Physics 224
The Interstellar Medium

Lecture #11: Dust Composition, Photoelectric Heating, Neutral Gas

Outline

- Part I: Dust Heating & Cooling continued
- Part III: Dust Emission & Photoelectric Heating
- Part II: Dust Composition
- Part IV: Neutral Gas

How we learn about dust

- Extinction: wavelength dependence of how dust attenuates (absorbs & scatters) light ✓
- Polarization: of starlight and dust emission
- Thermal emission from grains ←
- Microwave emission from spinning small grains
- Depletion of elements from the gas relative to expected abundance ←
- Presolar grains in meteorites or ISM grains from Stardust mission (7 grains!)

Dust Thermal Balance

Steady State emission = absorption.

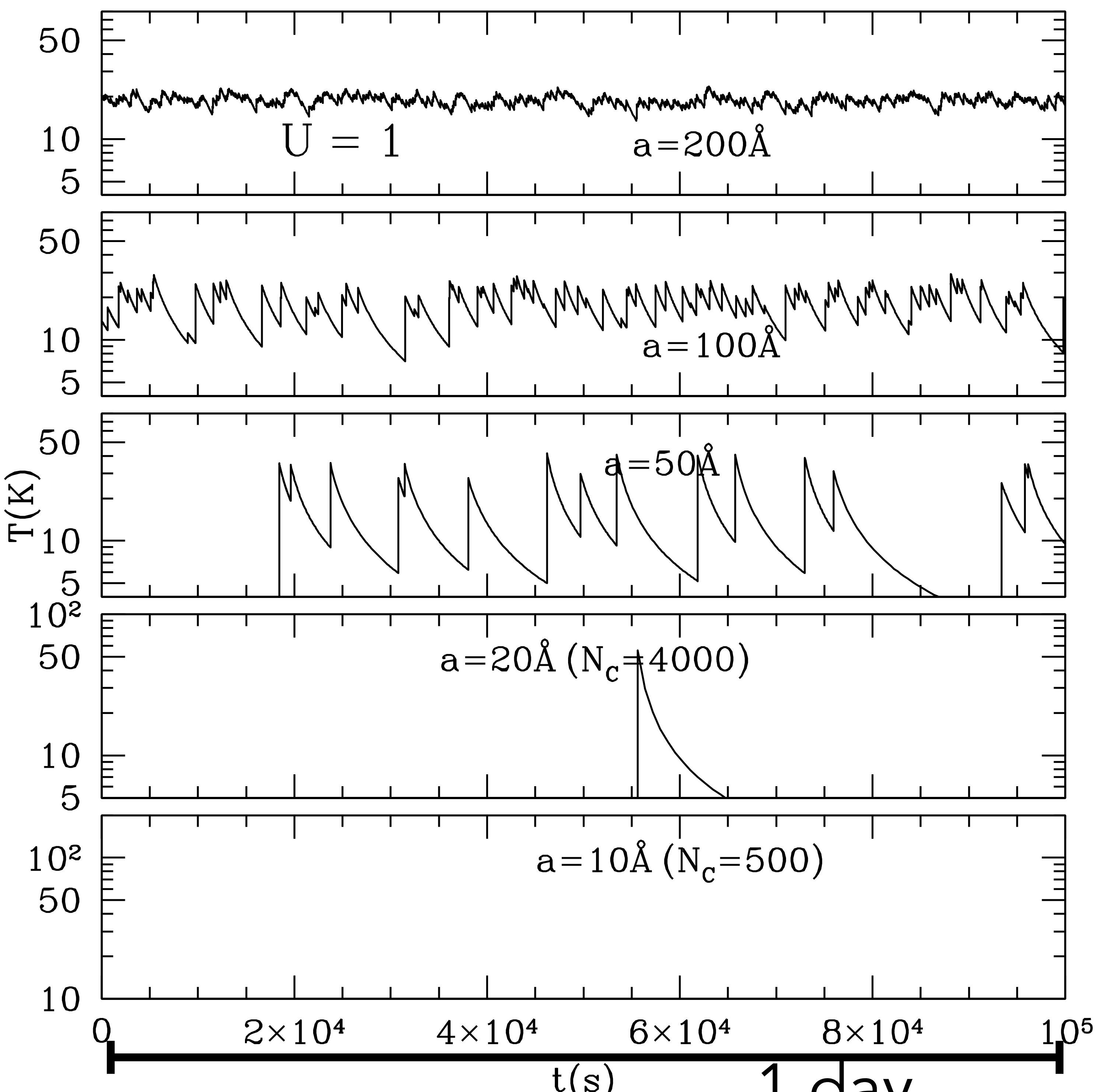
$$\left(\frac{dE}{dt}\right)_{\rm abs} = \langle Q_{\rm abs}\rangle_* \, \pi a^2 \; u_* \; c$$

$$\left(\frac{dE}{dt}\right)_{\rm em} = 4\pi a^2 \, \langle Q_{\rm abs}\rangle_{\rm T} \, \sigma T^4$$

$$T \approx 22.3 (a/0.1\mu m)^{-1/40} U^{1/6} K$$ carbon

$$T \approx 16.4 (a/0.1\mu m)^{1/15} U^{1/6} K$$ silicate

Dust Thermal Balance



Not all grains are in steady state…

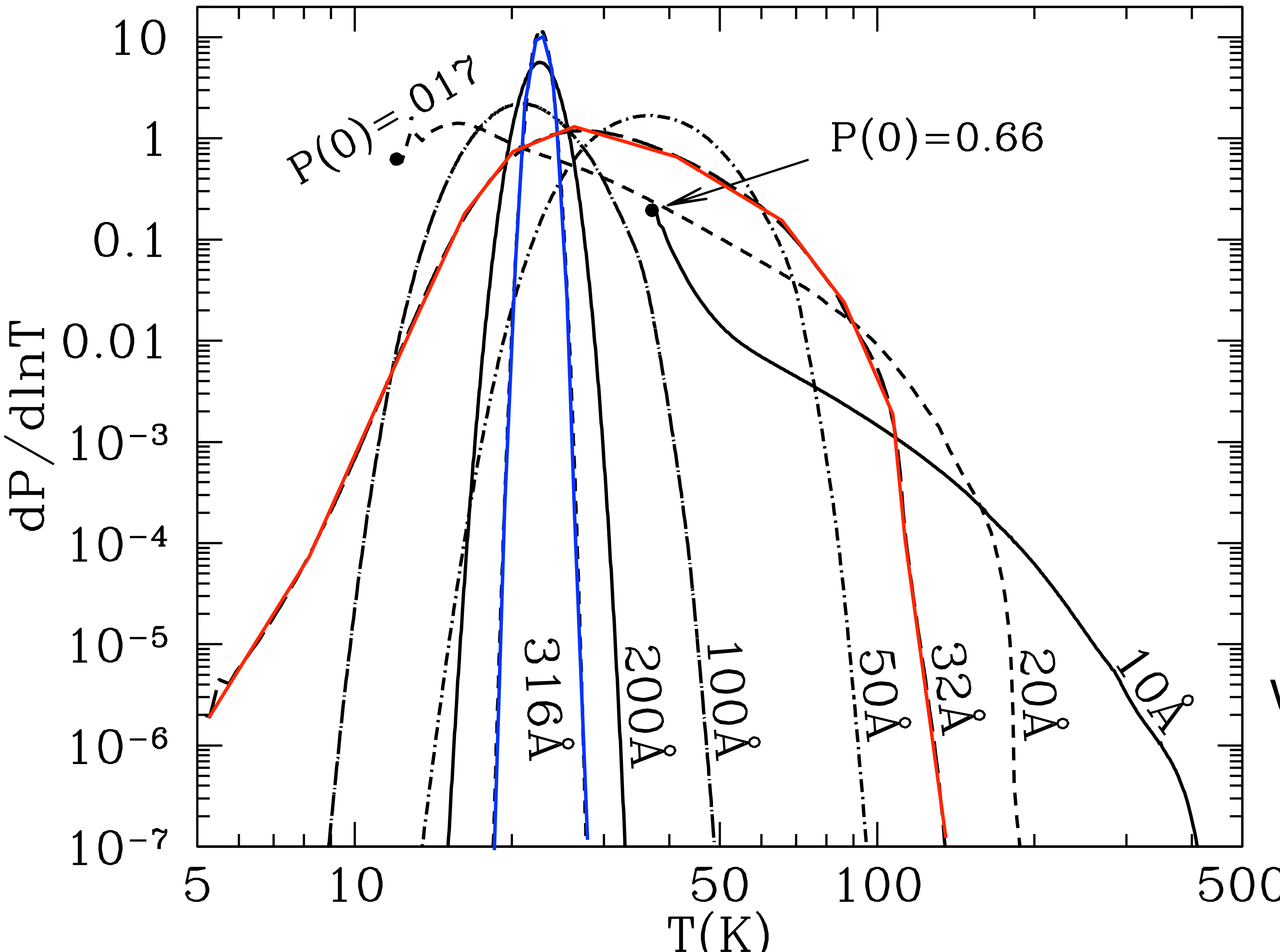
When:
$(dE/dt)_{cool}$ << photon absorption rate

and/or

$h\nu >> E_{ss}$

Need to consider non-steady state

Dust Thermal Balance



Probability of finding grain with temp T in average MW ISRF.

PDF narrows with increasing size.

Dust Thermal Balance

While it is unlikely to find a small grain at
very high temperatures, most energy is emitted there!

$$\left(\frac{dE}{dt}\right)_{\rm em} = 4\pi a^2 \left\langle Q_{\rm abs}\right\rangle_{\rm T} \sigma T^4$$

$$\langle Q_{\rm abs}\rangle_T \sim 1.3 \times 10^{-5} T^2$$ silicate

dE/dt ~ T^6

Dust Thermal Balance

Is collisional heating important?

absorption $$\left(\frac{dE}{dt}\right)_{\rm abs} = \langle Q_{\rm abs}\rangle_* \pi a^2\ u_*\ c$$

collisions $$\left(\frac{dE}{dt}\right)_0 = \quad n_{\rm H}\pi a^2 \langle v_{\rm H}\rangle 2kT\,\alpha$$

Assuming collisions with H
and dust grain is not charged.

factor ~unity
for energy transfer from
collider to grain

Dust Thermal Balance

Is collisional heating important?

$$\frac{(dE/dt)_{\rm col}}{(dE/dt)_{\rm abs}} = \frac{3.8 \times 10^{-6}}{U} \frac{\alpha}{\langle Q_{\rm abs} \rangle_*} \left(\frac{n_H}{30cm^{-3}}\right) \left(\frac{T}{10^2 K}\right)^{3/2}$$

radiation field strength normalized to MW average ISRF

collisional heating important in dense and/or hot gas

Dust Thermal Balance

Is collisional heating important?

More generally:

if grain and/or collider is charged, Coulomb focusing factor

density of colliders

$$\frac{(dE/dt)_{\rm coll}}{(dE/dt)_{\rm abs}} \approx \frac{2nkT}{u_*} \times \frac{\gamma}{\langle Q_{\rm abs} \rangle_*} \times \frac{(8kT/\pi m_e)^{1/2}}{c}$$

thermal pressure (thermal energy density) relative to starlight energy density

velocity of colliders relative to speed of light

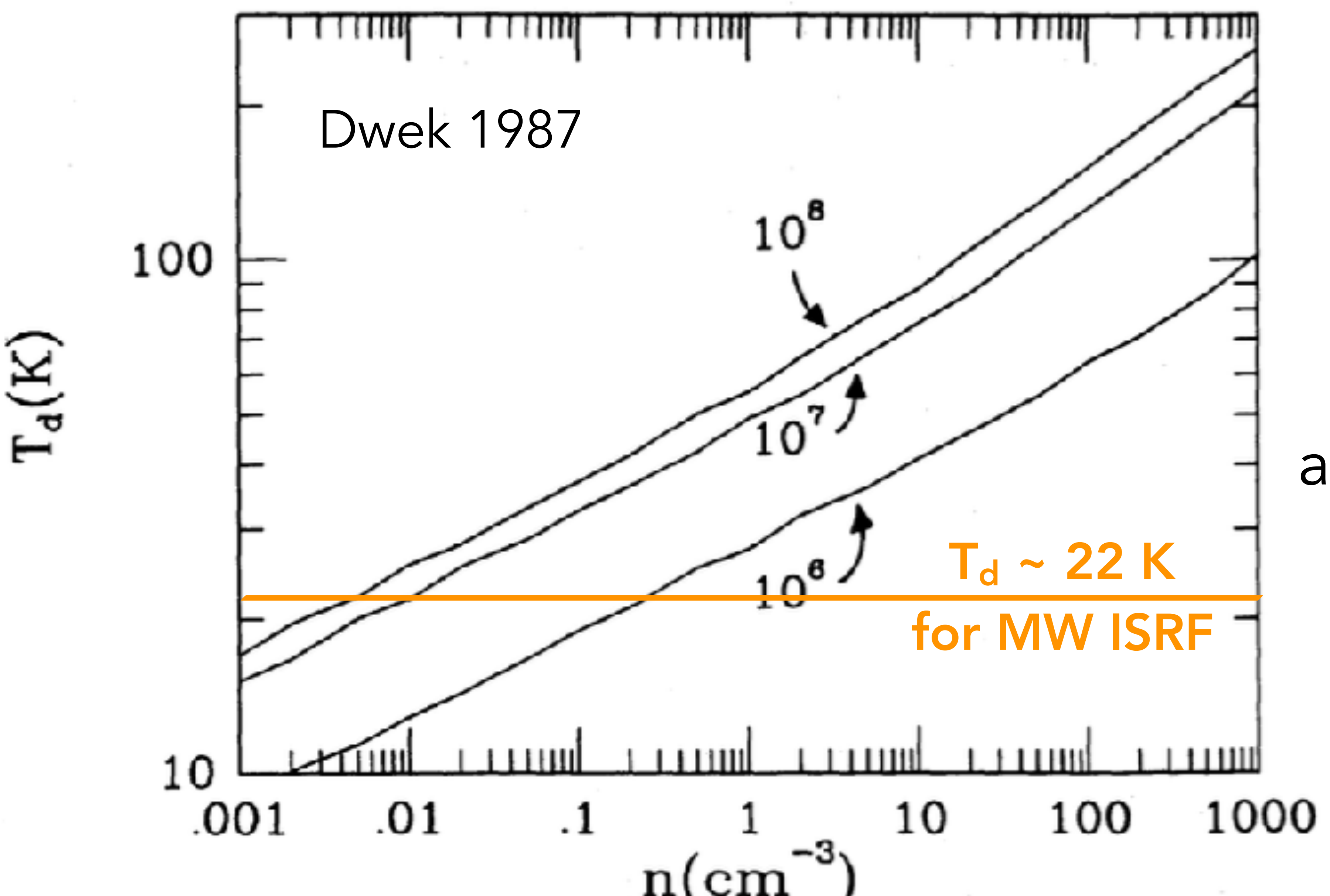
Dust Thermal Balance

Is collisional heating important?

