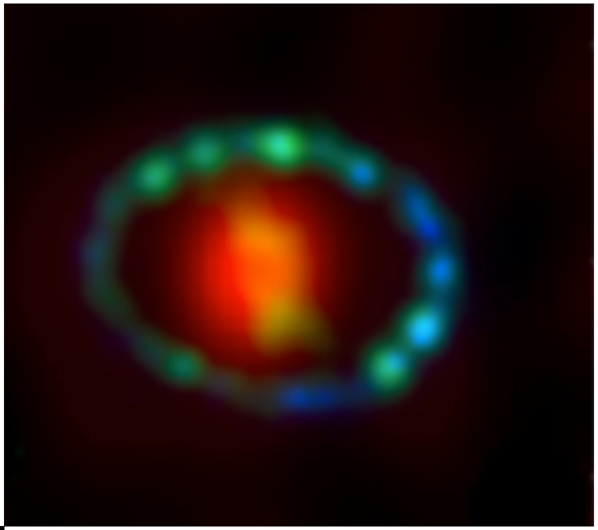


Extinction

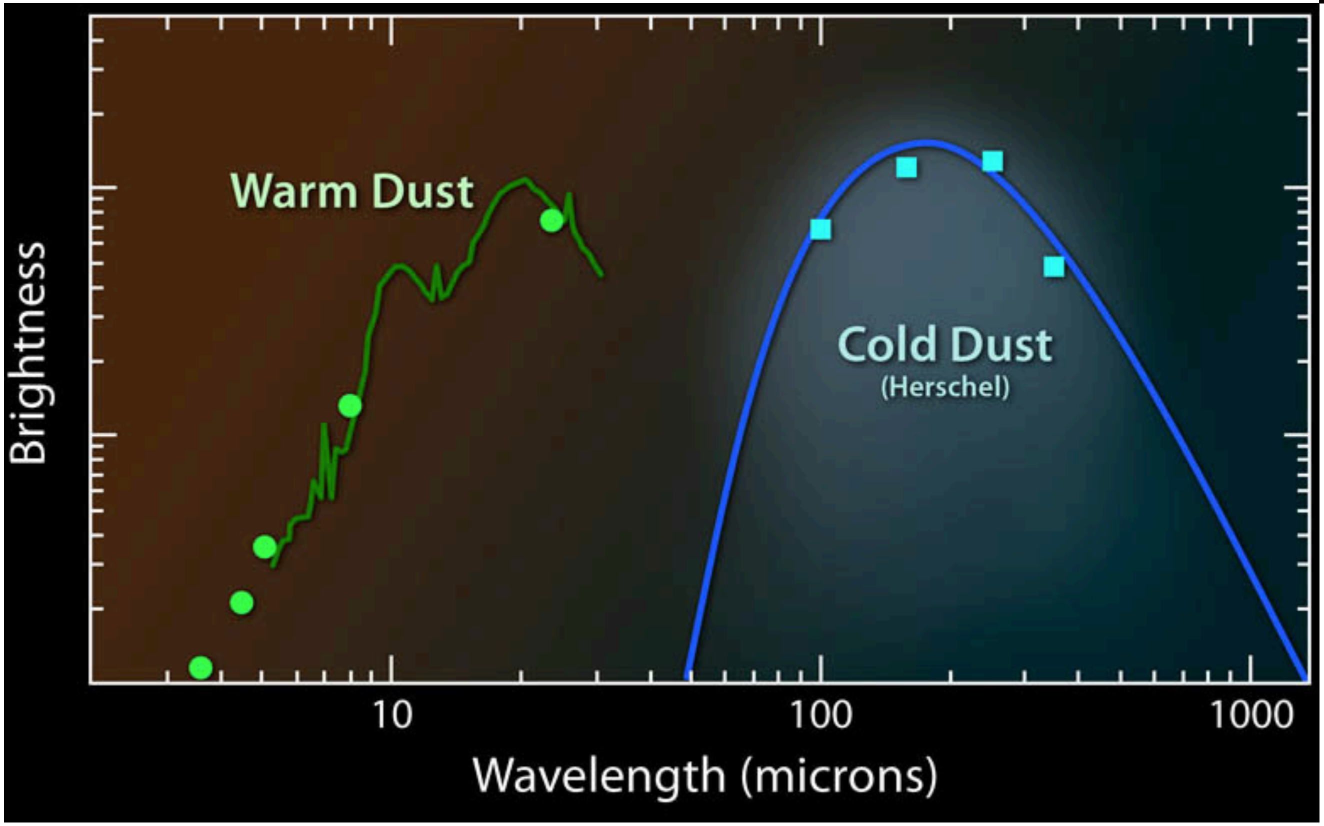


T. Montmerle

Dust Emission



- Herschel result on 1987a
  - Warm dust is heated up in the ring
  - Cold dust is in the center (T~20K)

