



清华大学天文系  
Department of Astronomy, Tsinghua University

# 8. Interstellar Dust

Instructor: Hui Li      TA: Chengzhe Li

Department of Astronomy

Tsinghua University

# Interstellar Dust: Direct Observed Properties

- Wavelength-dependent attenuation (“extinction”) of starlight by absorption and scattering, now observable at wavelengths as long as  $20\text{ }\mu\text{m}$  (“mid-infrared”), and as short as  $0.1\text{ }\mu\text{m}$  (“vacuum ultraviolet”).
- Polarization-dependent attenuation of starlight, resulting in wavelength-dependent polarization of light reaching us from reddened stars.
- Scattered light in reflection nebulae.
- Thermal emission from dust, at wavelengths ranging from the sub-mm to  $2\text{ }\mu\text{m}$ .
- Small-angle scattering of X-rays, resulting in “scattered halos” around X-ray point sources.
- Microwave emission from dust, probably from rapidly spinning ultrasmall grains.

# Interstellar Dust: Indirect Observed Properties

- Presolar grains preserved in meteorites, the dust samples from solar nebula in ancient time.
- “Depletion” of certain elements from the interstellar gas, with the missing atoms presumed to be contained in dust grains.
- The observed abundance of  $H_2$  in the ISM, which can only be understood if catalysis on dust grains is the dominant formation avenue.
- The temperature of interstellar diffuse H I and  $H_2$ , in part a result of heating by photoelectrons ejected from interstellar grains.

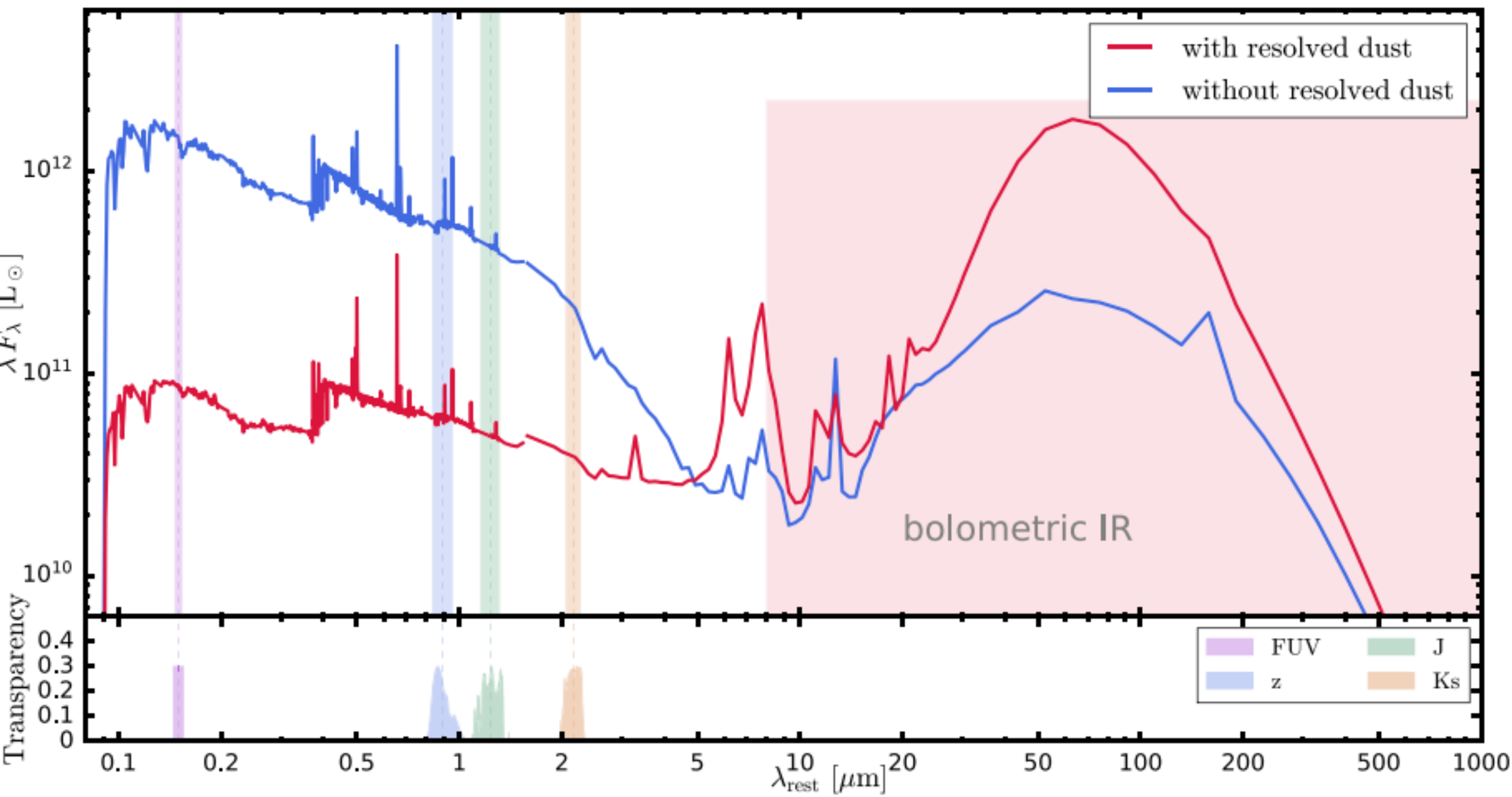
# Extinction

- The extinction  $A$ , measured in “mag” is defined by

$$\frac{A_\lambda}{\text{mag}} = 2.5 \log_{10} [F_\lambda^0 / F_\lambda]$$

- The relationship between extinction and optical depth is therefore very simple!

$$\frac{A_\lambda}{\text{mag}} = 2.5 \log_{10} [e^{\tau_\lambda}] = 1.086 \tau_\lambda$$

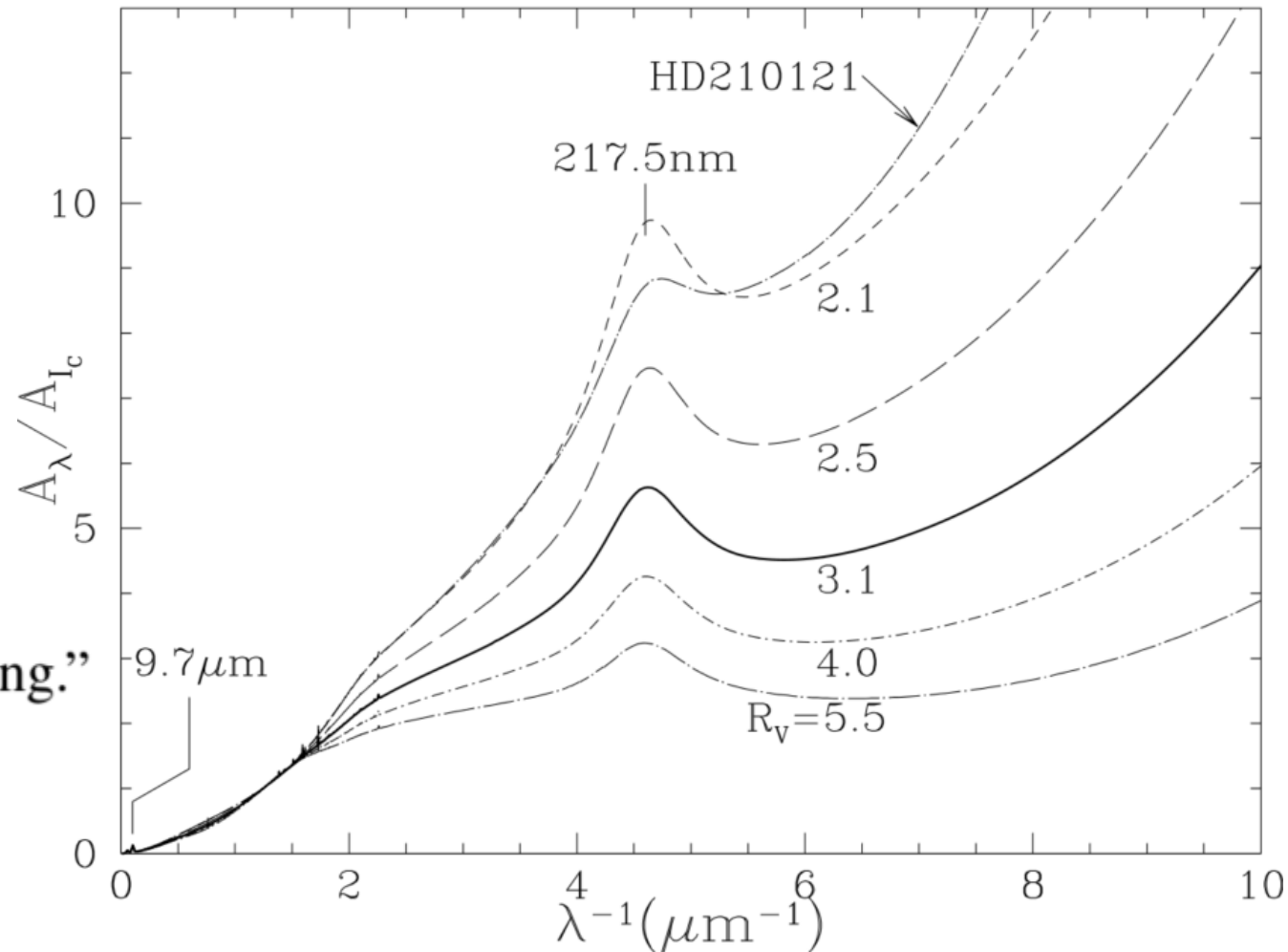


# Extinction Curve in the Local ISM

- The slope of the extinction curve at visible wavelength is characterized as:

$$R_V \equiv \frac{A_V}{A_B - A_V} \equiv \frac{A_V}{E(B - V)}$$

$E(B - V) \equiv A_B - A_V$  is the “reddening.”



## Dust-gas coupling

$$\tau_\lambda = \int_0^S n_d(s') \sigma_\lambda ds' \sim \sigma_\lambda \int_0^S n_d(s') ds' = \sigma_\lambda N_d$$

- Dust extinction appears to be relatively well-mixed with gas.
- Dust column density should also be related to gas column density.

$$\frac{N_H}{E(B - V)} = 5.8 \times 10^{21} \text{H cm}^{-2} \text{mag}^{-1}$$

- For sightlines with  $R_V=3.1$ ,

$$\frac{A_V}{N_H} = \frac{3.1}{5.8 \times 10^{21} \text{H cm}^{-2} \text{mag}^{-1}} = 5.3 \times 10^{-22} \text{mag cm}^2 \text{H}^{-1}$$

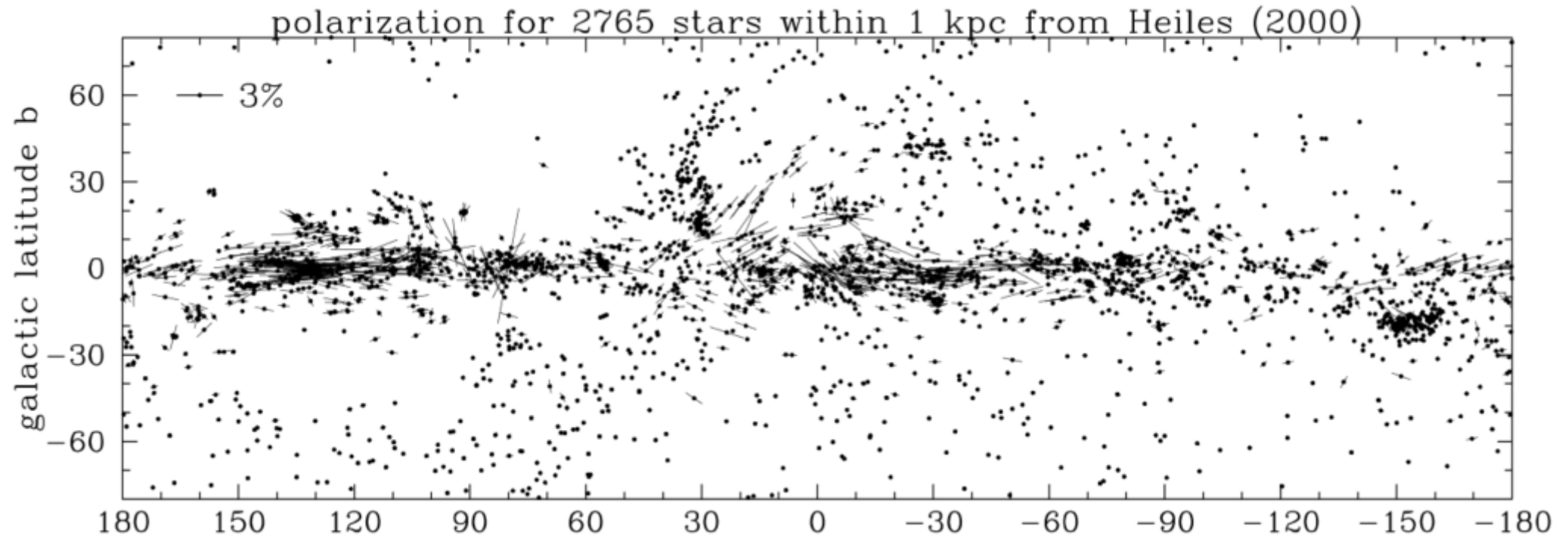
- So if you have a map of hydrogen column density, you can convert it to dust map.

# Implications of Dust Properties by Extinction Law

- “Mie scattering” theory
  - Assuming dust particles are spherical with radius  $a$ . The geometric cross-section of dust is  $\pi a^2$ . We define dimensionless efficiency factor  $Q_\lambda = \sigma_\lambda / \pi a^2$ .
  - When the wavelength  $\lambda \gg a$ ,  $Q_\lambda \sim 0$ ; when the wavelength  $\lambda \ll a$ ,  $Q_\lambda \sim 1$ .
  - When  $\lambda \sim a$ ,  $Q_\lambda \sim \frac{a}{\lambda}$ ,  $\sigma_\lambda \sim a^3 / \lambda$ !
- If the dust grains were large compared to the wavelength, we would be in the “geometric optics” limit, and the extinction cross section would be independent of wavelength, with  $R_V \gg 1$ .
- Grains smaller than the wavelength must be making an appreciable contribution to the extinction at all observed wavelengths, down to  $\lambda = 0.1 \mu\text{m}$ .