- in places where radiation energy density is very low, (e.g. cores of molecular clouds)
- in places where thermal pressure is very high (e.g. hot plasma behind shock waves in SNe)

Dust Thermal Balance

Collisional heating in hot, dense plasmas



Temperature of an 0.1 μm graphite particle for various gas temperatures as a function of density

Dust Emission

Emissivity
[erg/s/cm^3/Hz/sr]

integral over
grain size distribution

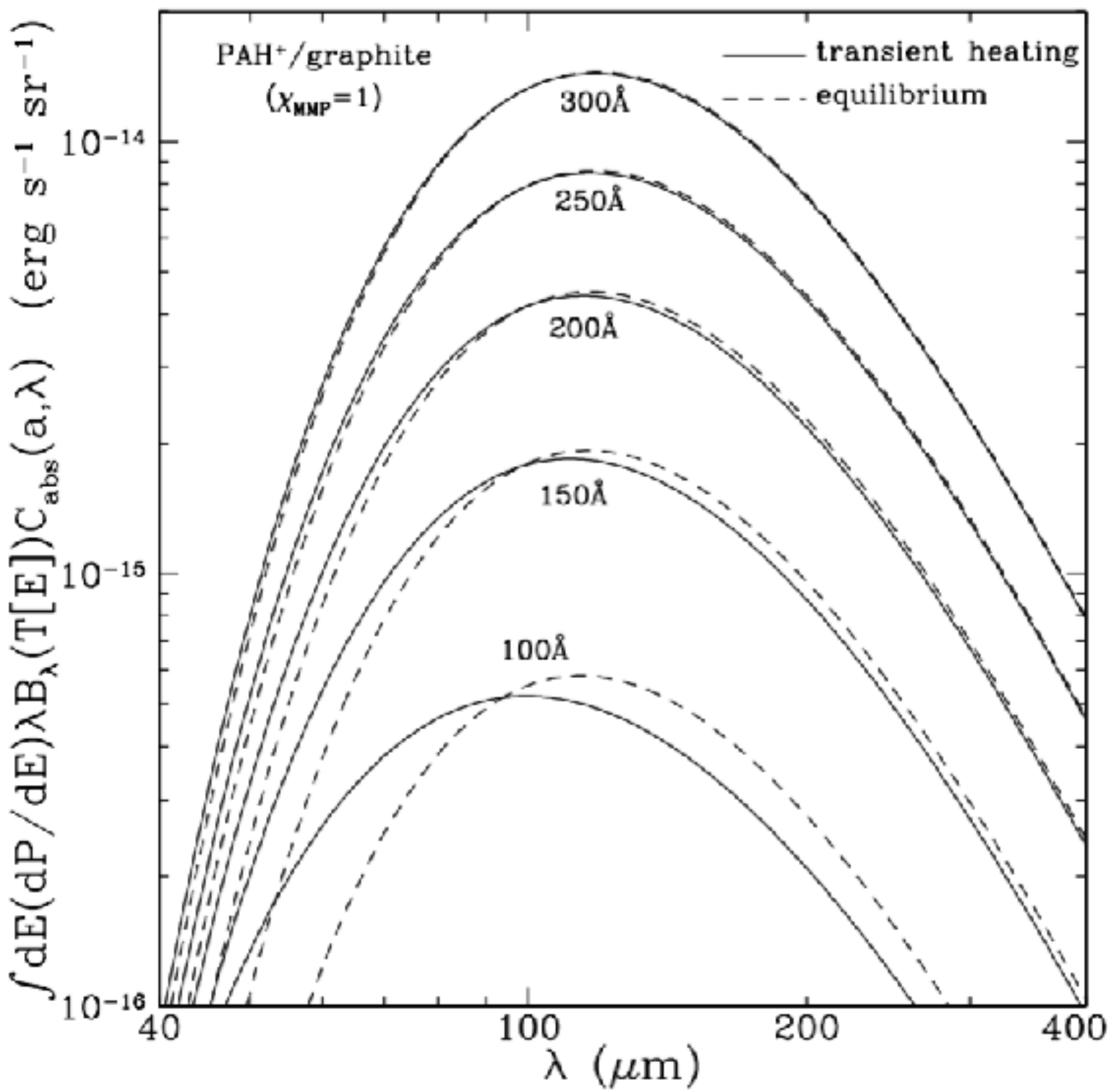
$$j_\nu = \sum_i \int da \frac{dn_i}{da} \int dT \left(\frac{dP}{dT}\right)_{i,a} Q_{\rm abs}(\nu; i, a)\ \pi a^2 B_\nu(T)$$

sum over
different grain
compositions

integral over
temperature probability
distribution function
for grain of size *a*
and composition *i*

energy/time/
solid angle/freq
emitted by a grain
of size *a* and
composition *i*

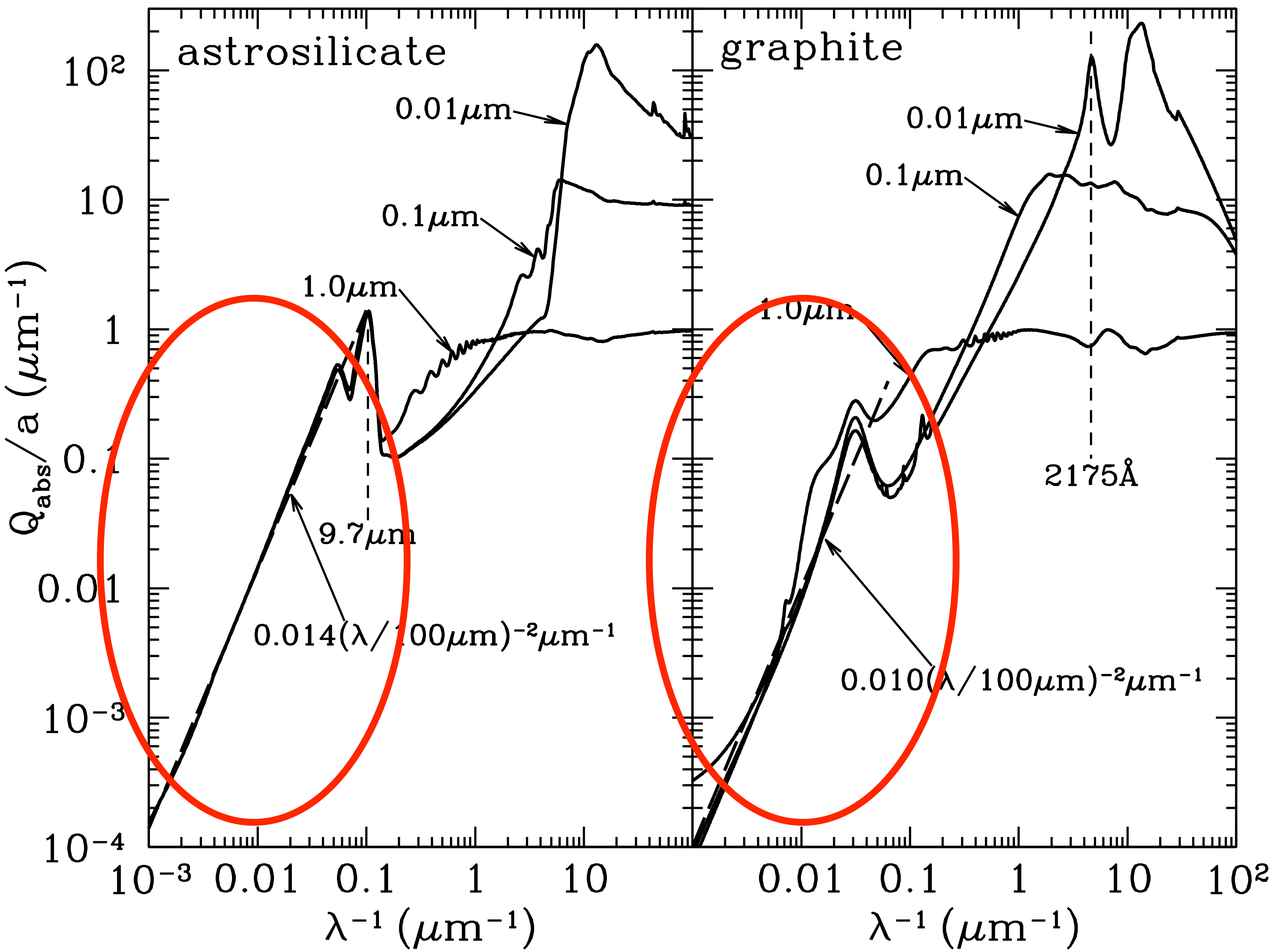
Dust Emission



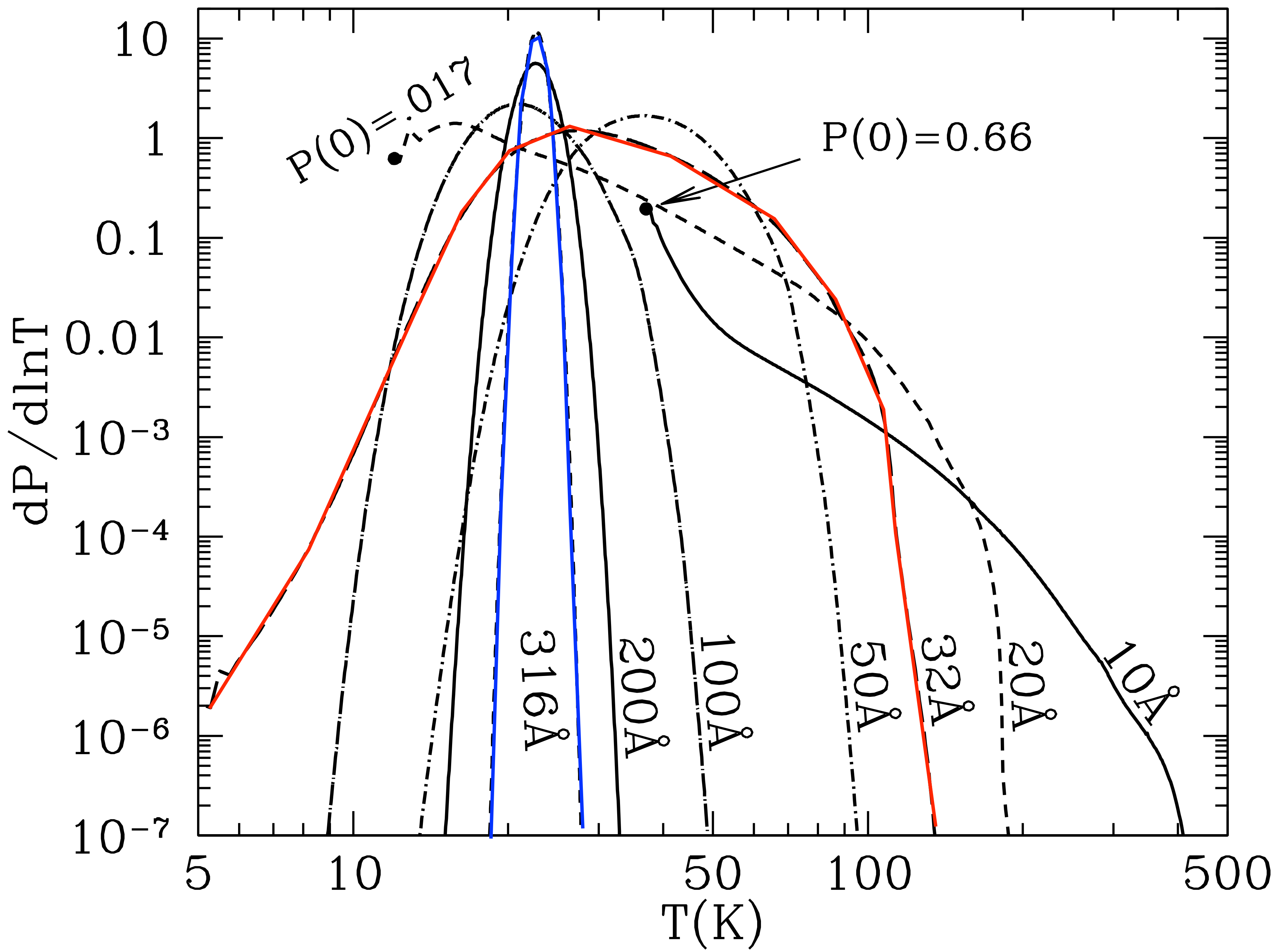
For grains that are large enough, dP/dT is ~delta function & Q_{abs} is smooth and prop to λ^{-2}.

Also T_{SS} is ~independent of grain size.