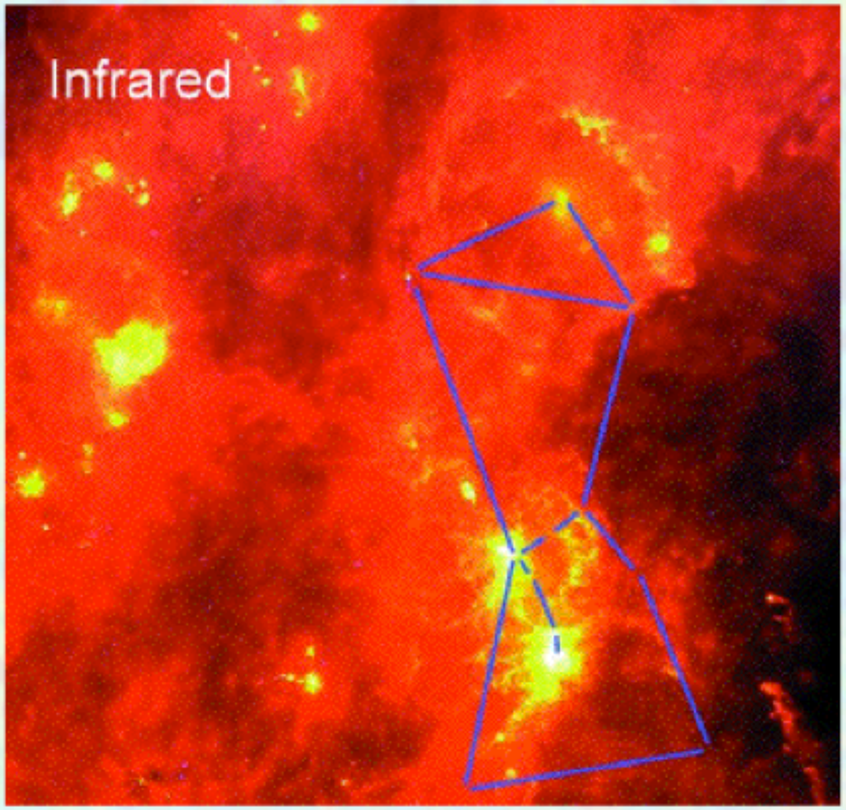


Examples

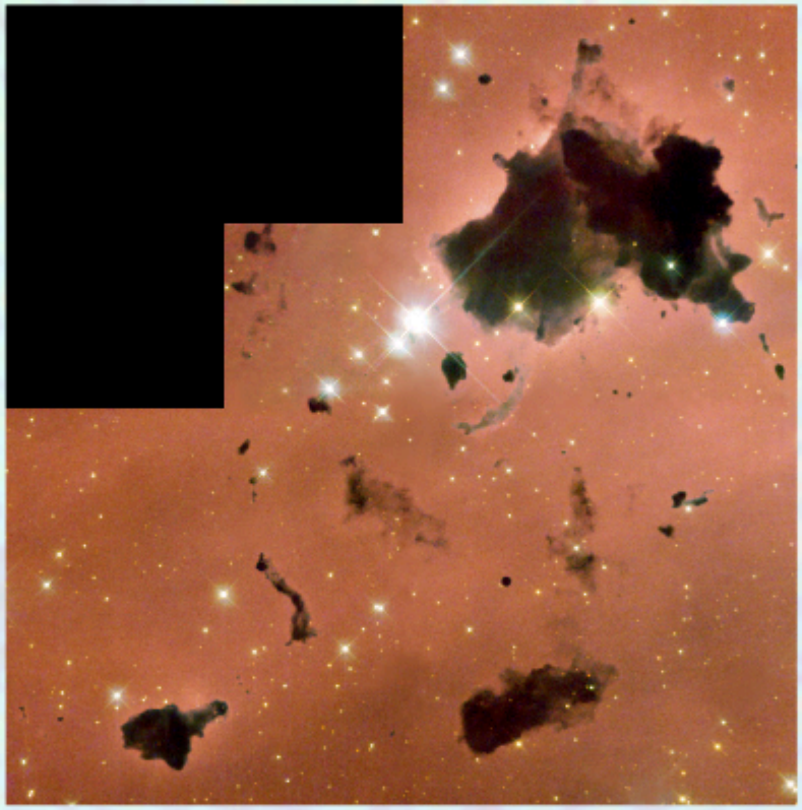
* Grains at thermal equilibrium at a distance r=0.5pc from an O_6 star
(R*=1.1 10^{12} m, T*=40000 K)