# Polarization by Dust Grains Aligned by Magnetic Fields



# Scattering of Starlight by Dust

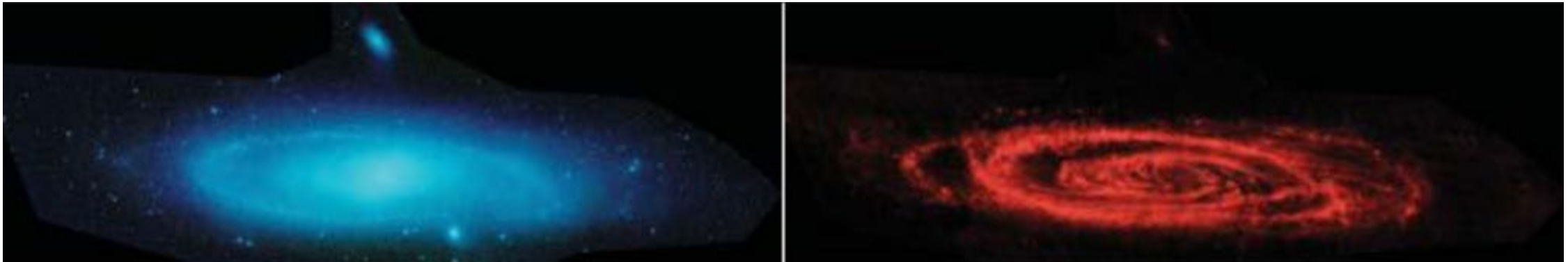
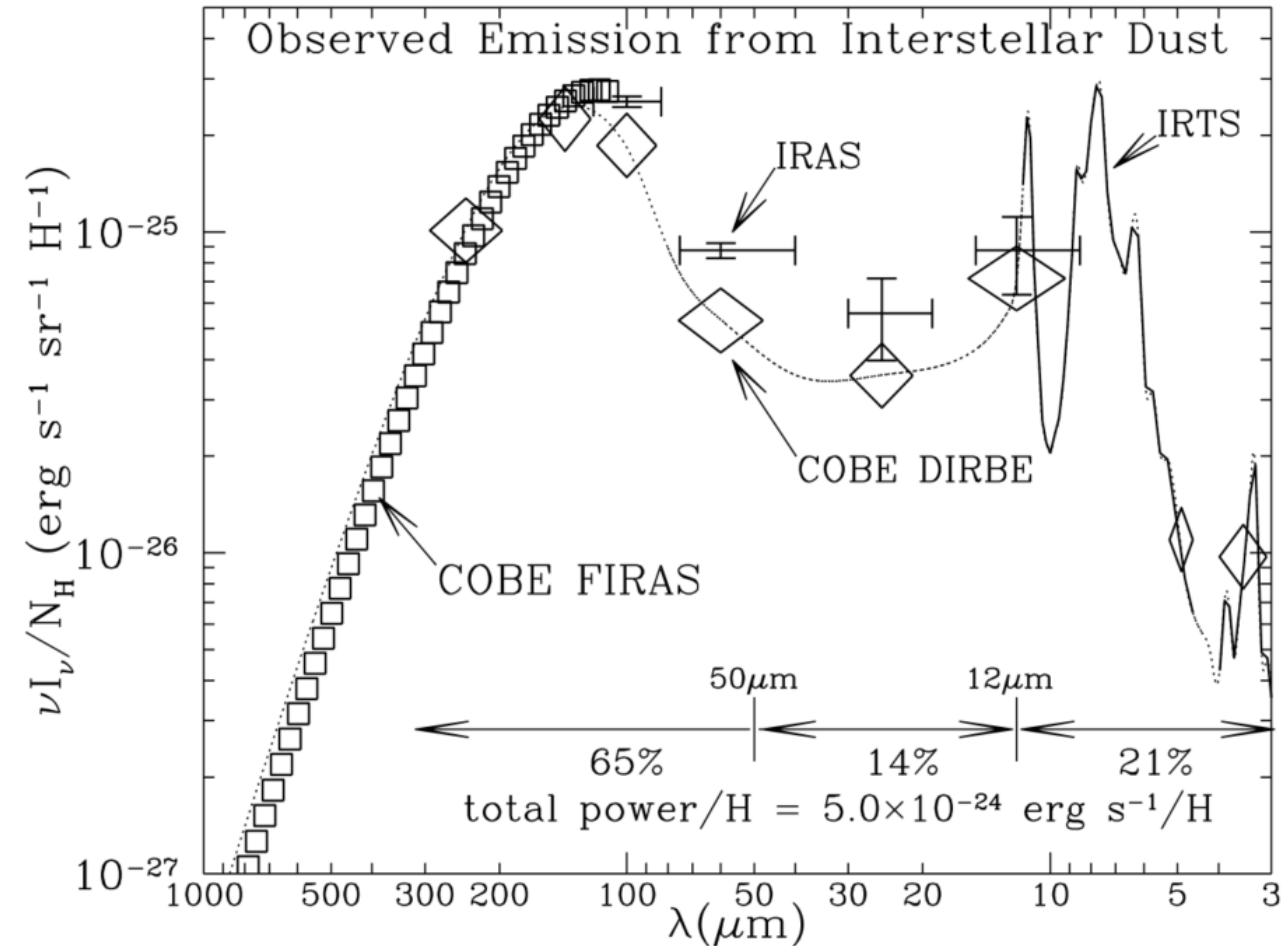
- Bluer lights are preferentially bright in the reflective regions.
- Stellar absorption lines appears in the spectra of the reflective nebulae.
- Correlated spatially with the IR emission.
- Dust particles dominating the scattering at  $\lambda \approx 0.6 \mu\text{m}$  have a  $> \sim \lambda/2\pi \approx 0.1 \mu\text{m}$ .



Trifid Nebula (M20)

# Infrared Emission

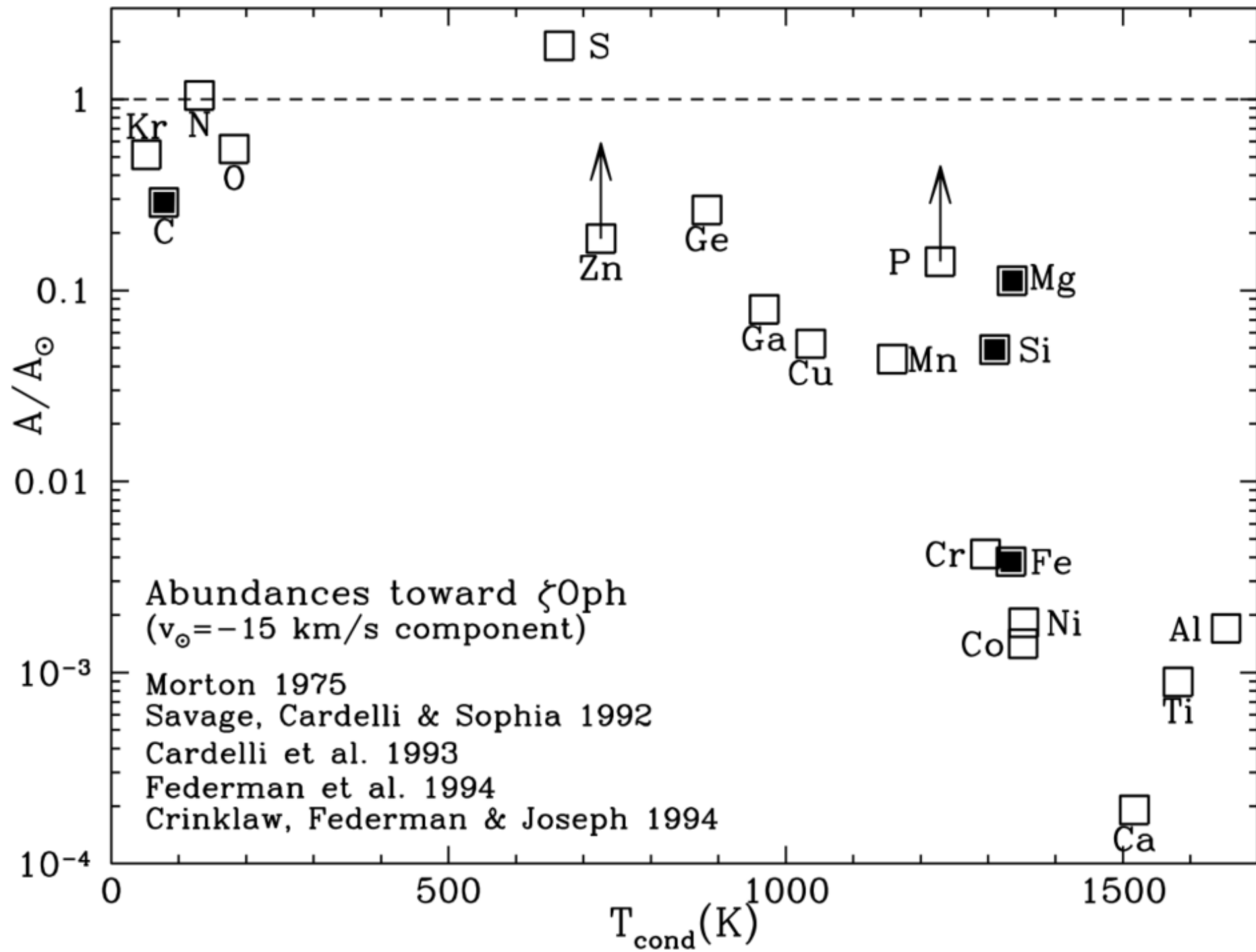
- The IR emission provides strong constraints on the nature of dust grains.
- Dust must include a component that can account for the fact that 1/3 of the radiated power is shortward of 50 micro.
- Strong emission features at 3, 6-8, and 12 micro.



M31-M32 star distribution and IR emission map

# Abundance Constraints

- Integral over the observed extinction indicates that the total grain mass relative to total hydrogen mass  $M_d/M_H \geq 0.008$ .
- Hydrogen cannot contribute to dust. He and Ne are chemically inert. The only way to get the above ratio is to build grains from the most abundant condensable elements: C, O, Mg, Si, S, Fe.
- Any observational constraints on the abundance of dust? Depletion of elements in the ISM!