←λ



At long wavelengths $Q_{abs}/a \propto \lambda^{-2}$ i.e. $Q_{abs} \propto a\lambda^{-2}$



dP/dlnT
T(K)
10
1
0.1
0.01
10−3
10−4
10−5
10−6
10−7
5
10
50
100
500
P(0)=.017
P(0)=0.66
316Å
200Å
100Å
50Å
32Å
20Å
10Å

Dust Emission

For “equilibrium” grain emission

$$j_\nu = \sum_i \int da \frac{dn_i}{da} \int dT \left(\frac{dP}{dT}\right)_{i,a} Q_{\rm abs}(\nu; i, a)\ \pi a^2 B_\nu(T)$$

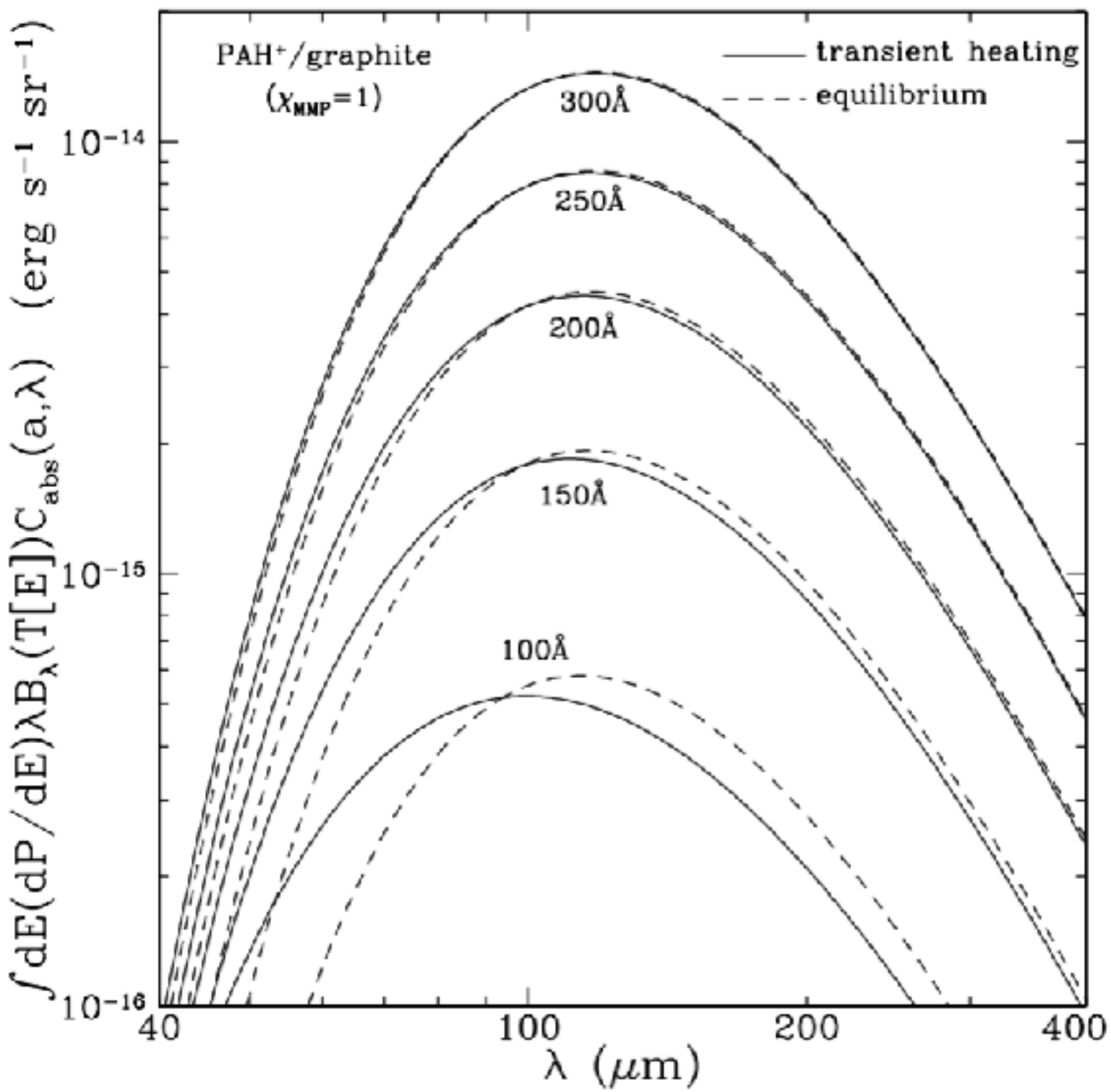
delta function at T_{SS}

$\pi a^3 Q_{abs,0} \lambda^{-2} B_\nu(T_{SS})$

can go outside integral over size distribution

End up with: $j_\nu =$ function that depends on grain pop × $B_\nu(T_{SS})$

Dust Emission



For grains that are large enough, dP/dT is ~delta function & Q_{abs} is smooth and prop to λ^{-2}.

Also T_{SS} is ~independent of grain size.

Change of units:

S_λ = surface brightness

(typical unit: MJy/sr or Jy/arsec^2)

"Modified Blackbody"

Only works for equilibrium emission!

$$\kappa_\lambda = \frac{\kappa^{S}_{\mathrm{eff},160}}{160^{-\beta_{\mathrm{eff}}}}\lambda^{-\beta_{\mathrm{eff}}}$$

from Gordon et al. 2014

In general, the surface brightness of dust with temperature, T_d, is

$$S_\lambda = \tau_\lambda B_\lambda(T_d) \quad (1)$$

$$= N_d \pi a^2 Q_\lambda B_\lambda(T_d) \quad (2)$$

$$= \frac{\Sigma_d}{m_d}\pi a^2 Q_\lambda B_\lambda(T_d) \quad (3)$$

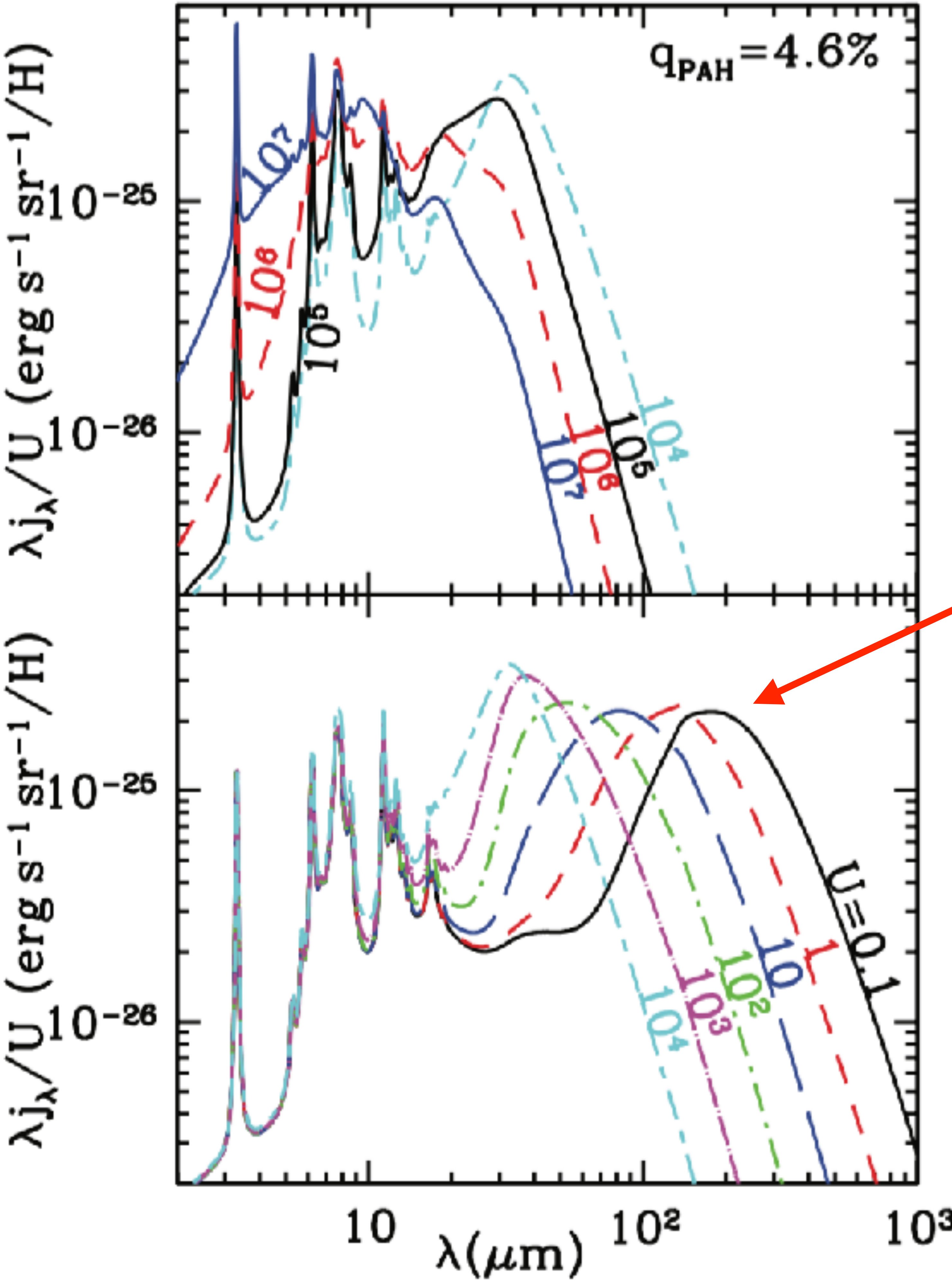
$$= \frac{\Sigma_d}{\frac{4}{3}a^3\rho}\pi a^2 Q_\lambda B_\lambda(T_d) \quad (4)$$

$$= \frac{3}{4a\rho}\Sigma_d Q_\lambda B_\lambda(T_d) \quad (5)$$

$$= \kappa_\lambda \Sigma_d B_\lambda, \quad (6)$$

where τ_λ is the dust optical depth, N_d is the dust column density, a is the grain radius, Q_λ is the dust emissivity, B_λ is the Planck function, Σ_d is the dust surface mass density, m_d is the mass of a single dust grain, ρ is the grain density, κ_λ is the grain absorption cross section per unit mass. These equations can be evaluated in standards units (e.g., cgs or MKS). We found it convenient to express Σ_d in $M_\odot$ pc^{-2}, κ_λ in cm^2 g^{-1}, and B_λ and S_λ in MJy sr^{-1} and then Equation (6) is

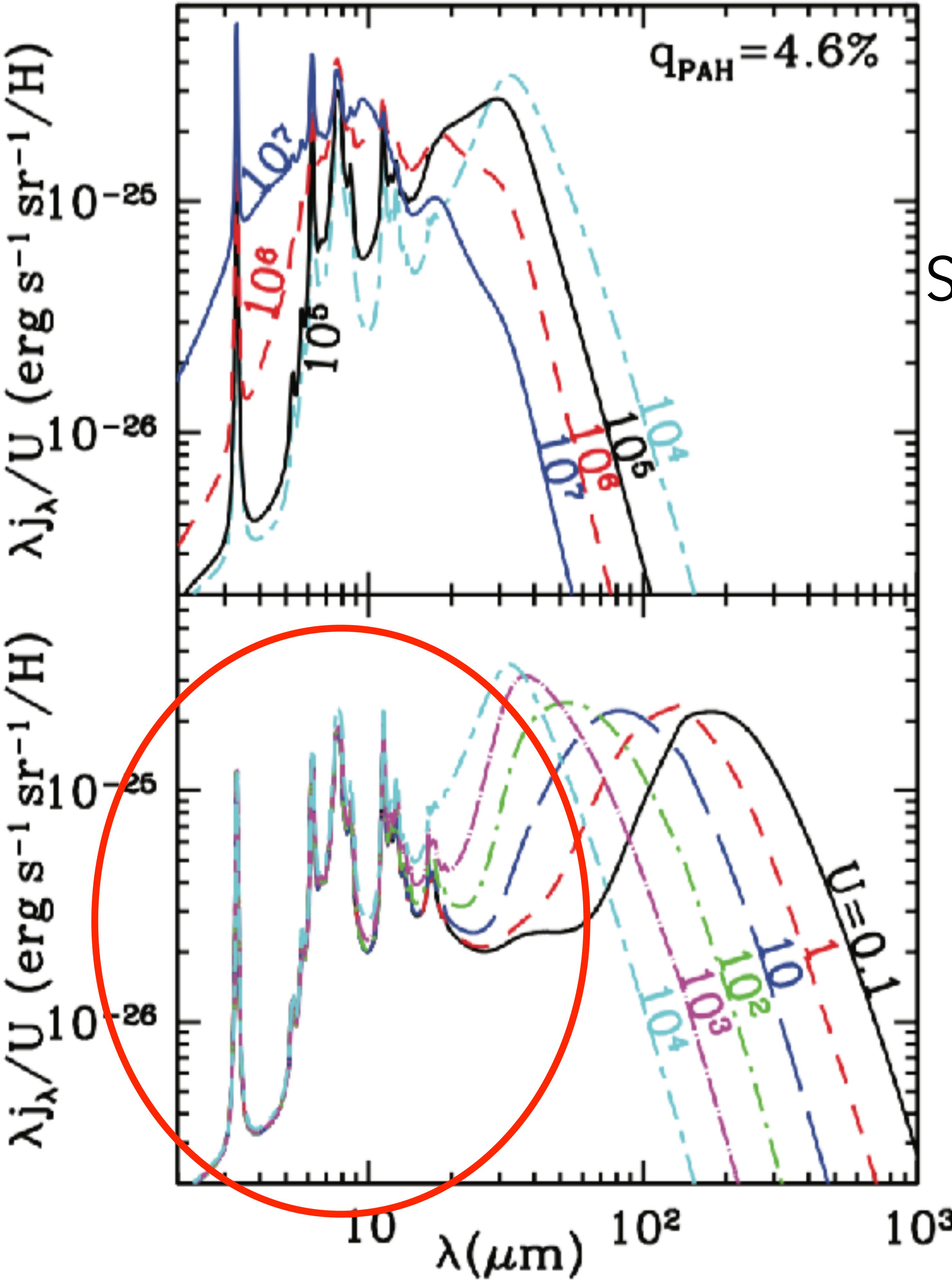
$$S_\lambda = (2.0891 \times 10^{-4})\kappa_\lambda \Sigma_d B_\lambda. \quad (7)$$



Draine & Li 2007 dust model

As strength of radiation field increases, $T_{d,ss}$ goes up like $U^{1/6}$.