⟹ Tg= 650 K

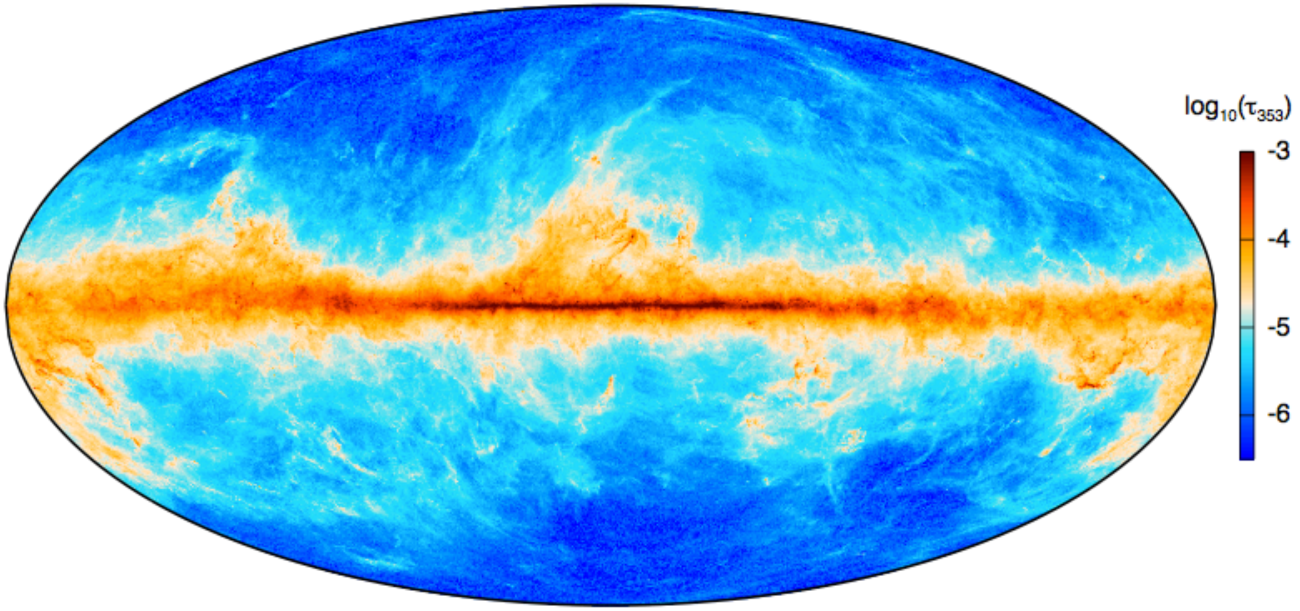
* Grains in diffuse medium, heated by ISRF:
a=0.1μm, Tgraphite=18.8 K, Tsilicate=15.4 K
(Draine & Lee Model (1984))