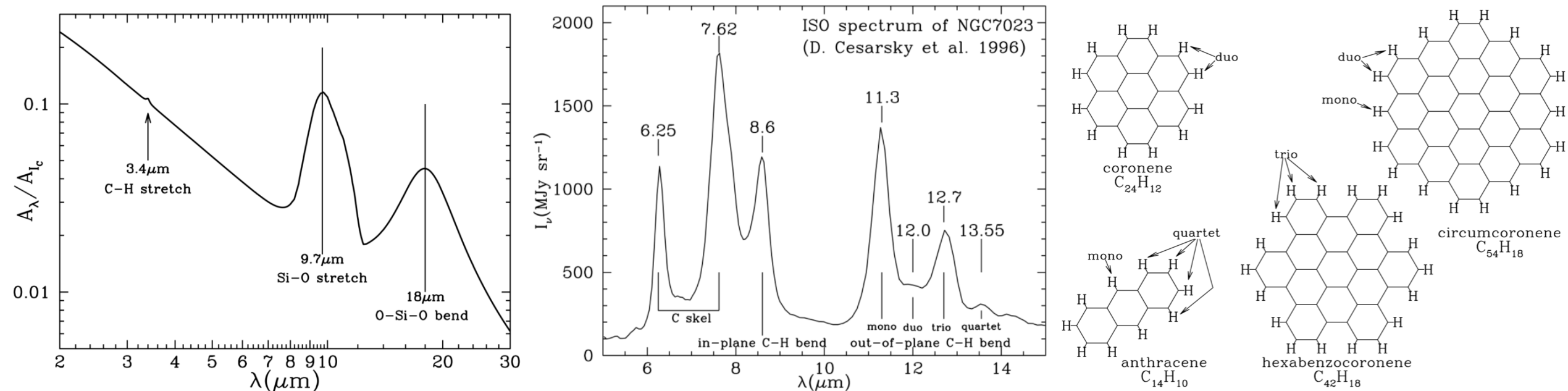


## Possible Materials for Dust Grains

- Silicates, e.g., **pyroxene** composition  $\text{Mg}_x\text{Fe}_{1-x}\text{SiO}_3$ , or **olivine** composition  $\text{Mg}_{2x}\text{Fe}_{2-2x}\text{SiO}_4$  ( $0 \leq x \leq 1$ )
- Oxides of silicon, magnesium, and iron (e.g.,  $\text{SiO}_2$ ,  $\text{MgO}$ ,  $\text{Fe}_3\text{O}_4$ )
- Carbon solids (graphite, amorphous carbon, and diamond)
- Hydrocarbons (e.g., polycyclic aromatic hydrocarbons)
- Carbides, particularly silicon carbide ( $\text{SiC}$ )
- Metallic Fe

# Spectral Features of Dust

- The 2175Å feature in the extinction curves is thought to be caused by some form of sp<sup>2</sup>-bonded carbon material in the dust grains.
- The 3.4, 9.7 and 18 micro IR absorption features are believed to be caused by Silicates.
- Vibrational transitions in PAH are responsible for the IR emission features.



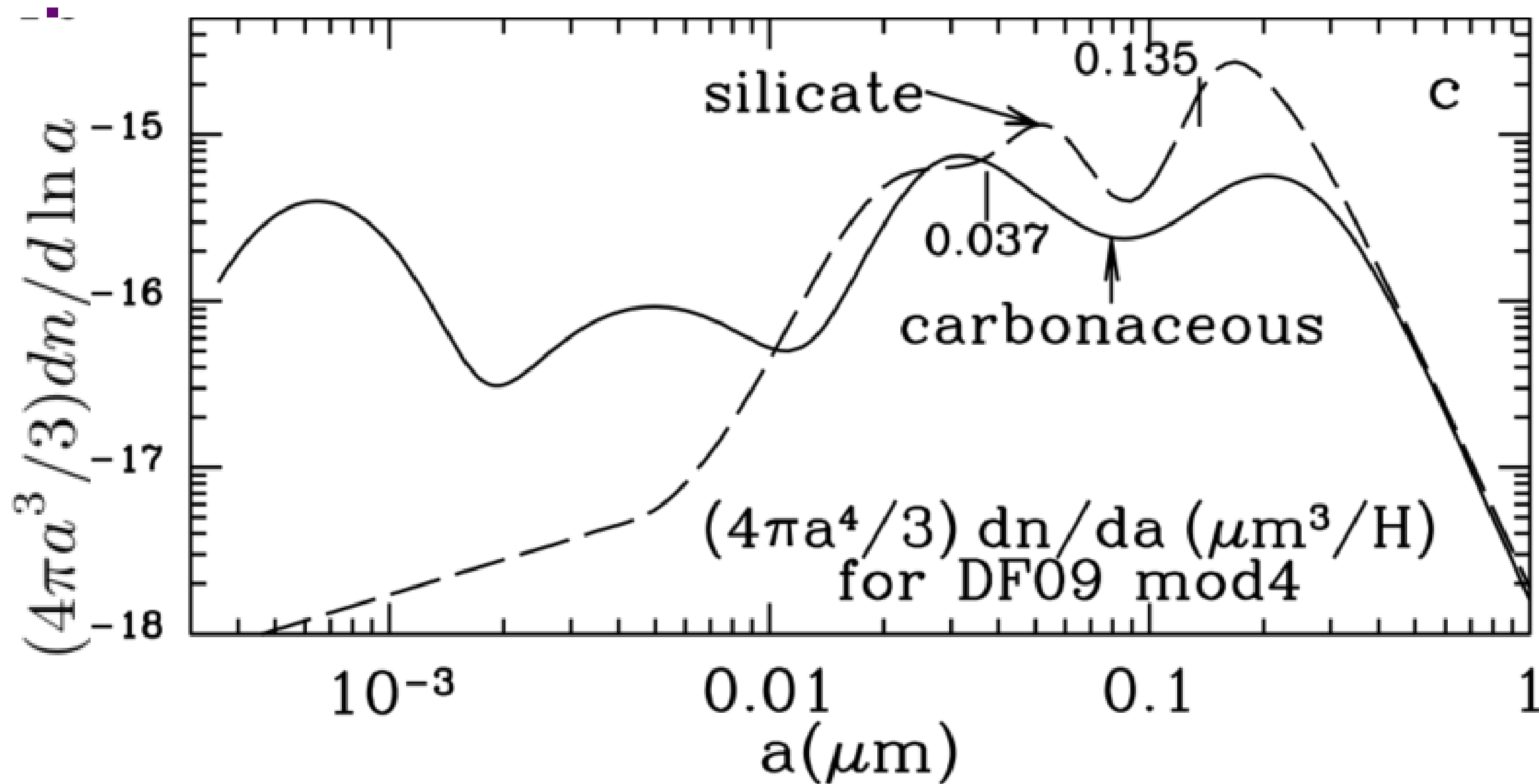
# Models for Dust: Composition and Geometry of Dust.

- A class of models that has met with some success assumes the dust to consist of two materials: (1) amorphous silicate ( $\sim 3.7 \text{ g/cm}^3$ ), and (2) carbonaceous material ( $\sim 2.2 \text{ g/cm}^3$ ).
- The famous Mathis-Rumpl-Nordsieck 1977 (MRN) size distribution could reproduce the observed extinction from near IR to UV.