This part of the spectrum is well-described by "modified blackbody"



Draine & Li 2007
dust model

Stochastically Heated Dust:
Intensity of radiation field doesn't change shape of spectrum and $j_\nu \propto U$

why:

- temp of small grains depends on average photon energy which isn't changing here (i.e. dP/dT doesn't depend on U)
- grains cool completely between photon absorptions

Photoelectric Heating

Almost all photons absorbed by dust go to heating the grain, but a small fraction go to:

Luminescence = radiative transition in grain

(fluorescence - prompt, phosphorescence - delayed)

Photoelectric Effect = ejecting electron from grain

Photoelectric Heating

$$\left(\frac{dN}{dt}\right)_{\rm pe} = \int d\nu \frac{u_\nu c}{h\nu} \pi a^2 Q_{\rm abs} \, Y_{\rm pe}$$

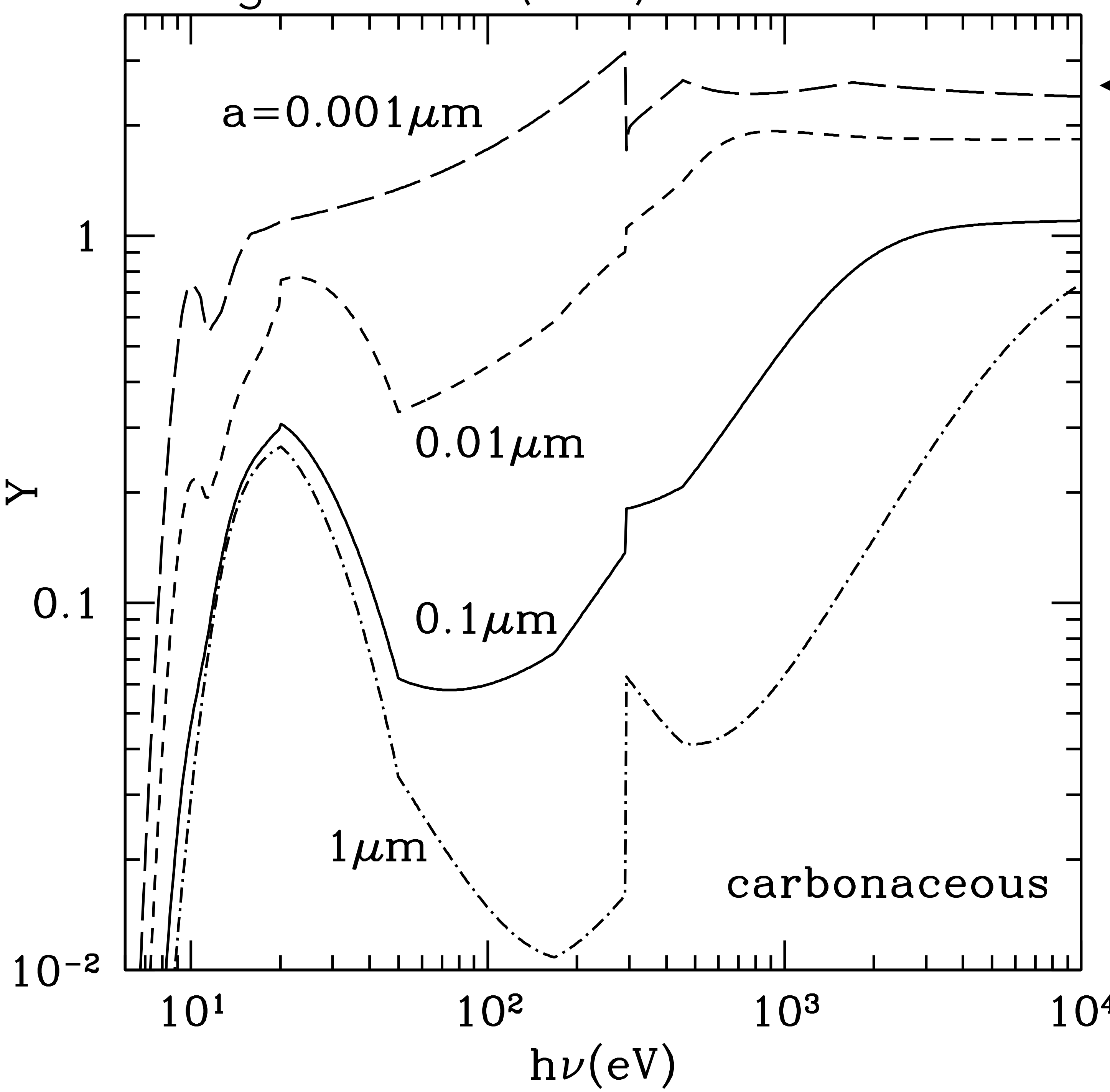
nvσ

rate at which photoelectrons are ejected

Y_{PE} (hν,a,Φ)
function of photon energy, grain size, composition, *grain charge*

Photoelectric Heating

Weingartner et al. (2006)



For small grains and energetic photons, more than 1 electron can be ejected.

PE yield for uncharged carbonaceous grains of various sizes for different absorbed photon energies.

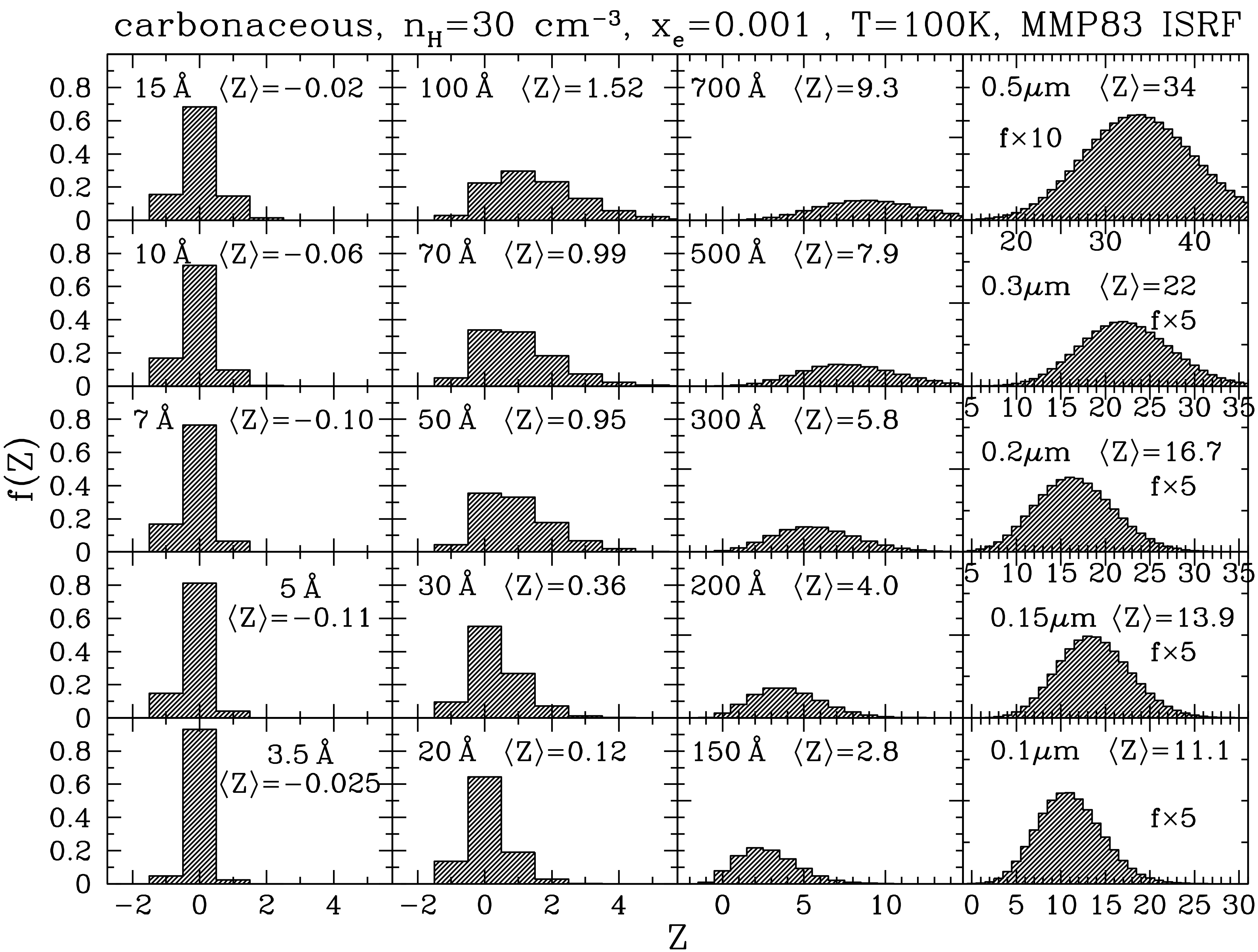
Photoelectric Heating

Grains are charged in the ISM!

Competition between:

collisions & sticking of electrons	negatively charges grain	depends on: electron density, temperature, grain size, charge, "sticking" coeff
&		
photoelectric ejection of electrons	positively charges grain	depends on: photon density, grain size, charge, PE yield

Grain Charge



What is dust made of?

Dust Composition

- Spectroscopic features in absorption
- Spectroscopic features in emission
- Depletions of heavy elements from the gas

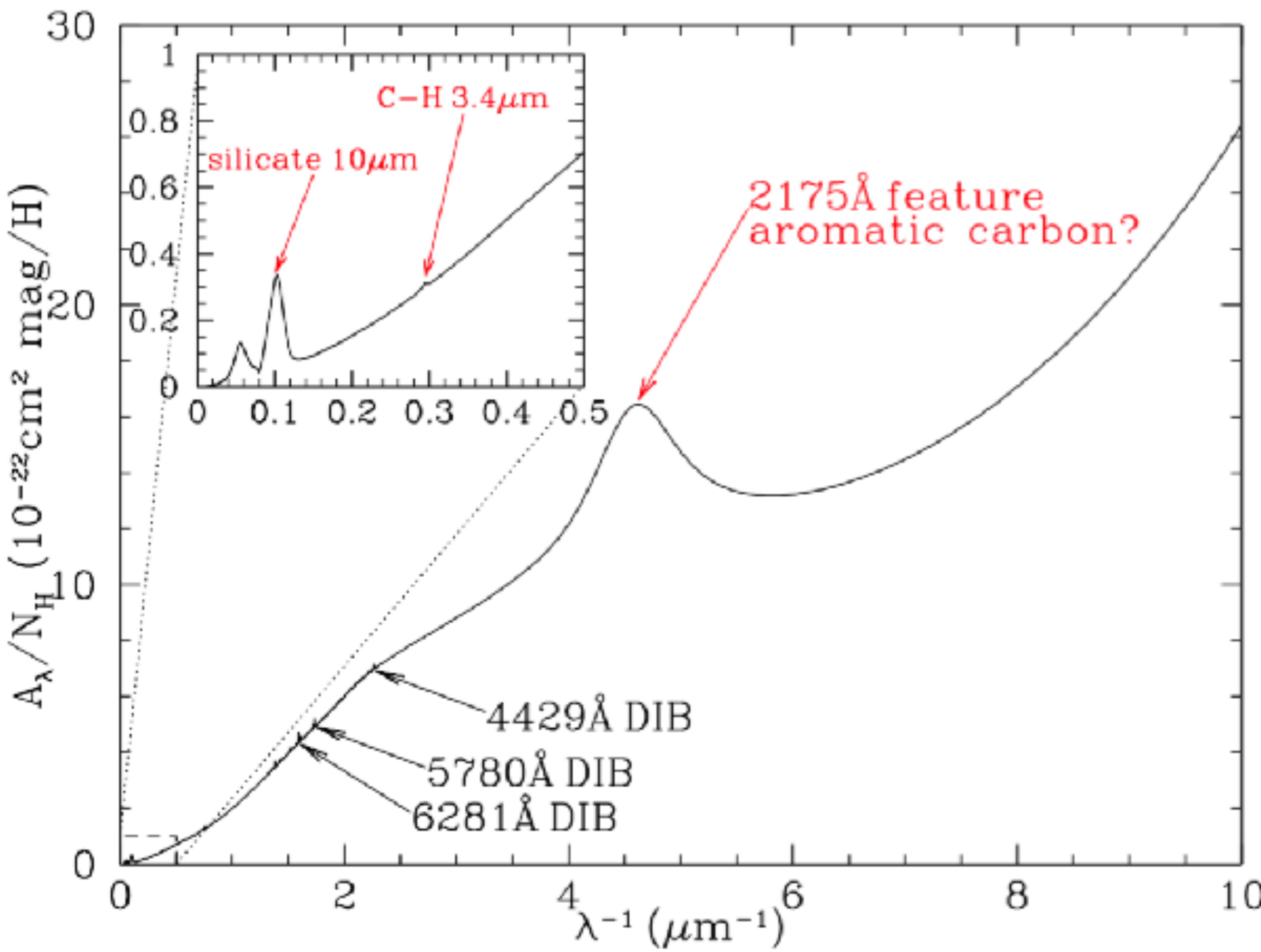
Dust Composition

The problem with spectroscopic features:

for macroscopic particles:
absorption & emission is mostly continuous and any features there are broad