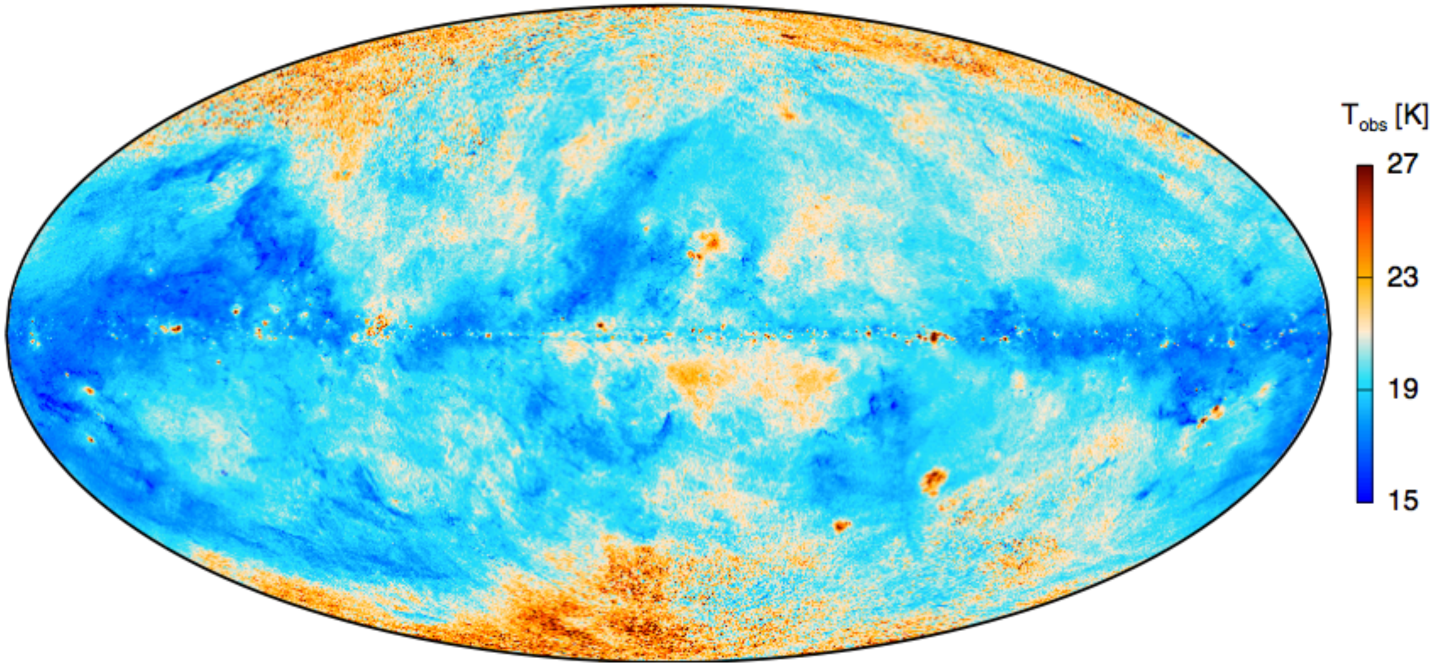
* Grain in a Bock globule : T ~ 14 K.