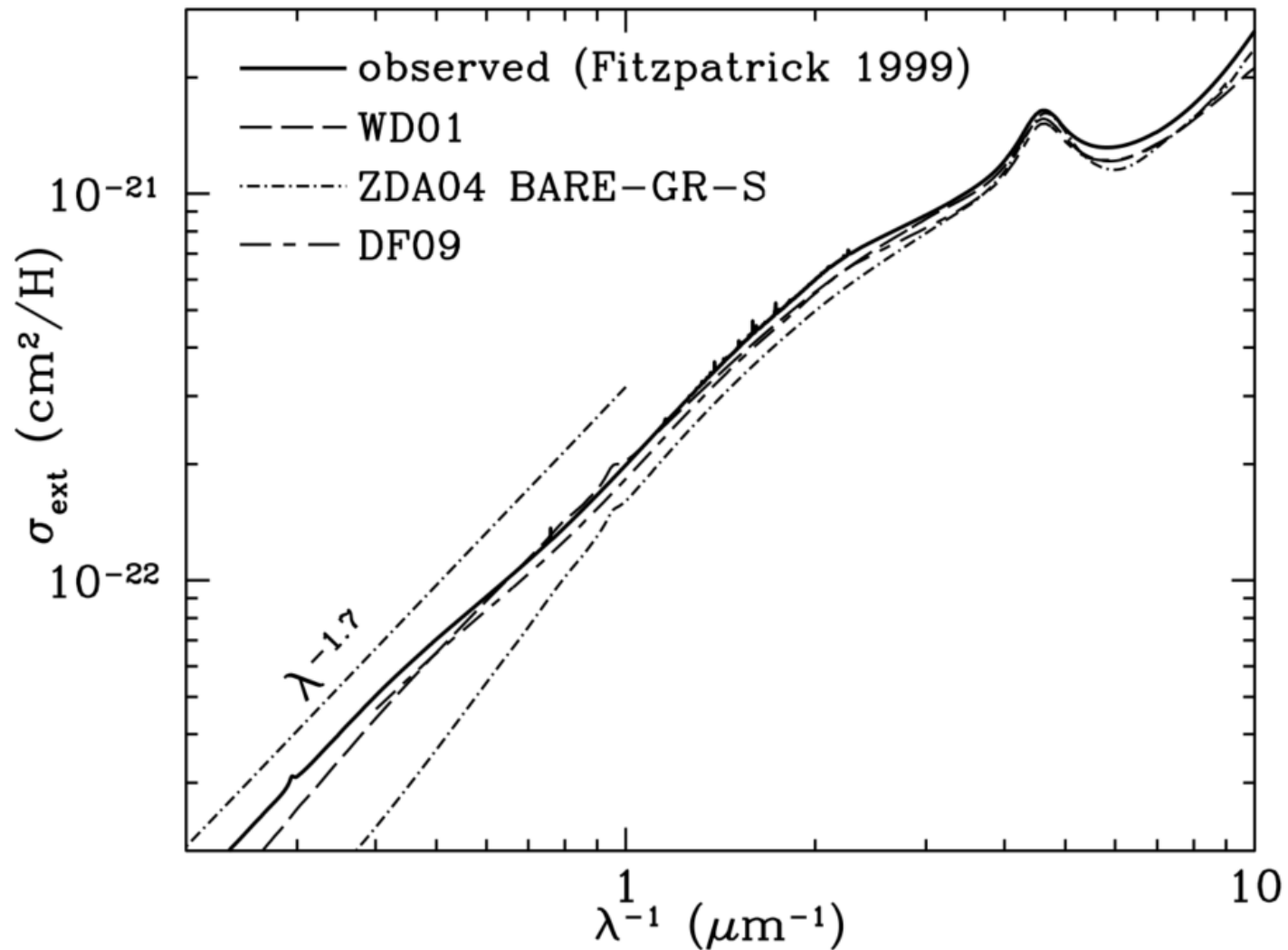
$$dn/da \propto a^{-3.5}$$

- This size distribution has most of the mass in the larger grains, and most of the surface area in the smaller grains.
- More sophisticated dust models includes Weingartner & Draine 2001, Zubko+2004, Draine & Li 2007, Draine & Fraise 2009; Das+2010.

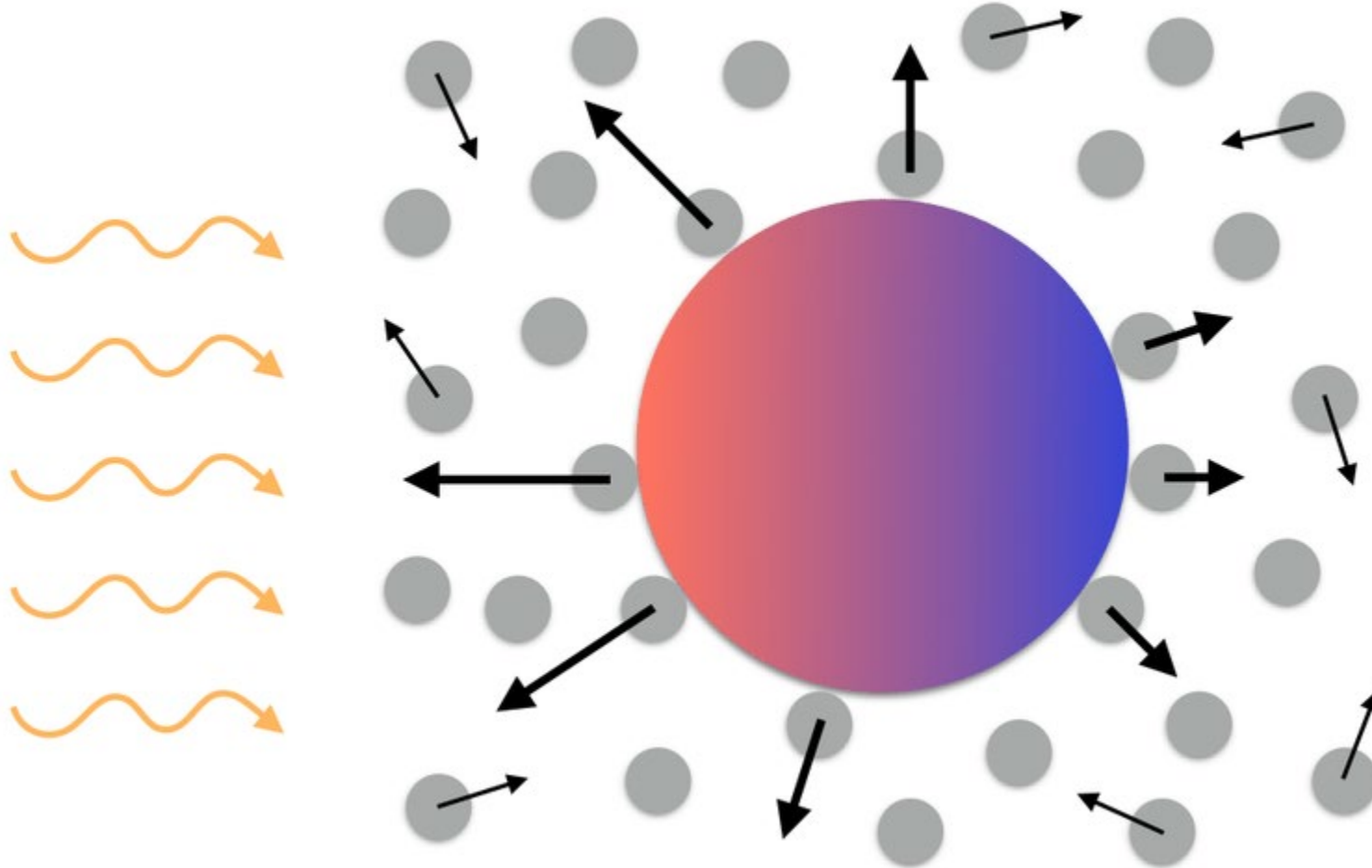




## Reproduce Observed Extinction for $R_V \sim 3.1$



## Physics of Dust Grains: Interaction with Radiation and Gas.



# Dust Temperature: Heating

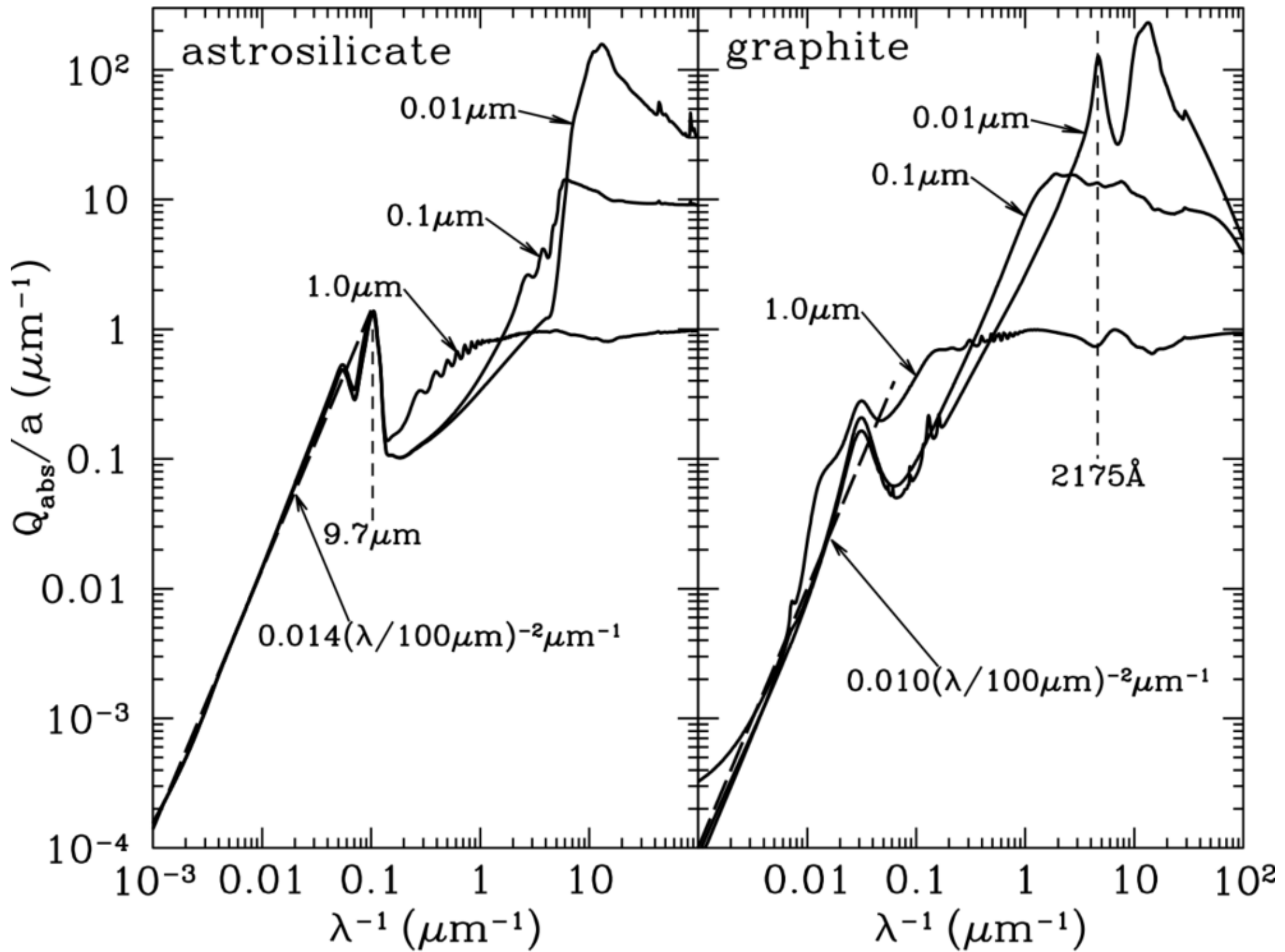
- When an optical or ultraviolet photon is absorbed by a grain, an electron is raised into an excited electronic state.
- If the electron is sufficiently energetic, it may be able to escape from the solid as a “photoelectron.” The PE with free energy will heat the ambient gas and becomes the dominated heating mechanism around UV radiation fields.
- In most solids or large molecules, the electronically excited state will deexcite nonradiatively, with the energy going into many vibrational modes – i.e., heat of dust particles.