Dust Composition

Spectroscopic features in absorption

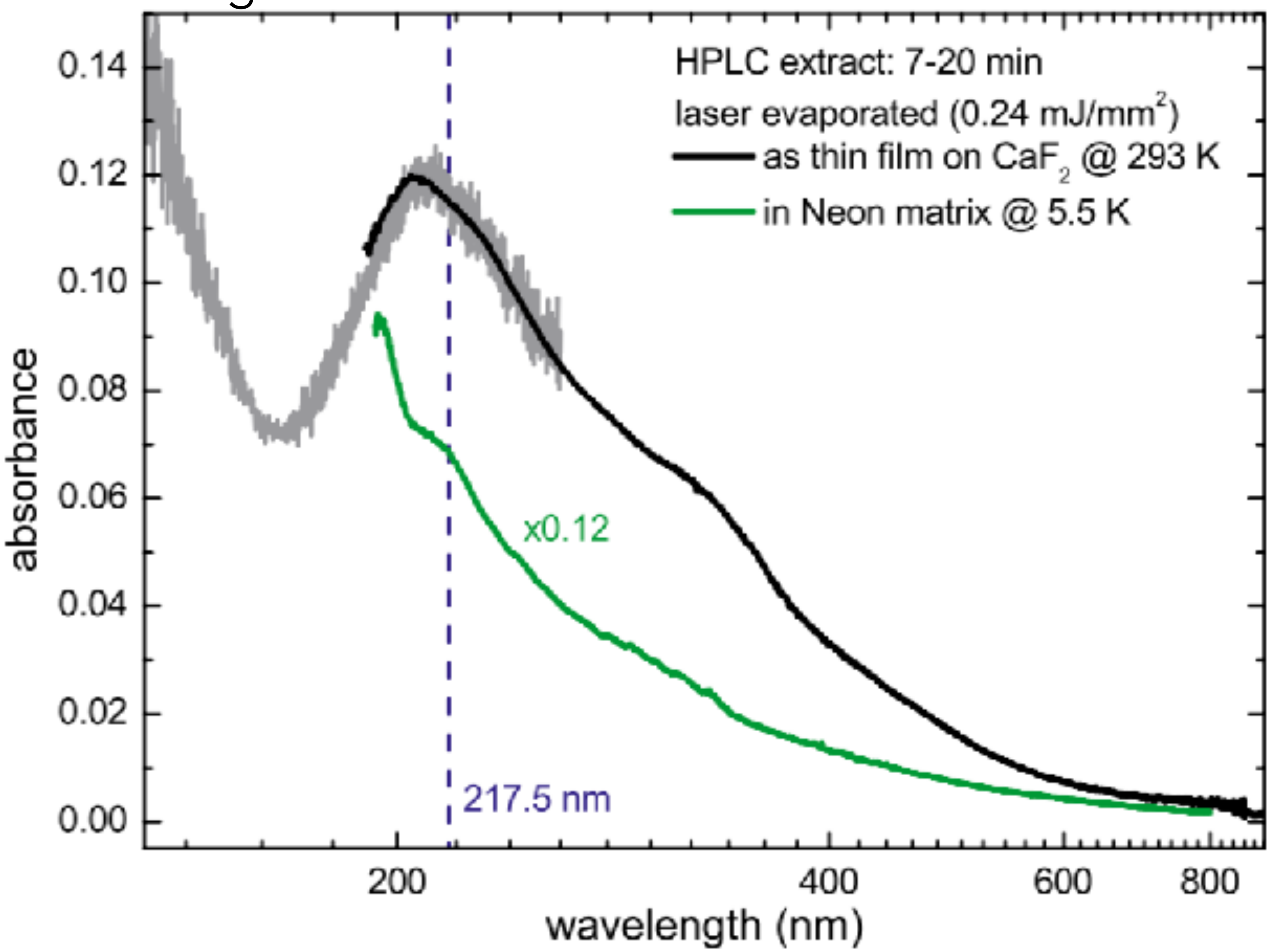


2175 Å bump:

- strong
- central λ fixed
- width varies a bit
- widespread in the MW
- rare at low metallicity!

Dust Composition

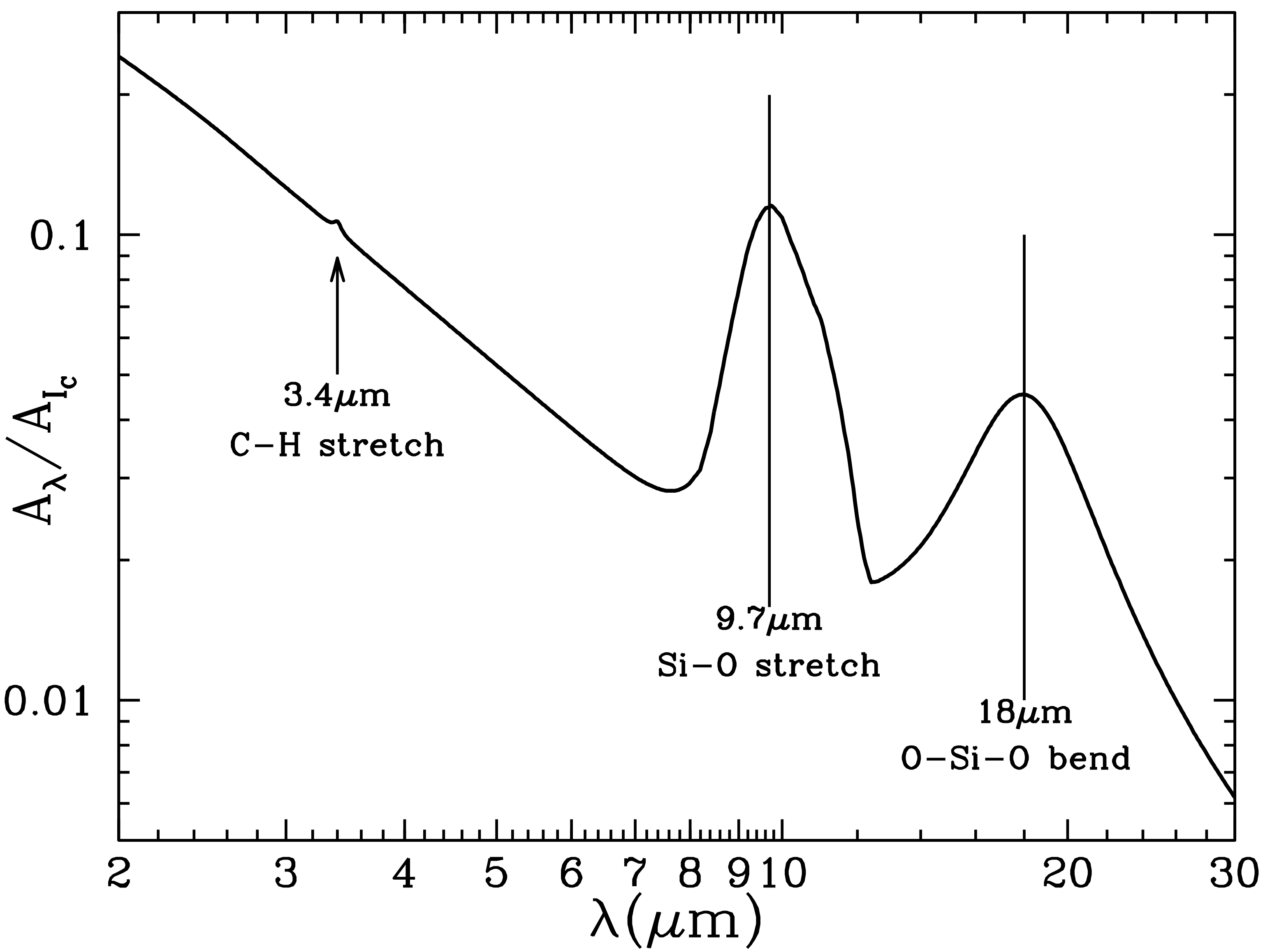
Steglich et al. 2010



Mixtures of PAHs in the lab can reproduce similar shapes, from a transition in C-C bonds.

Dust Composition

Spectroscopic features in absorption

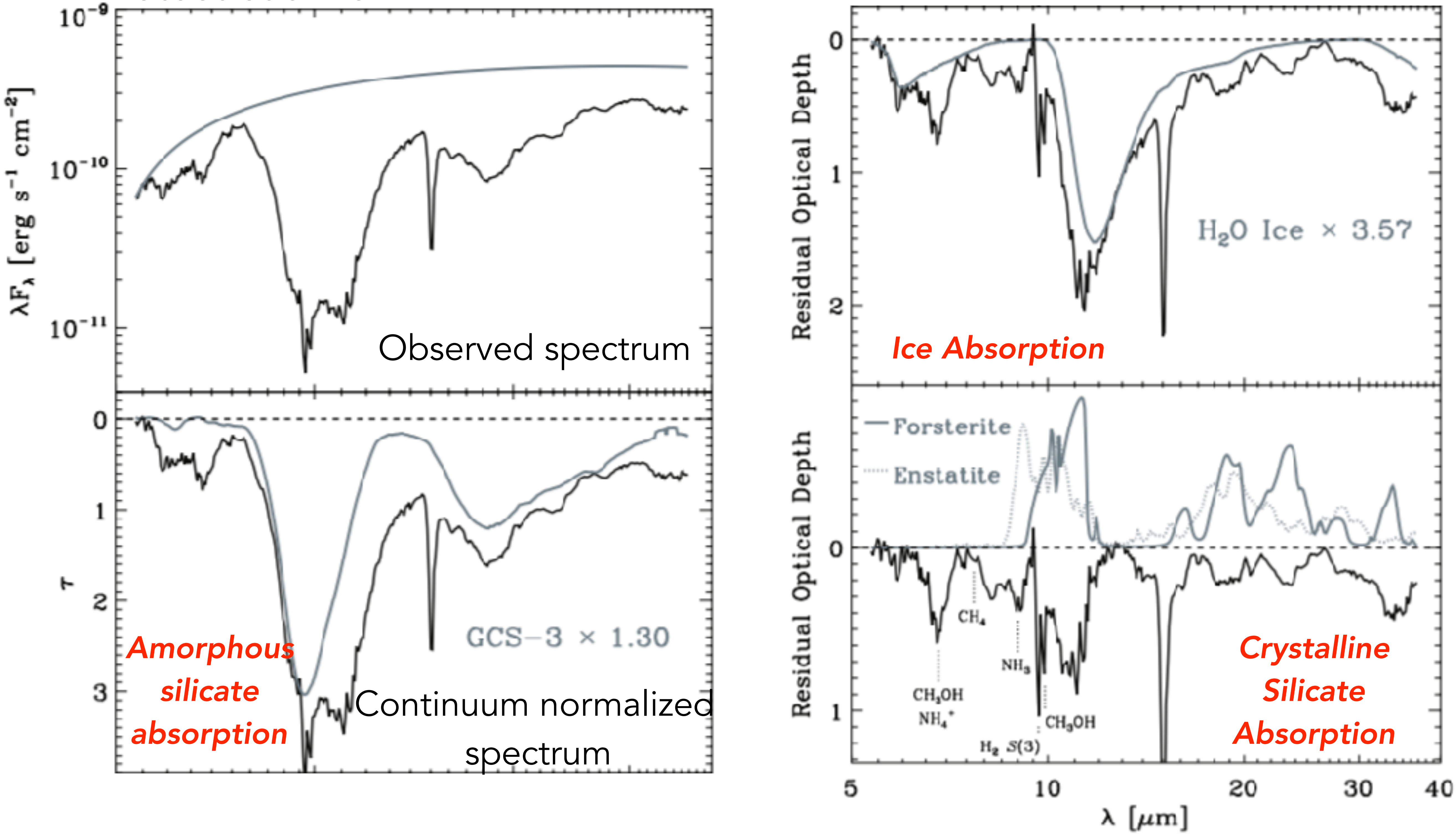


Silicate bending/ stretching modes at 9.7 and 18 μm.

Smooth profile = amorphous silicate

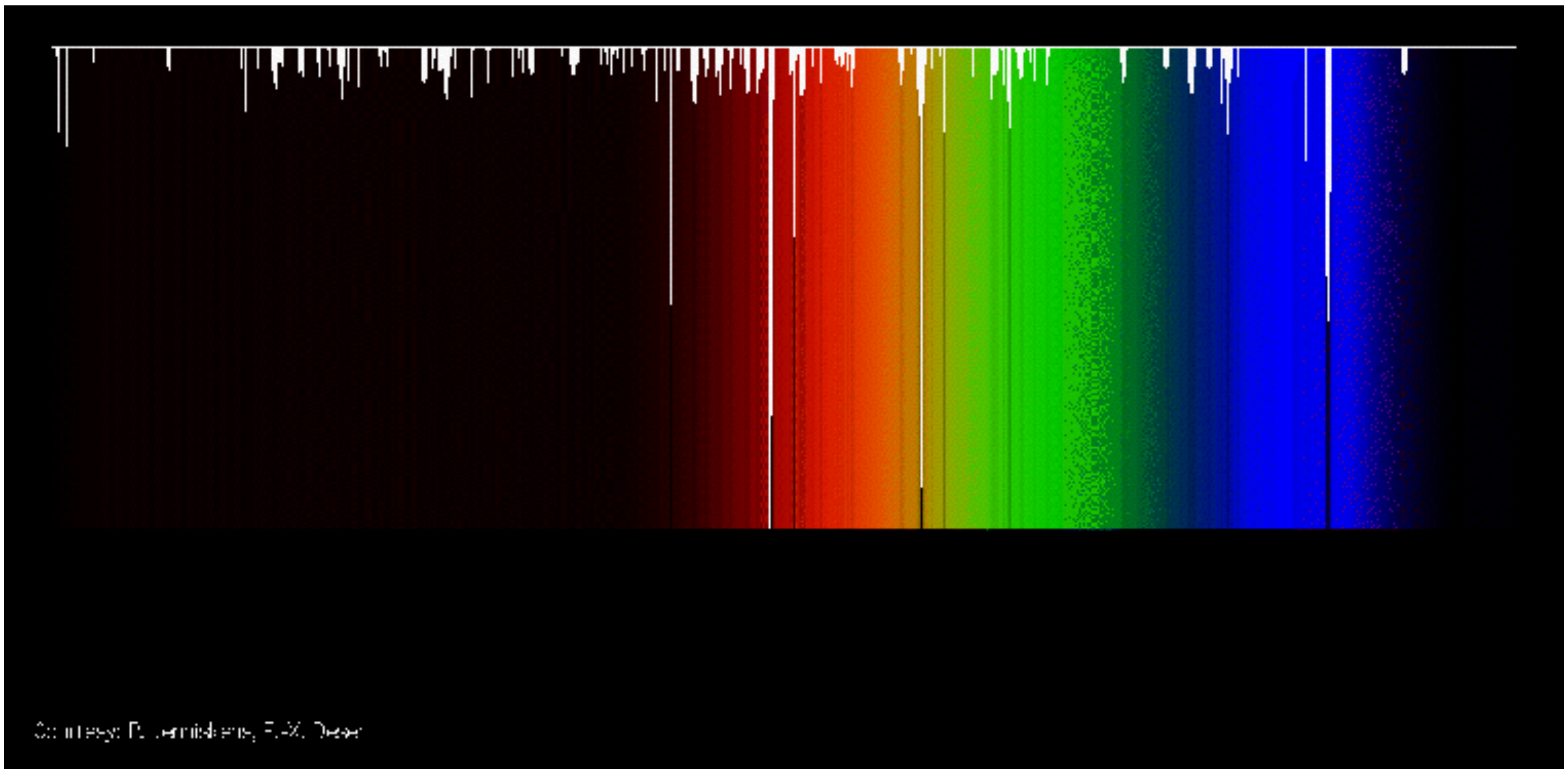
Silicate Absorption in a protostar in Orion

