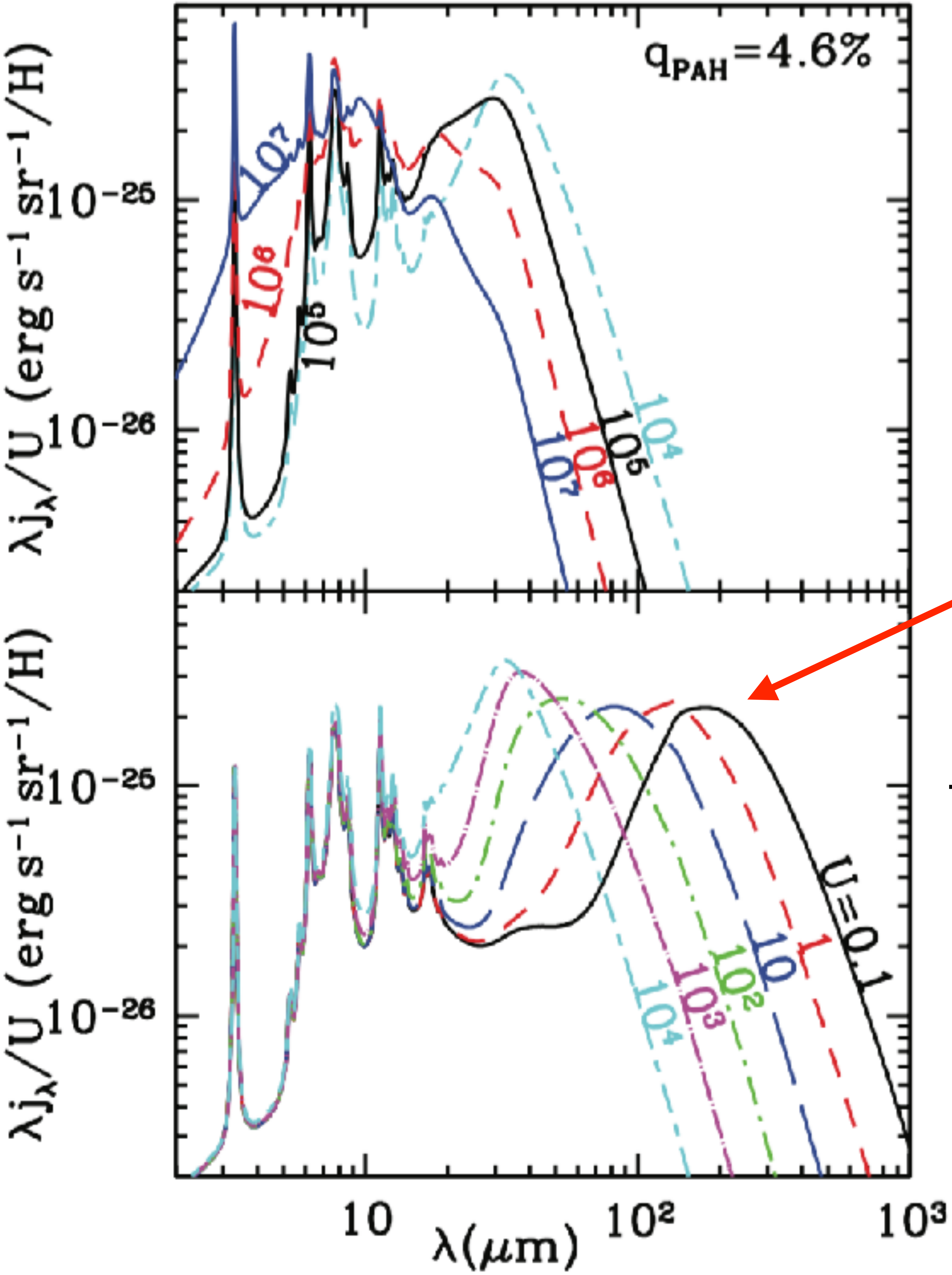
Physics 224
The Interstellar Medium

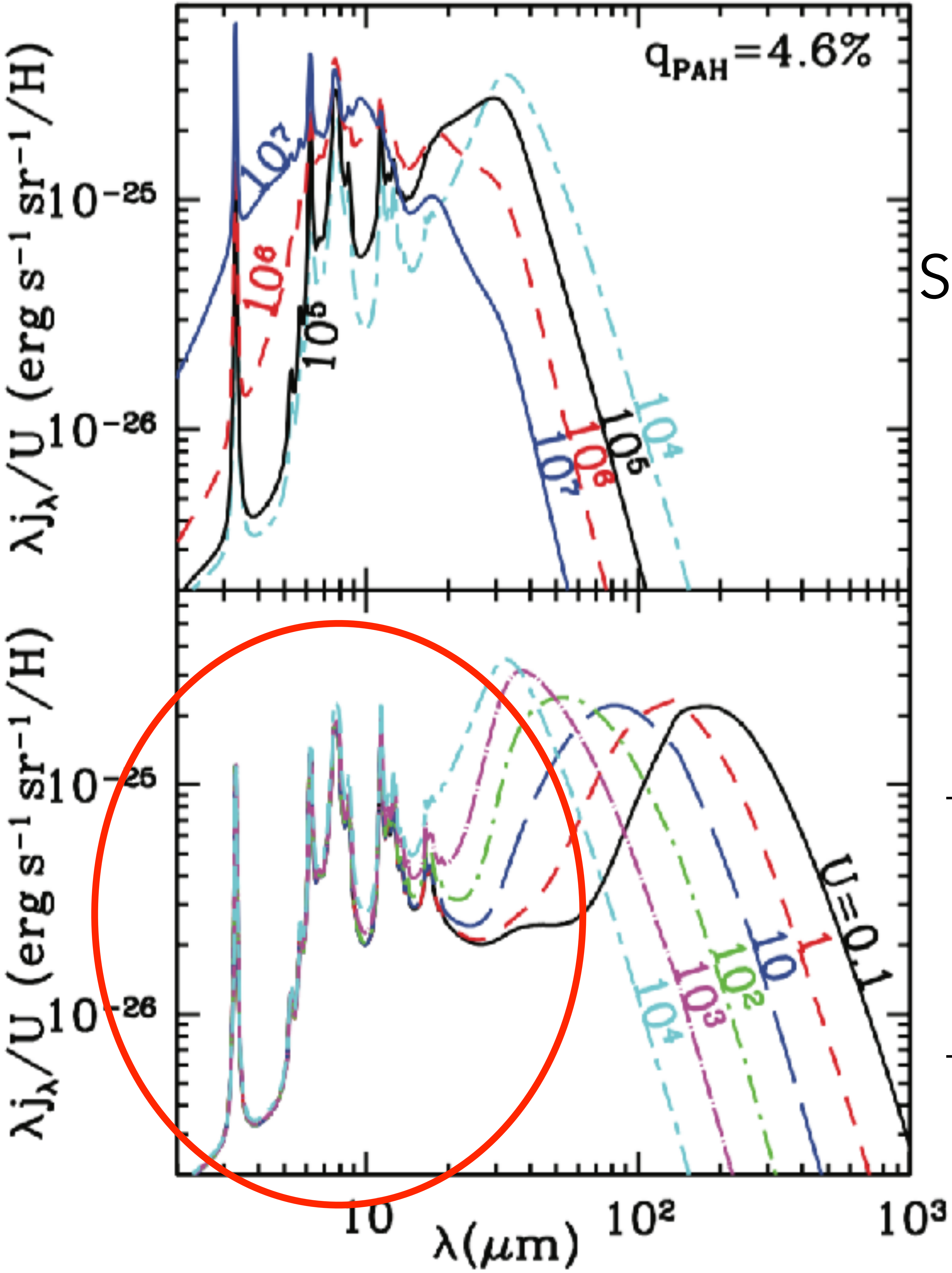
Lecture #13