$$\left(\frac{dE}{dt}\right)_{\text{abs}} = \int \frac{u_{\nu} d\nu}{h\nu} \times c \times h\nu \times Q_{\text{abs}}(\nu) \pi a^2$$

$$= \langle Q_{\text{abs}} \rangle_{\star} \pi a^2 u_{\star} c$$

Spectrum-averaged absorption cross-section

$$\langle Q_{\text{abs}} \rangle_{\star} \equiv \frac{\int d\nu u_{\star \nu} Q_{\text{abs}}(\nu)}{u_{\star}}$$



# Dust Temperature: Cooling

Planck-averaged emission efficiency

$$\langle Q_{\text{abs}} \rangle_T \equiv \frac{\int d\nu B_\nu(T) Q_{\text{abs}}(\nu)}{\int d\nu B_\nu(T)}$$

- Grains lose energy by infrared emission, at a rate

$$\left( \frac{dE}{dt} \right)_{\text{emiss.}} = \int d\nu 4\pi B_\nu(T_d) C_{\text{abs}}(\nu) = 4\pi a^2 \langle Q_{\text{abs}} \rangle_{T_d} \sigma T_d^4$$

- If  $Q$  can be approximated as a power-law in frequency  $Q_{\text{abs}}(\nu) = Q_0 (\nu/\nu_0)^\beta = Q_0 (\lambda/\lambda_0)^{-\beta}$

$$\langle Q_{\text{abs}} \rangle_T \approx 1.3 \times 10^{-6} (a/0.1 \mu\text{m}) (T/\text{K})^2 \quad (\text{silicate})$$

$$\approx 8 \times 10^{-7} (a/0.1 \mu\text{m}) (T/\text{K})^2 \quad (\text{graphite}).$$

# Dust Temperature: Steady-State Grain Temperature

- Cooling and heating balance leads to a steady state dust temperature  $T_{ss}$ .

$$4\pi a^2 \langle Q_{\text{abs}} \rangle_{T_{ss}} \sigma T_{ss}^4 = \pi a^2 \langle Q_{\text{abs}} \rangle_{\star} u_{\star} c$$

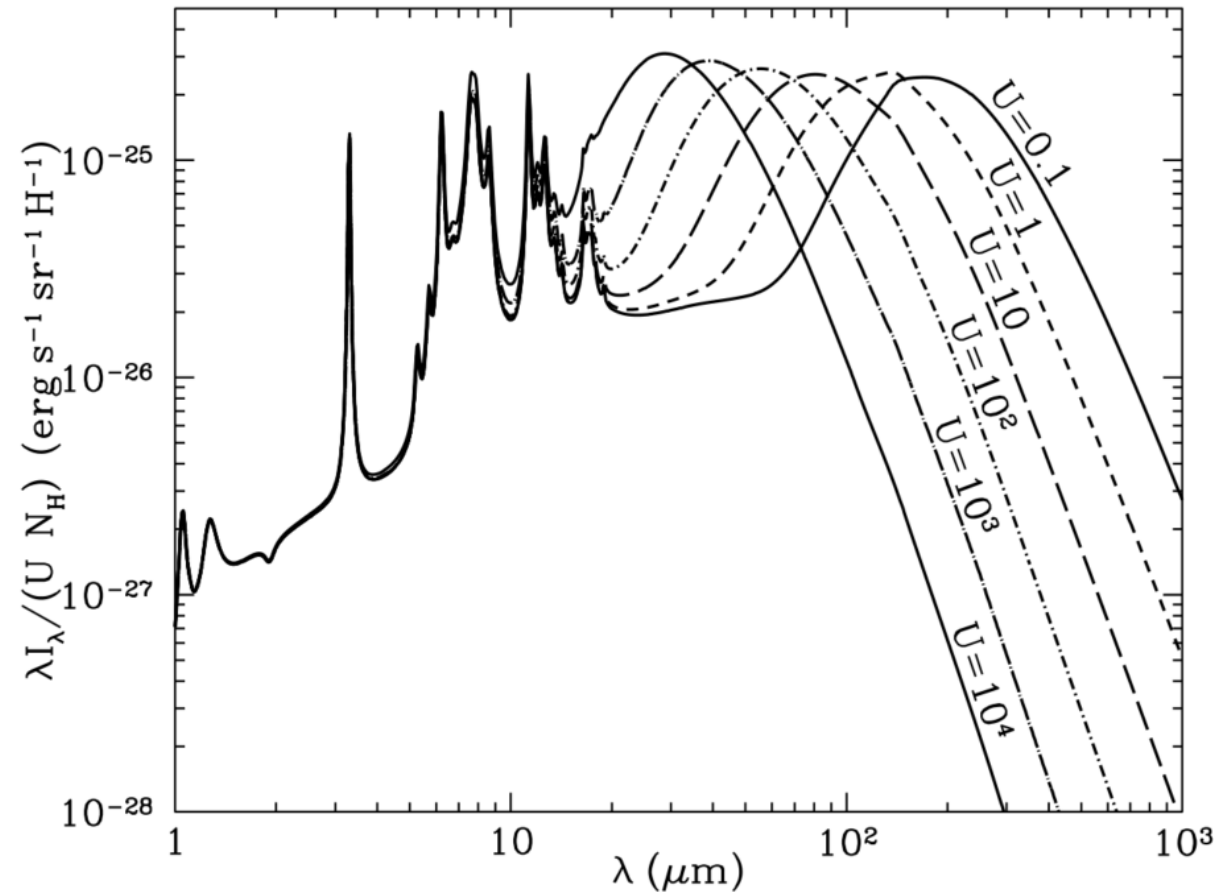
$$T_{ss} = \left( \frac{h\nu_0}{k} \right)^{\beta/(4+\beta)} \left[ \frac{\pi^4 \langle Q_{\text{abs}} \rangle_{\star} c}{60\Gamma(4+\beta)\zeta(4+\beta)Q_0\sigma} \right]^{1/(4+\beta)} u_{\star}^{1/(4+\beta)}$$

$$\approx 16.4 (a/0.1 \mu\text{m})^{-1/15} U^{1/6} \text{ K} , \text{ silicate, } 0.01 \lesssim a \lesssim 1 \mu\text{m}$$

$$\approx 22.3 (a/0.1 \mu\text{m})^{-1/40} U^{1/6} \text{ K} , \text{ graphite, } 0.005 \lesssim a \lesssim 0.15 \mu\text{m}$$

# The IR emission from Dust

- Calculation IR emissivity from dust requires a grain model to provide the size distributions  $dn_i/da$  for each composition  $i$ , the absorption cross sections  $C_{\text{abs}}$ , and the temperature distribution functions of dust ( $dP/dT$ ).
- The Draine & Li 2007 model reproduced many interesting features of the IR radiation of dust.
- The thermal emission peak shifts toward shorter wavelength as  $U$  is increased because grains become warmer.
- The PAH emission features account for ~25% of the total power but do not change as the radiation intensity is changed.