Poteet et al 2011



Dust Composition

Spectroscopic features in absorption



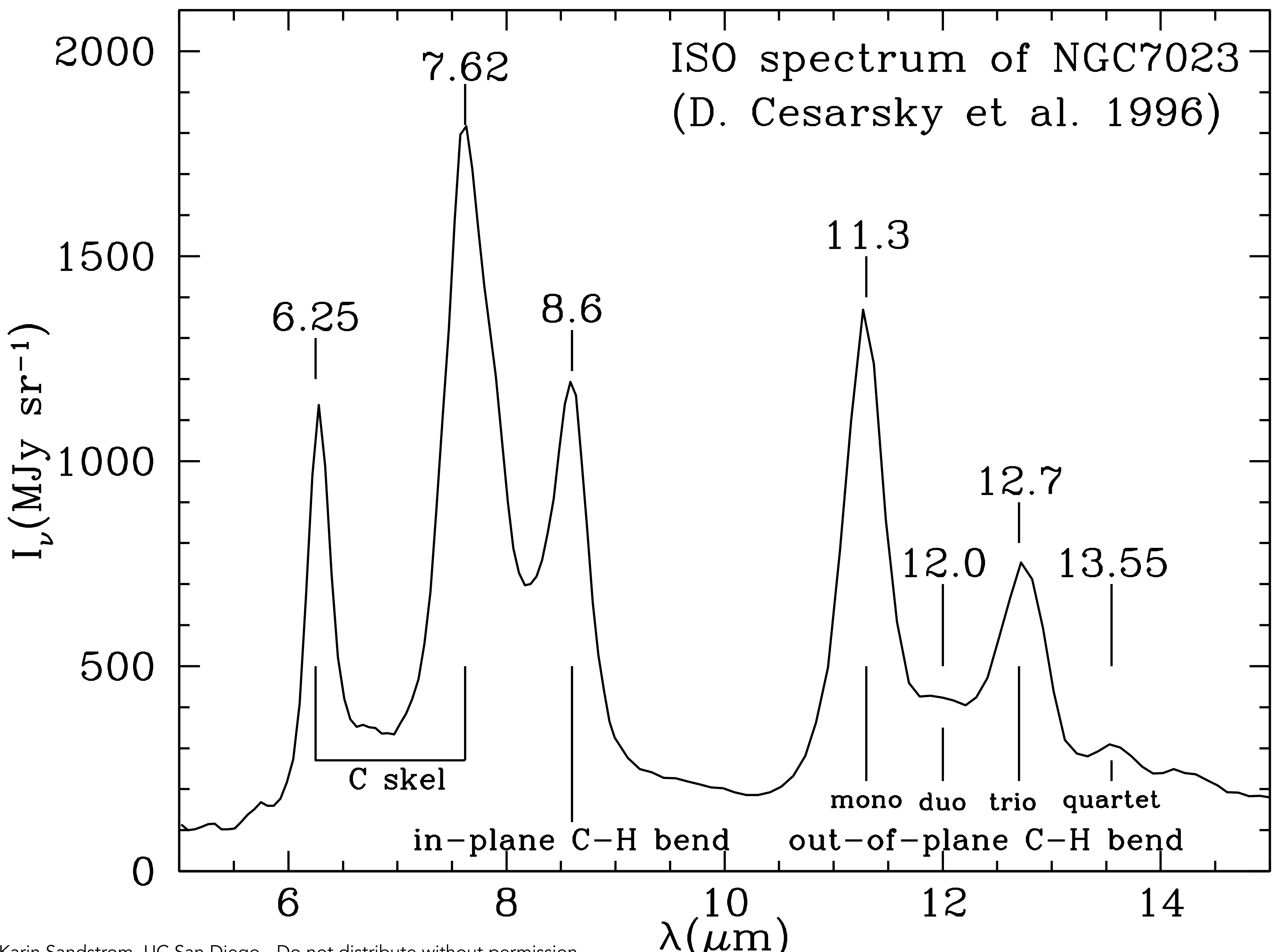
Two bands identified with C_{60}^{+}

Campbell et al. 2015

> 400 near-IR to near-UV absorption features
Discovered in 1922, vast majority unidentified.

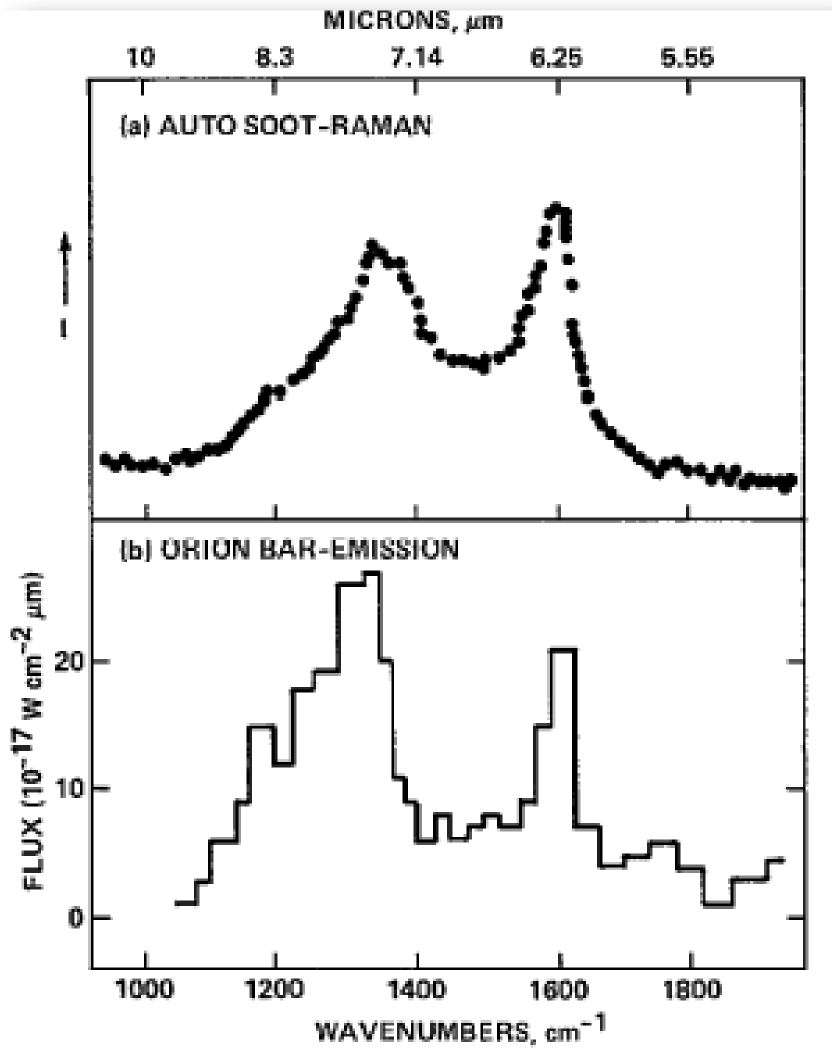
Dust Composition

Spectroscopic features in emission



Polycyclic Aromatic Hydrocarbons
(probably)

Dust Composition



POLYCYCLIC AROMATIC HYDROCARBONS AND THE UNIDENTIFIED INFRARED EMISSION BANDS: AUTO EXHAUST ALONG THE MILKY WAY!

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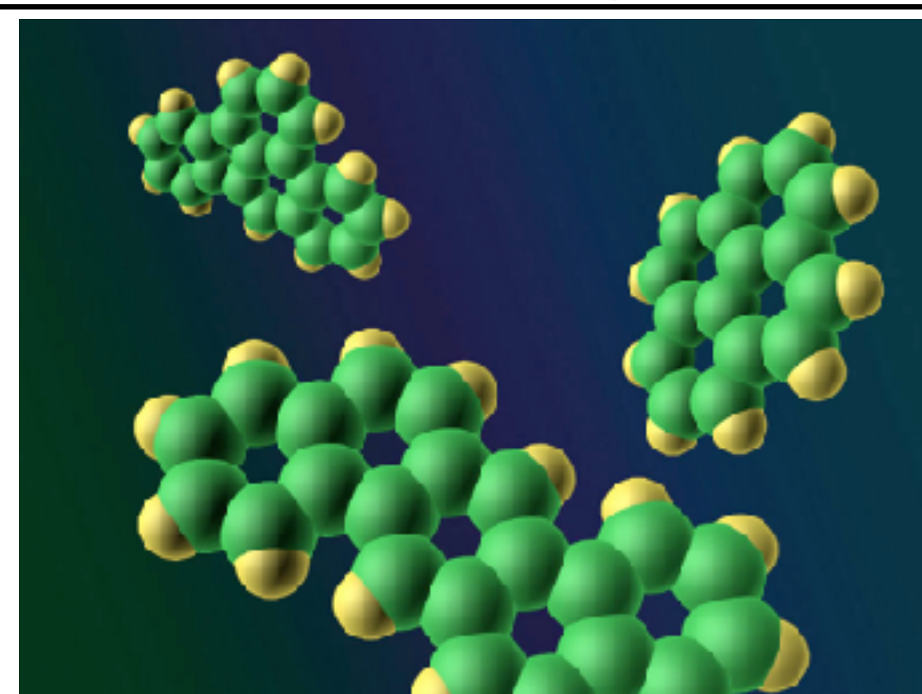
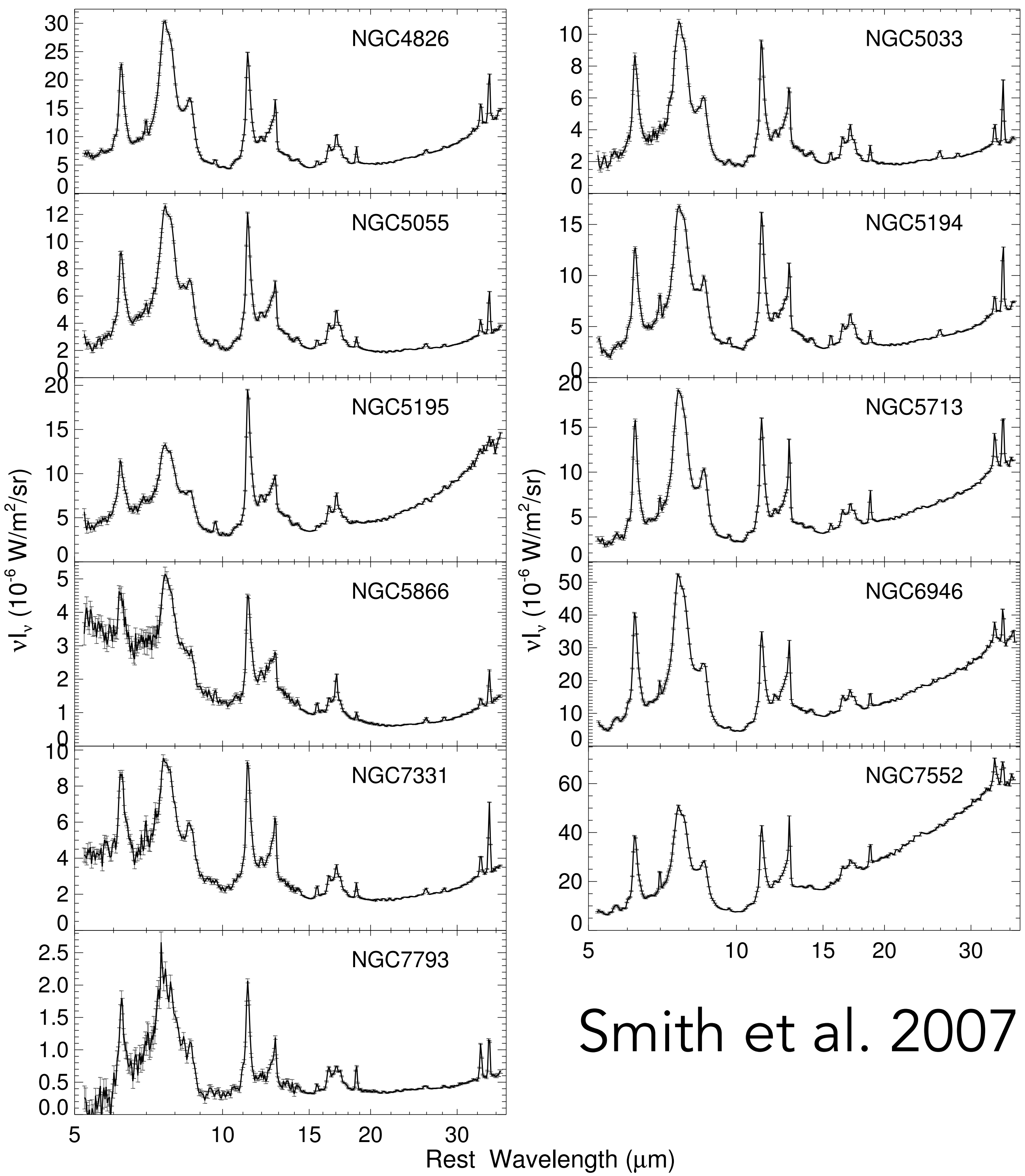
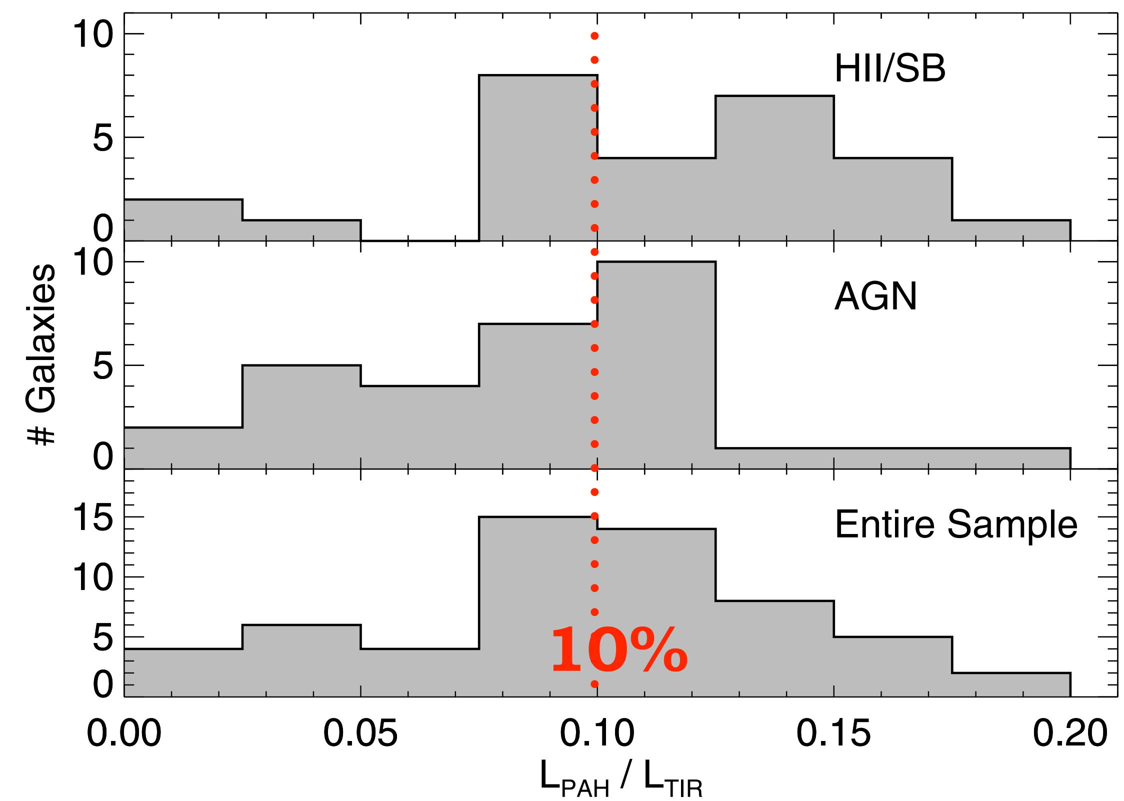