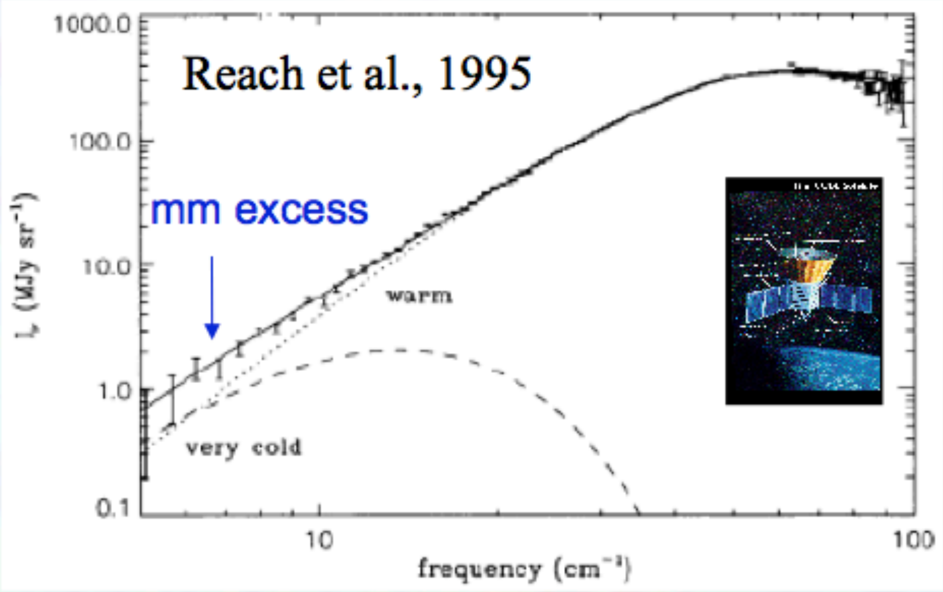


Planck



- Average T~19 K

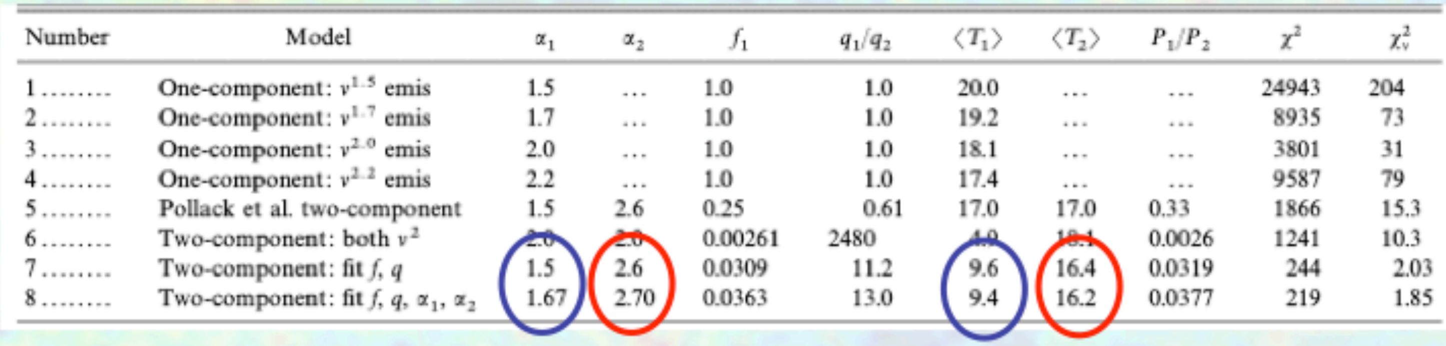




⇒ **mm** excess
⇒ very cold dust (5-7 K)

mm excess is actually strongly correlated to FIR emission
This lead Reach et al. to <u>reject</u> "very cold" dust.

Finkbeiner et al. 1999 (FSD) 2 components= Graphite + Silicate



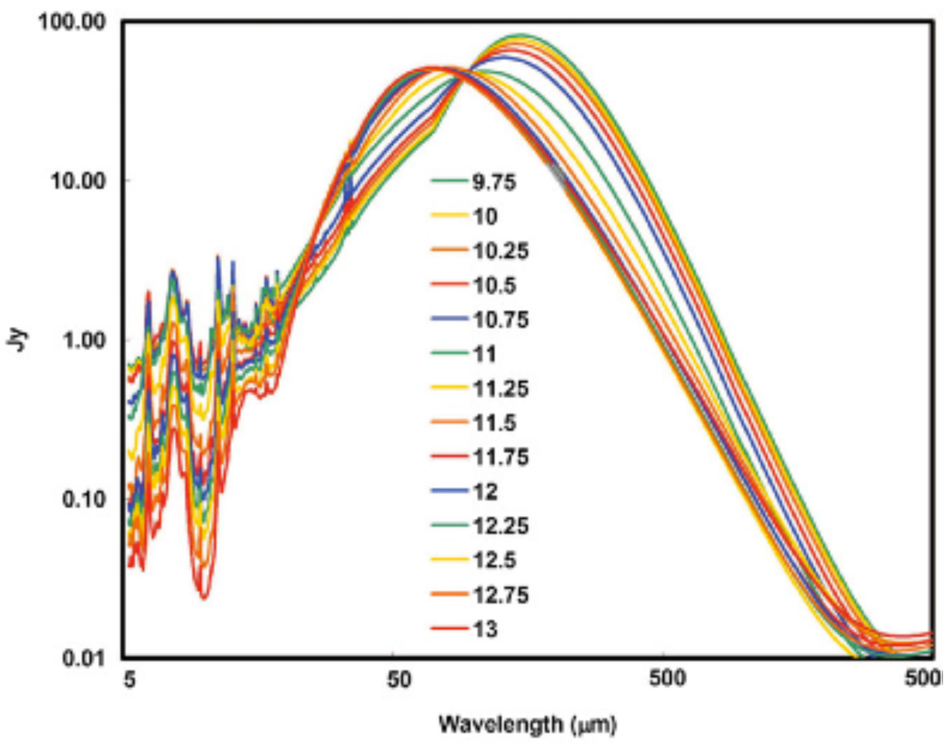
Number	Model	α_1	α_2	f_1	q_1/q_2	$\langle T_1 \rangle$	$\langle T_2 \rangle$	P_1/P_2	χ^2	χ^2_ν
1	One-component: $\nu^{1.5}$ emis	1.5	...	1.0	1.0	20.0	...	...	24943	204
2	One-component: $\nu^{1.7}$ emis	1.7	...	1.0	1.0	19.2	...	...	8935	73
3	One-component: $\nu^{2.0}$ emis	2.0	...	1.0	1.0	18.1	...	...	3801	31
4	One-component: $\nu^{2.2}$ emis	2.2	...	1.0	1.0	17.4	...	...	9587	79
5	Pollack et al. two-component	1.5	2.6	0.25	0.61	17.0	17.0	0.33	1866	15.3
6	Two-component: both ν^2	2.0	2.0	0.00261	2480	4.0	18.1	0.0026	1241	10.3
7	Two-component: fit f, q	1.5	2.6	0.0309	11.2	9.6	16.4	0.0319	244	2.03
8	Two-component: fit f, q, α_1, α_2	1.67	2.70	0.0363	13.0	9.4	16.2	0.0377	219	1.85