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

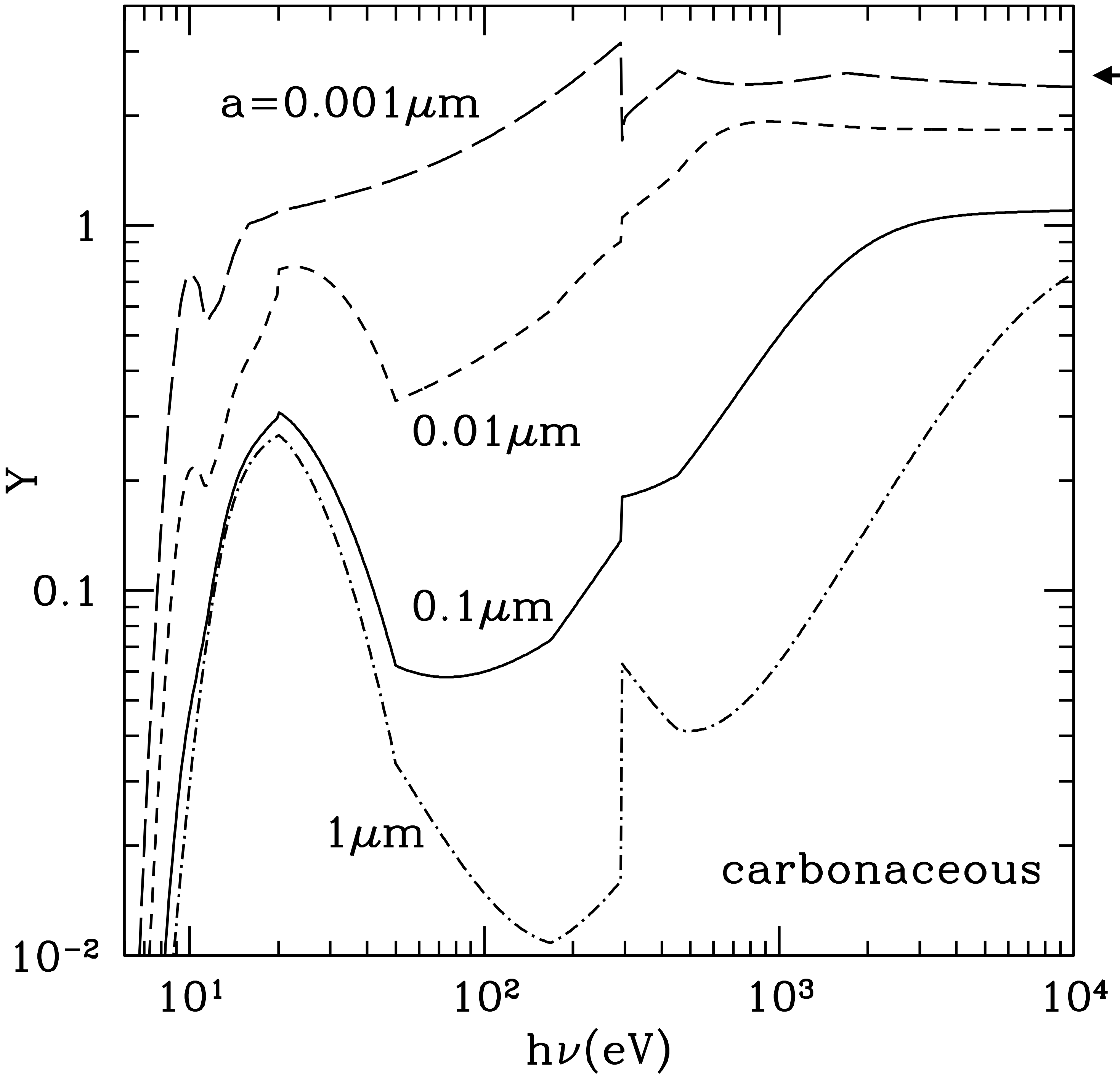
$$\boxed{\left(\frac{dN}{dt}\right)_{\mathrm{pe}}} = \int d\nu \underbrace{\frac{u_\nu c}{h\nu}\,\pi a^2 Q_{\mathrm{abs}}}_{n v \sigma}\; Y_{\mathrm{pe}}$$