Dust Composition

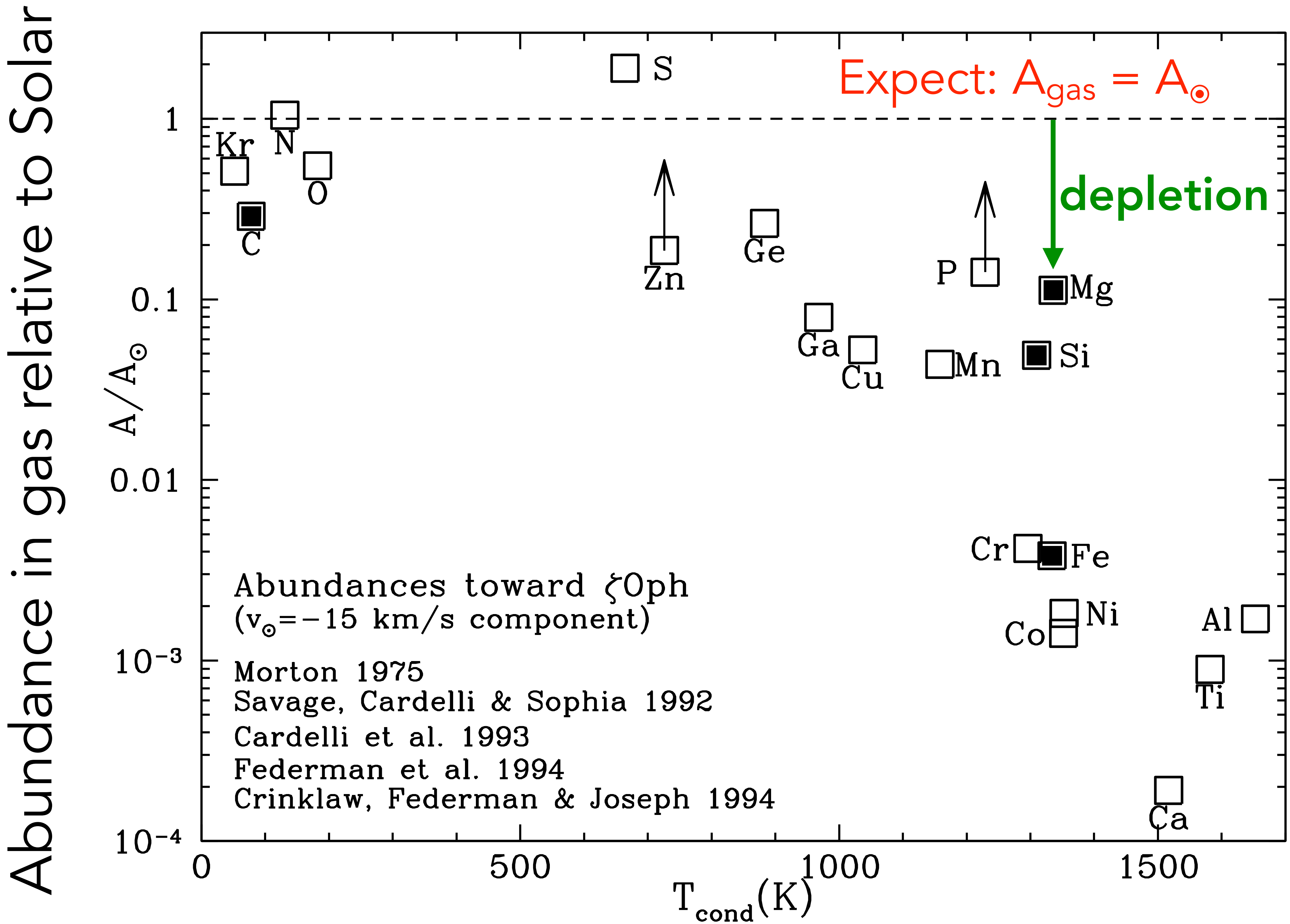


Smith et al. 2007



PAHs radiate ~10% of the infrared emission from ~solar metallicity galaxies.

Depletions



Abundance in gas relative to Solar
Expect: $A_{gas} = A_\odot$
depletion
$A/A_\odot$
1
0.1
0.01
10^{-3}
10^{-4}
0
500
1000
1500
T_{cond}(K)
S
Kr
N
O
C
Zn
Ge
P
Mg
Ga
Cu
Mn
Si
Cr
Fe
Ni
Co
Al
Ti
Ca
Abundances toward ζOph
($v_\odot$=−15 km/s component)
Morton 1975
Savage, Cardelli & Sophia 1992
Cardelli et al. 1993
Federman et al. 1994
Crinklaw, Federman & Joseph 1994

Depletions

The Astrophysical Journal, 700:1299–1348, 2009 August 1 doi:10.1088/0004-637X/700/2/1299

A UNIFIED REPRESENTATION OF GAS-PHASE ELEMENT DEPLETIONS IN THE INTERSTELLAR MEDIUM*

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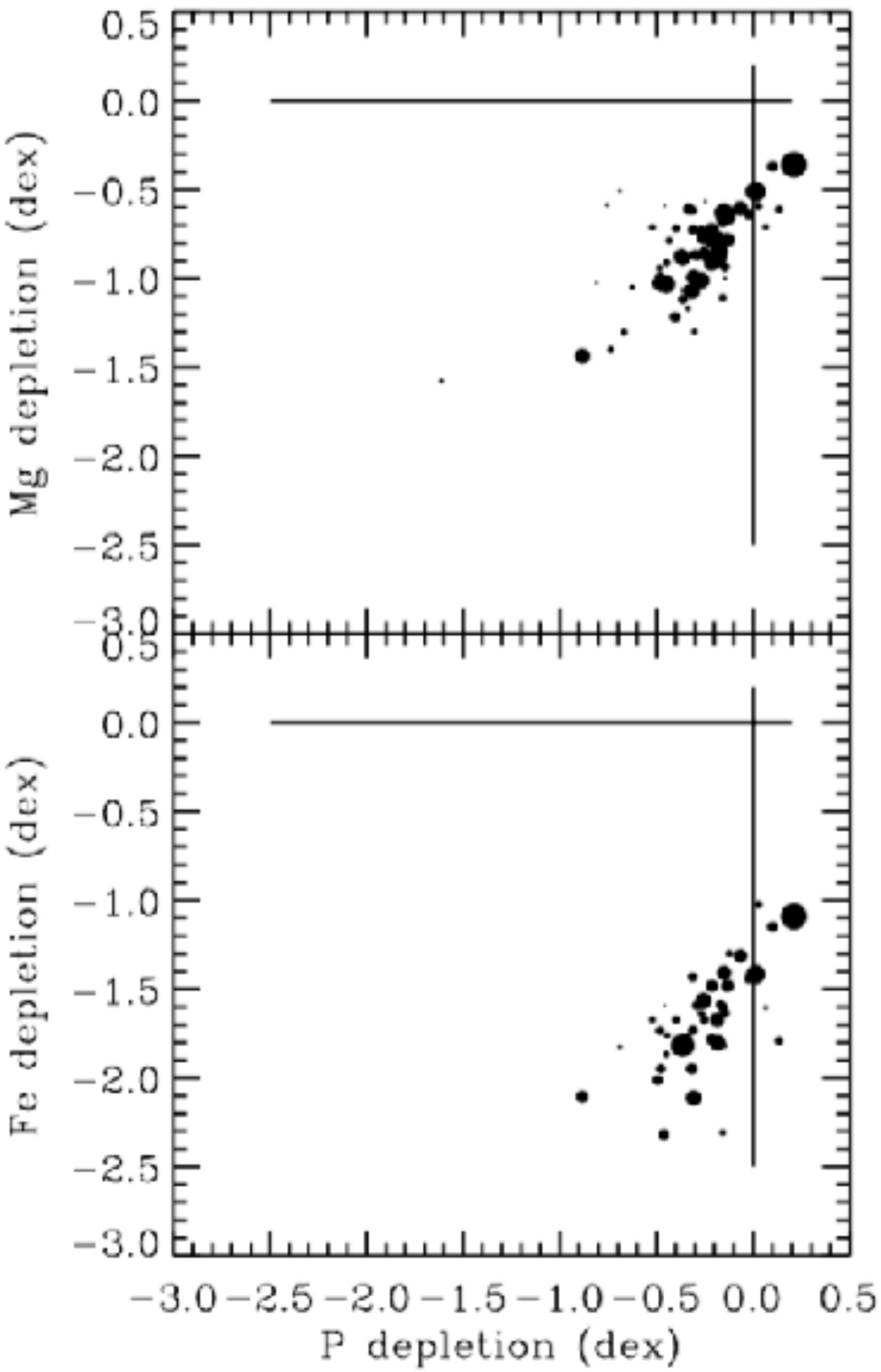
ABSTRACT

A study of gas-phase element abundances reported in the literature for 17 different elements sampled over 243 sight lines in the local part of our Galaxy reveals that the depletions into solid form (dust grains) are extremely well characterized by trends that employ only three kinds of parameters. One is an index that describes the overall level of depletion applicable to the gas in any particular sight line, and the other two represent linear coefficients that describe how to derive each element's depletion from this sight-line parameter. The information from this study reveals the relative proportions of different elements that are incorporated into dust at different stages of grain growth. An extremely simple scheme is proposed for deriving the dust contents and metallicities of absorption-line systems that are seen in the spectra of distant quasars or the optical afterglows of gamma-ray bursts. Contrary to presently accepted thinking, the elements sulfur and krypton appear to show measurable changes in their depletions as the general levels of depletions of other elements increase, although more data are needed to ascertain whether or not these findings are truly compelling. Nitrogen appears to show no such increase. The incorporation of oxygen into solid form in the densest gas regions far exceeds the amounts that can take the form of silicates or metallic oxides; this conclusion is based on differential measurements of depletion and thus is unaffected by uncertainties in the solar abundance reference scale.