2 T models can fit sky brightness distribution beautifully, but requires to explain the physical origin of the very cold dust at 9K

Dust emission from Galaxies

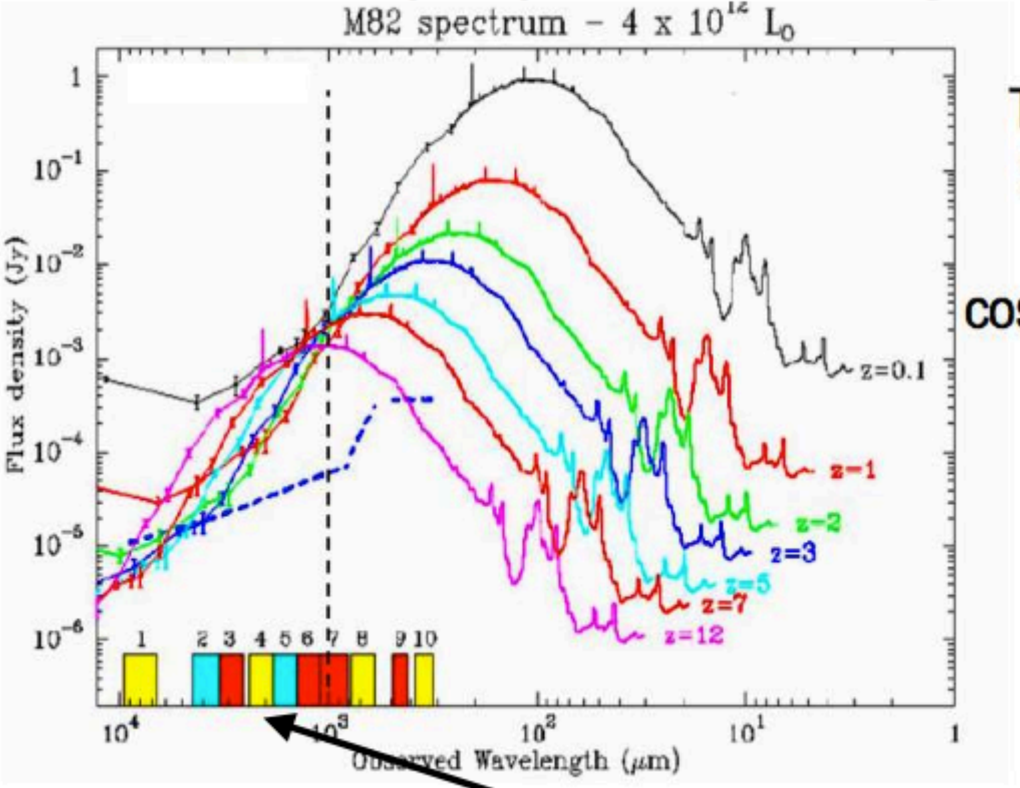
- 5-20 μm dominated by Polyclic Aromatic Hydrocarbons
- λ>20 μm dominated by the thermal emission of the main grain population
- λ>60 μm dominated by the emission from large grains