rate at which
photoelectrons are
ejected

$Y_{PE}\,(h\nu, a, \Phi)$
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

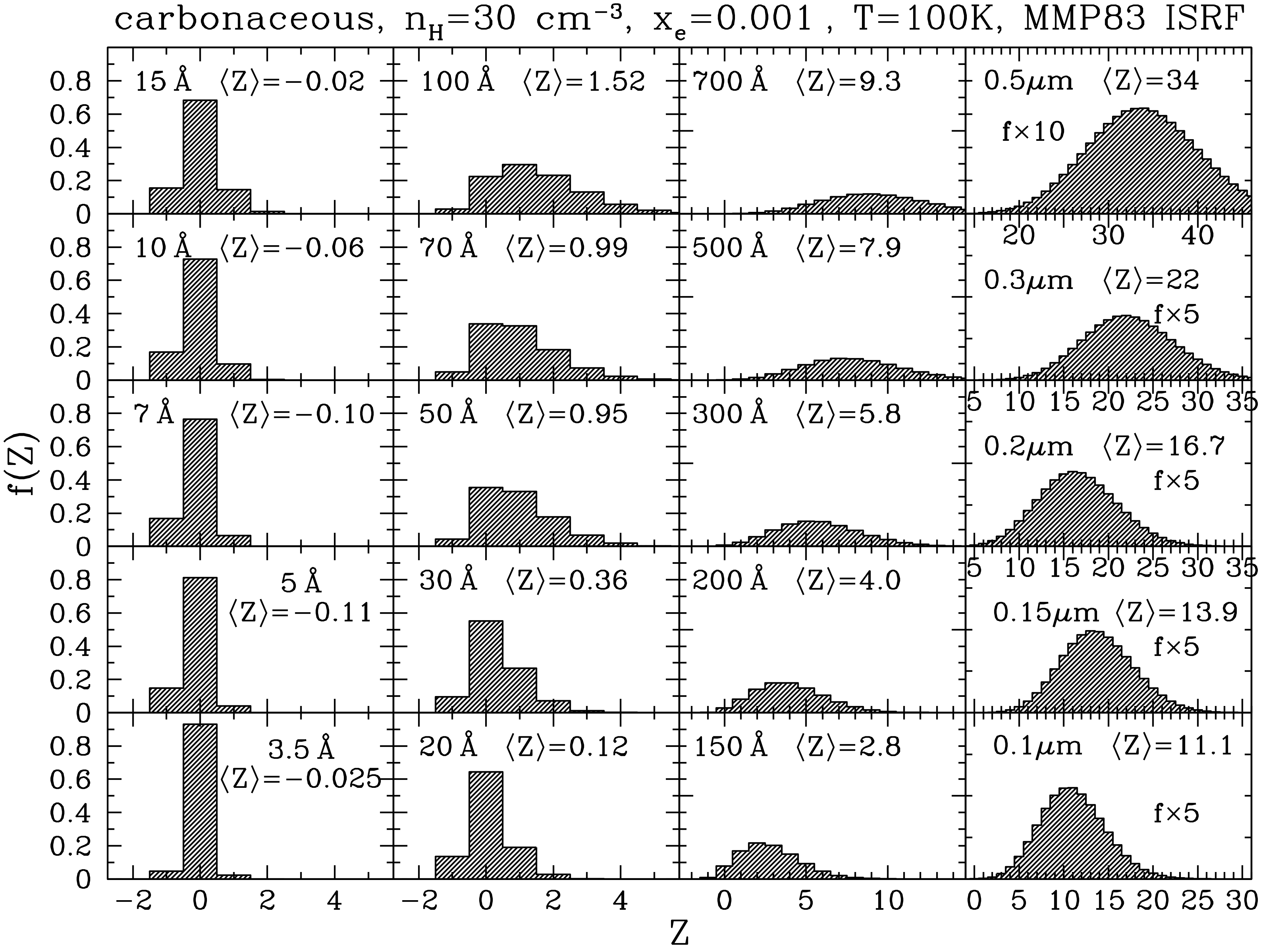
&