Key words: ISM: abundances – ISM: atoms – ultraviolet: ISM

Online-only material: machine-readable tables

Depletions



Jenkins 2009:

compiled depletion measurements for 17 elements on ~250 lines-of-sight

Model for depletions includes:

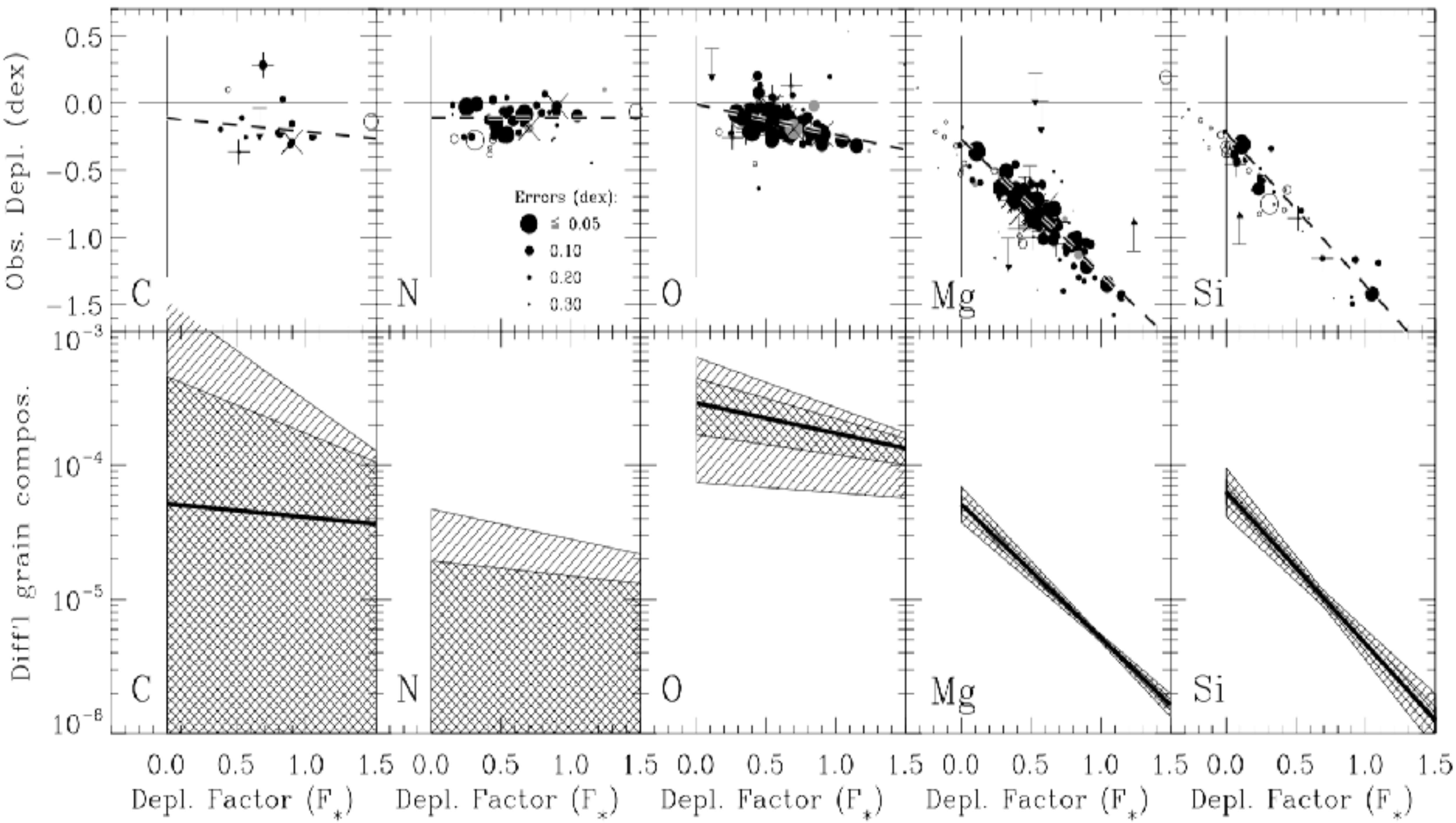
F_* = parameterization of overall depletion

$[X_{gas}/H]_0$ = “baseline” or “initial” depetion

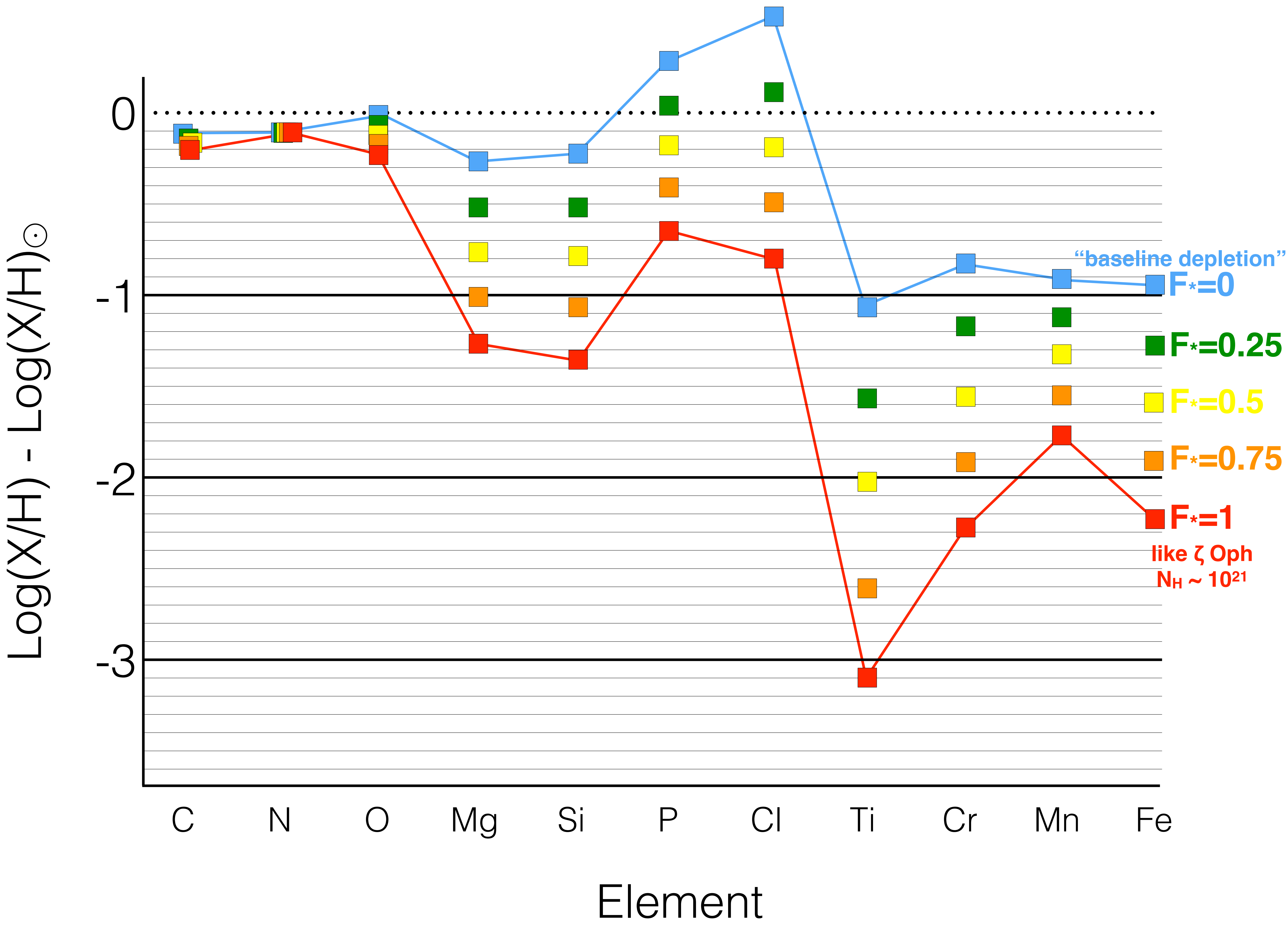
A_X = depletion rate for element X as a function of F_*

$$[X_{\text{gas}}/\text{H}]_{\text{fit}} = [X_{\text{gas}}/\text{H}]_0 + A_X F_*$$

Depletions

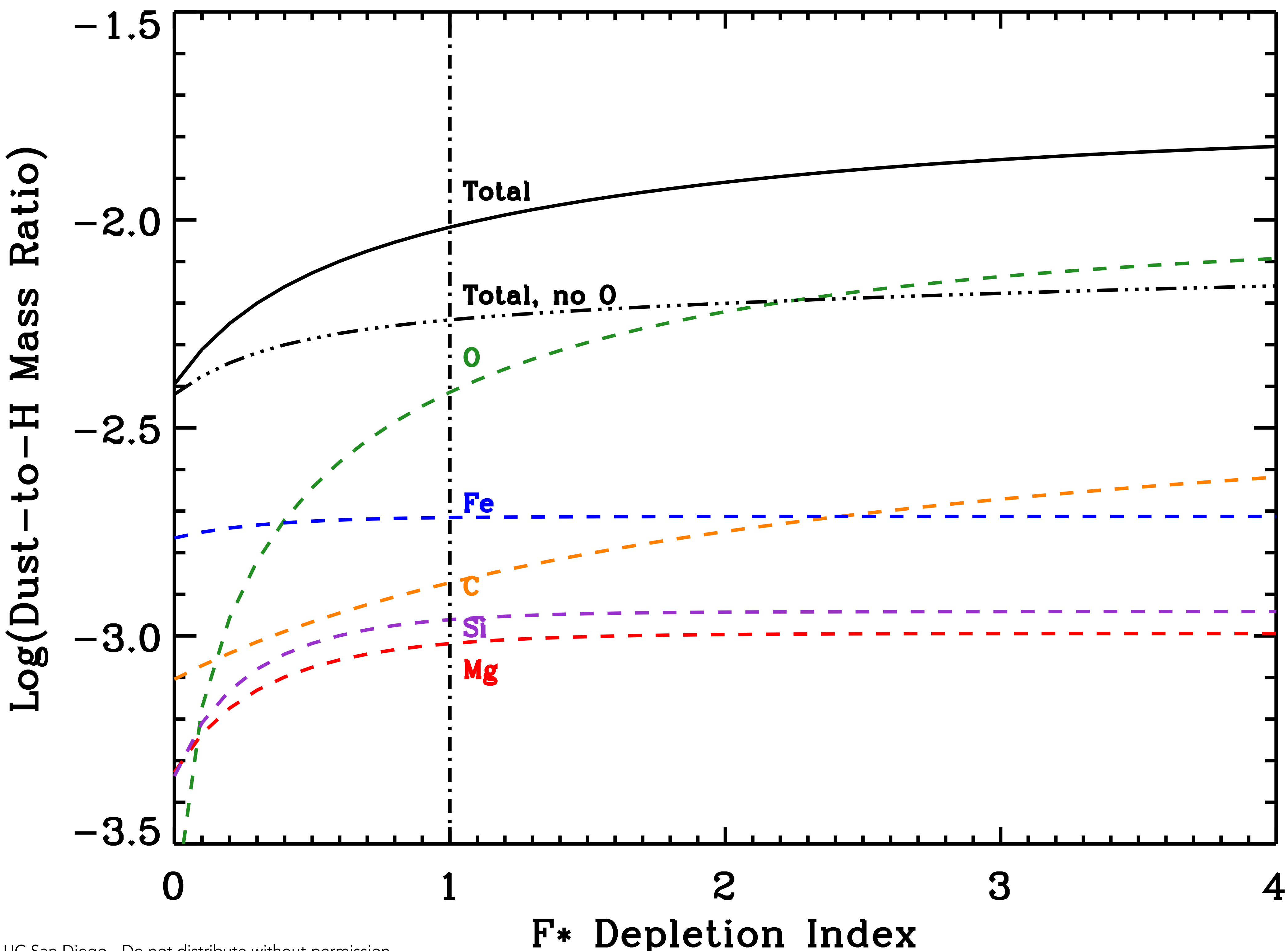


Obs. Depl. (dex)
0.5
0.0
−0.5
−1.0
−1.5
Errors (dex):
≤ 0.05
0.10
0.20
0.30
C
N
O
Mg
Si
Diff'l grain compos.
10^{-3}
10^{-4}
10^{-5}
10^{-6}
0.0 0.5 1.0 1.5
Depl. Factor (F_*)

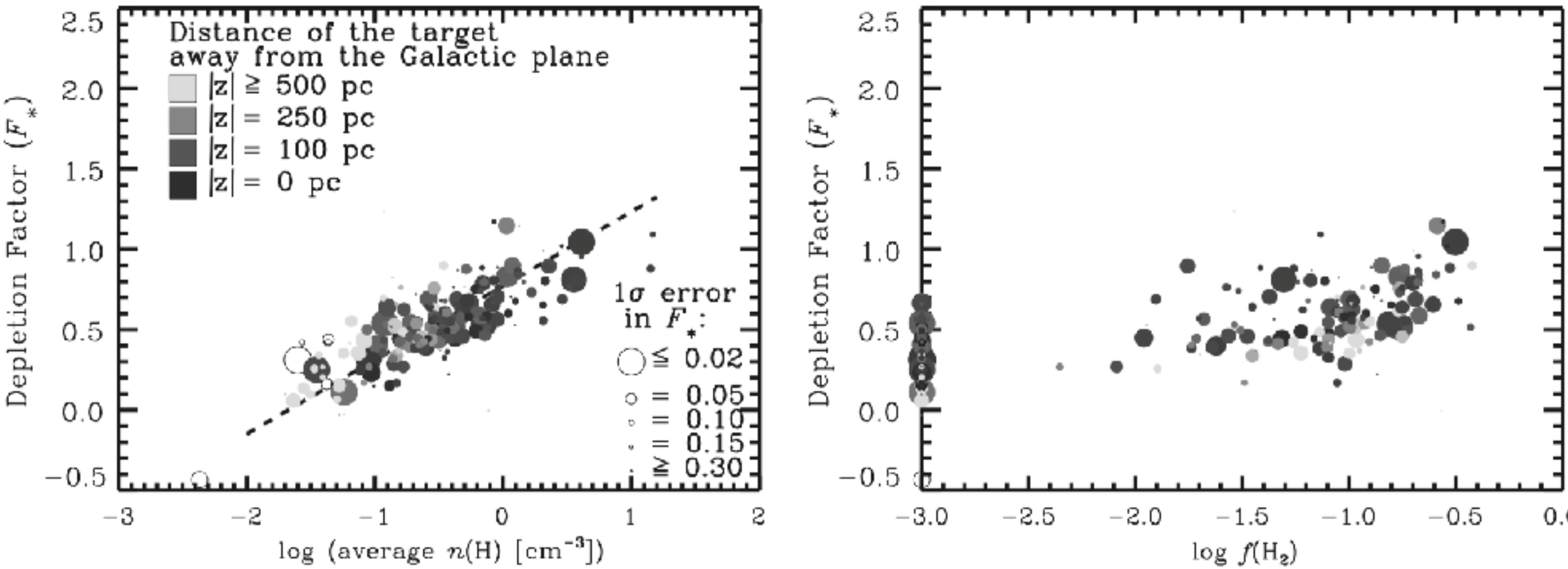


Log(X/H) - Log(X/H)⊙
0
-1
-2
-3
C
N
O
Mg
Si
P
Cl
Ti
Cr
Mn
Fe
Element
“baseline depletion”
F*=0
F*=0.25
F*=0.5
F*=0.75
F*=1
like ζ Oph
N_H ~ 10^{21}

Dust Composition



Dust Composition



The observation that F* depends on density and H_2 fraction shows us that grains evolve in the ISM.

Dust is Awesome.