Rieke et al. 2009



In the High Z Universe Dust is Our Friend

- FIR emission from dust has a negative 'K' correction (the observed flux is only weakly dependent on distance)
- It is thus relatively easy to detect distant galaxies in the FIR



The steep submm SED counteracts the $1/D^2$ cosmological dimming

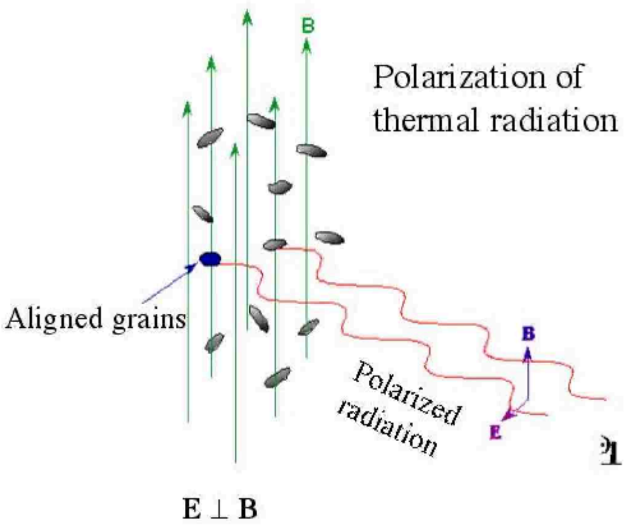
R. Maiolino

ALMA bands

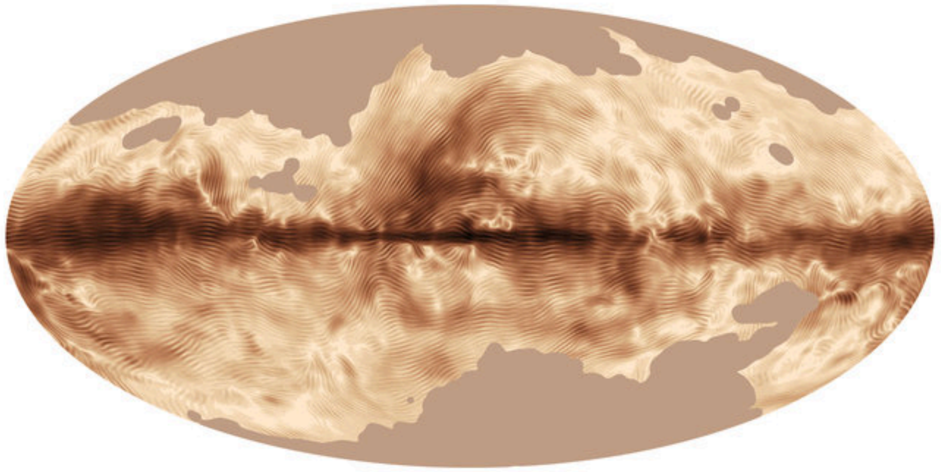
Polarization

- Polarization was first observed by Hiltner and Hall in 1949
  - Demonstrates grains are non-spherical and are aligned (presumably) by B fields

- Polarization due to `linear dichroism’
  - E.g. the cross section is larger in 1 direction than the other one



Planck Image of Polarized Light



Polarization

- Max polarization is @ 5.5µm but ranges between 0.34 and 1.0µm
- Polarization rises through UV, peaks in optical, and falls thereafter
  - Not like the monotonic decrease of extinction from UV to IR
    - *Suggests that grains responsible for UV extinction do not contribute to polarization: e.g. there are a mix of grains*
- Grains are spinning!
  - Rotation velocity of ~1e5 Hz