$$j_{\nu} = \sum_i \int da \frac{dn_i}{da} \int dT \left( \frac{dP}{dT} \right)_{i,a} C_{\text{abs}}(\nu; i, a) B_{\nu}(T)$$



# Collisional Heating and Cooling of Dust

- Consider a neutral, spherical grain of radius  $a$ , at rest in a gas with temperature  $T_{\text{gas}}$ . The net rate of collisional heating by the gas can be written as

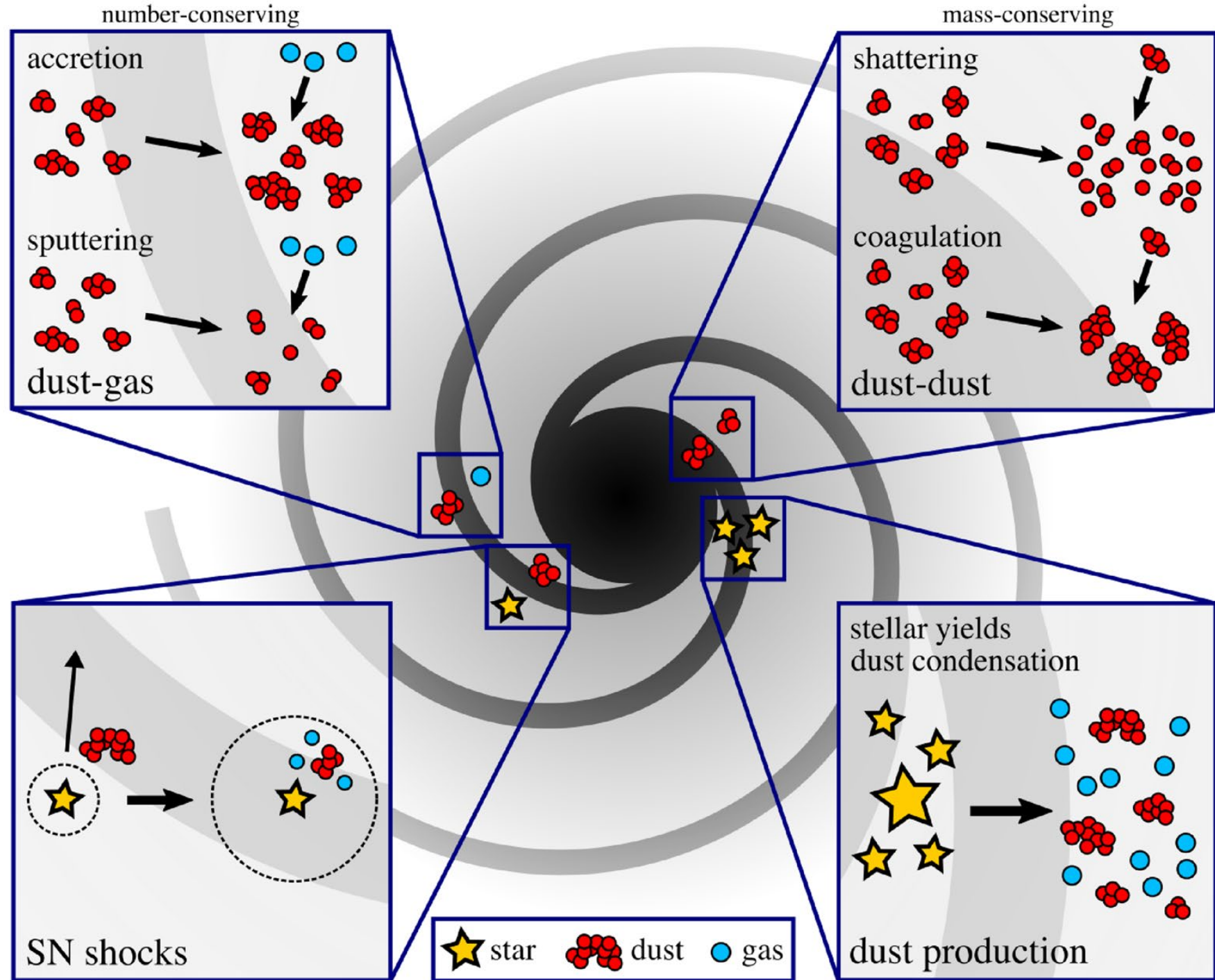
$$\left(\frac{dE}{dt}\right)_{\text{gas}} = \sum_i n_i \left(\frac{8kT_{\text{gas}}}{\pi m_i}\right)^{1/2} \pi a^2 \times \alpha_i \times 2k(T_{\text{gas}} - T_{\text{dust}})$$

- In atomic H, the ratio of collisional heating to radiative heating is

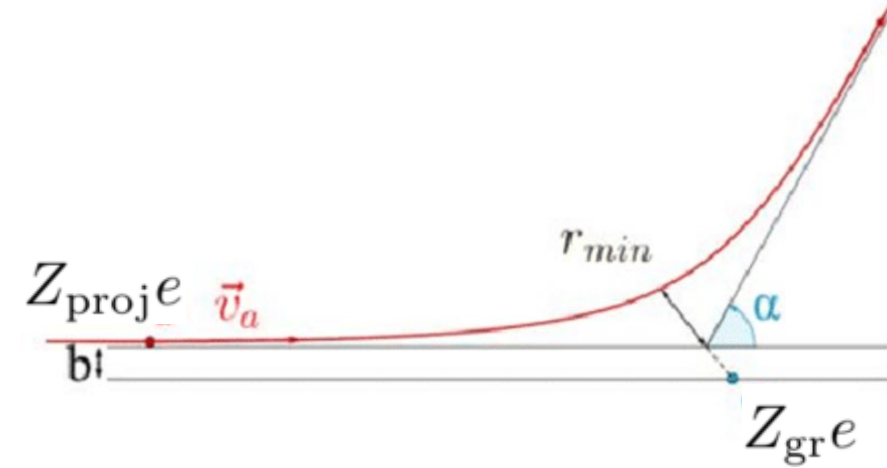
$$\begin{aligned} \frac{(dE/dt)_{\text{gas}}}{(dE/dt)_{\text{abs}}} &= \frac{n_{\text{H}}(8kT/\pi m_{\text{H}})^{1/2} 2\alpha_{\text{H}}kT}{\langle Q_{\text{abs}} \rangle_{\star} u_{\star} c} \times 1.05 \\ &= \frac{3.8 \times 10^{-6}}{U} \frac{\alpha_{\text{H}}}{\langle Q_{\text{abs}} \rangle_{\star}} \left(\frac{n_{\text{H}}}{30 \text{ cm}^{-3}}\right) \left(\frac{T_{\text{gas}}}{10^2 \text{ K}}\right)^{3/2} \end{aligned}$$

- IR emission between days 6000 and 8000 of SN 1987A was dominated by  $\sim 180$  K silicate dust, heated by a plasma with  $n_{\text{e}} \approx 3 \times 10^4 \text{ cm}^{-3}$  and  $T \approx 5 \times 10^6 \text{ K}$ .

# Grain Physics: Production / Destruction



# Grain Physics: Charges



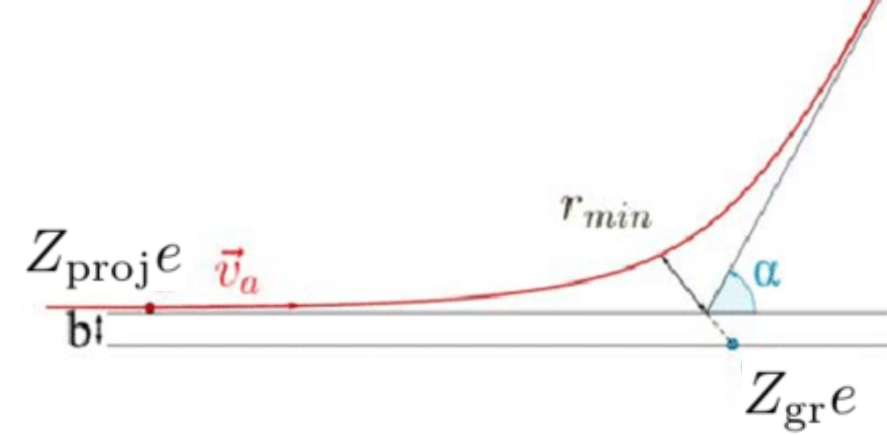
- Interaction between charged grain and approaching projectile!
- Angular momentum conservation leads to the speed of the projectile at closest is  $(2E/m_{proj})^{1/2}b/r_{min}$

- Energy conservation leads to 
$$E = \left(\frac{b}{r_{min}}\right)^2 E + \frac{Z_{gr}Z_{proj}e^2}{r_{min}}$$