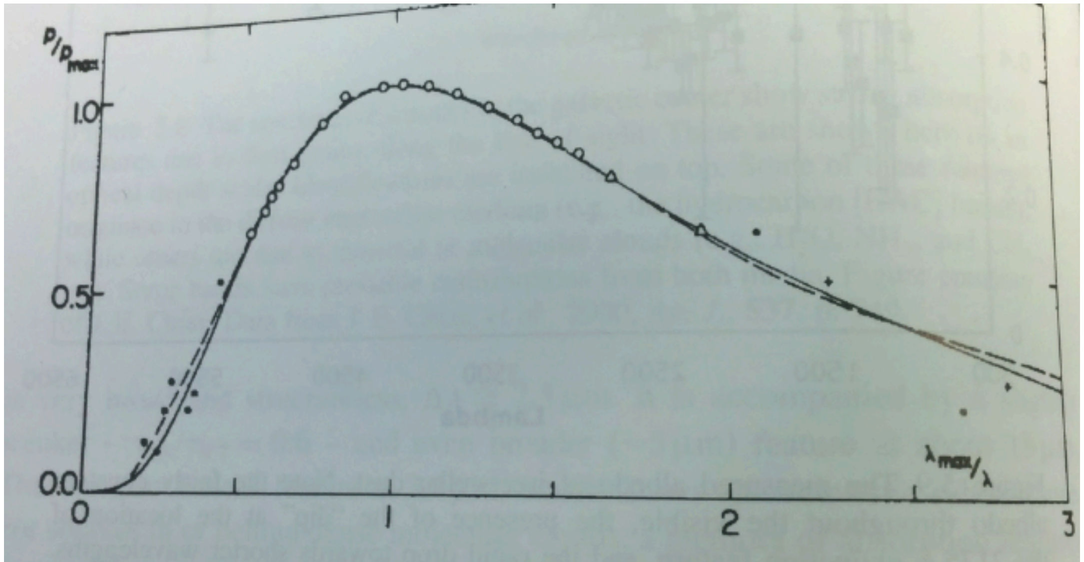
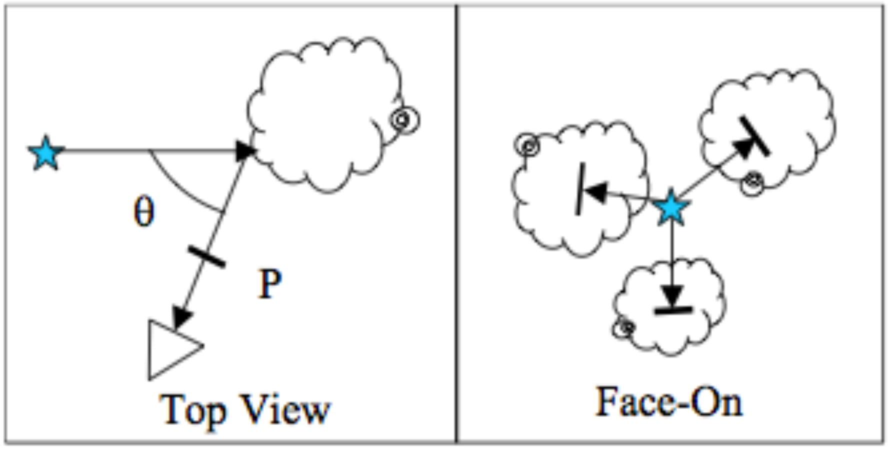


Figure 5.10 The normalized interstellar polarization curve as a function of the normalized wavelength (actually frequency) with $p(\lambda_{max})$ the maximum polarization at the wavelength, λ_{max}.

Other Forms of Polarizations

- Scattering !
  - It introduces, always, polarization



- Far-IR polarization:
  - Large grains heated to equilibrium have temps of 30-50K and radiate at 60-100 μm
  - Emission is larger along the long axis (in contrast to transmission)
    - *This gives a net polarization of the thermal radiation with P aligned with the long axis*
    - *For the transmission case P is aligned along the short*

Recap on Dust

- Dust is responsible for extinction (IR to UV) and shape the SED of galaxies
- Galaxies are bright at IR due to dust emission

- Dust comes in many sizes: power law $a^{-3.5}$
  - Interpretation of extinction curve, scattering

- Dust is made by a mix of grains: graphites, silicates, ice
  - PAHs, temperature map of the Galaxy, polarization vs extinction

- Dust grains are aligned by the magnetic field:
  - Polarization