- By setting  $r_{min}=a$ , the maximum impact parameter  $b_{max}$  can be solved!

$$\sigma(E) = \pi b_{max}^2(E) = \pi a^2 \left[ 1 - \frac{Z_{gr}Z_{proj}e^2}{aE} \right]$$

# Grain Physics: Charges

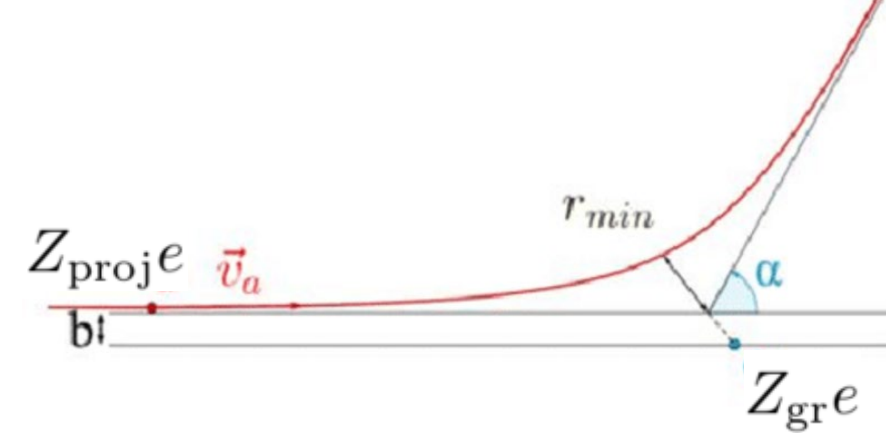


- The collision rate between grain and thermal gas is

$$\begin{aligned} \left( \frac{dN}{dt} \right)_{\text{proj}} &= n_{\text{proj}} \int_{E_{\text{min}}}^{\infty} \sigma(E) v f_E dE \\ &= \pi a^2 n_{\text{proj}} \left( \frac{8kT}{\pi m_{\text{proj}}} \right)^{1/2} F(Z_{\text{proj}} \phi) , \\ \phi &\equiv \frac{Z_{\text{gr}} e^2}{a k T} , \quad F(x) \equiv \begin{cases} (1 - x) & \text{if } x < 0 \\ e^{-x} & \text{if } x > 0 \end{cases} \end{aligned}$$

- The function  $F$  is the amount by which Coulomb focusing changes the collision rate relative to the rate for an uncharged grain.

# Grain Physics: Charges



- The rate of collision with ions balances the rate of collisions with electrons:

$$Z_i n_i s_i m_i^{-1/2} (1 - Z_i \phi) = n_e s_e m_e^{-1/2} e^\phi$$

- For pure hydrogen plasma:  $(1 - \phi)e^{-\phi} = \sqrt{1836.1}$

- The final steady-state grain charge is

$$Z_{\text{gr}} = \frac{Ua}{e} = -2.504 \frac{akT}{e^2} = -150 \left( \frac{a}{0.1 \mu\text{m}} \right) T_4$$

# Grain Physics: Dynamics in the ISM

- The motion and rotation of dust grains is determined by the forces and torques that act upon them.
- Drag force of dust by gas similar to aerodynamical drag ( $F \sim v^2$ ).

$$\frac{d\mathbf{v}_d}{dt} = -\frac{K_s(\mathbf{v}_d - \mathbf{v}_g)}{m_d} \quad \frac{d\mathbf{v}_g}{dt} = -\frac{\nabla P}{\rho_g} + \frac{\rho_d K_s(\mathbf{v}_d - \mathbf{v}_g)}{\rho_g m_d}$$

- In terms of relative velocity

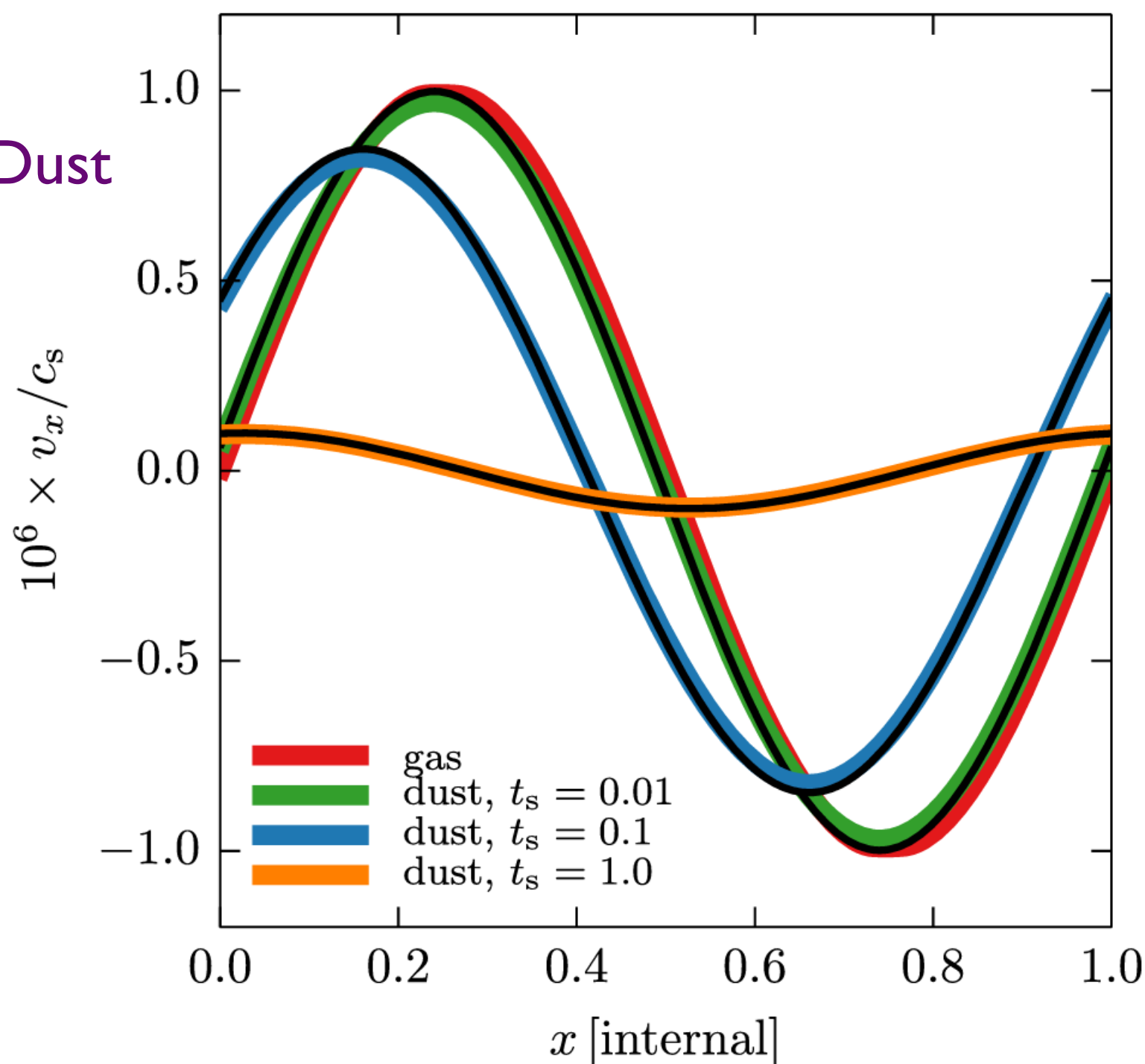
$$\frac{d(\mathbf{v}_d - \mathbf{v}_g)}{dt} = -\frac{\mathbf{v}_d - \mathbf{v}_g}{t_s}$$

Stopping timescale:

$$t_s = \frac{m_d \rho_g}{K_s(\rho_g + \rho_d)} \\ = \frac{\sqrt{\pi \gamma} a \rho_{gr}}{2\sqrt{2} \rho_g c_s} \left( 1 + \frac{9\pi}{128} \left| \frac{\mathbf{v}_d - \mathbf{v}_g}{c_s} \right|^2 \right)^{-1/2}$$

## Decoupling of Gas and Dust

- Dust most closely follows the gas when the stopping time-scale is short, corresponding to high drag.
- When stopping time is long, which is the case for large grains, gas and dust start to decouple between each other.



# Grain Physics: Other Forces

- Lorentz Force for charged dust grains in magnetic fields.
- Radiation pressure onto dust and recoil forces.
- Thermal and suprathermal rotation of large grains.
- Alignment of dust grains (angular momentum and magnetic fields)