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

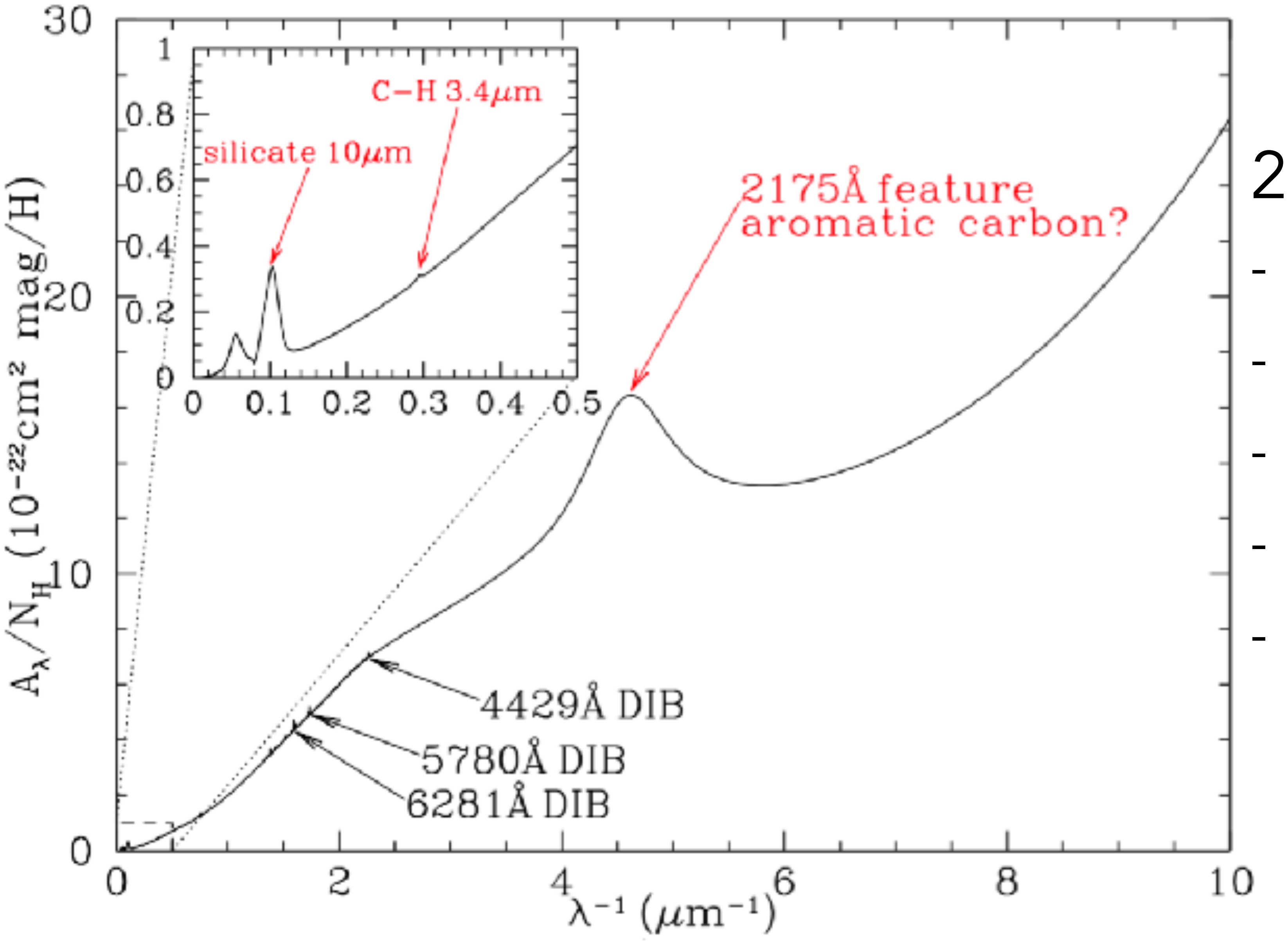
Dust Composition

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

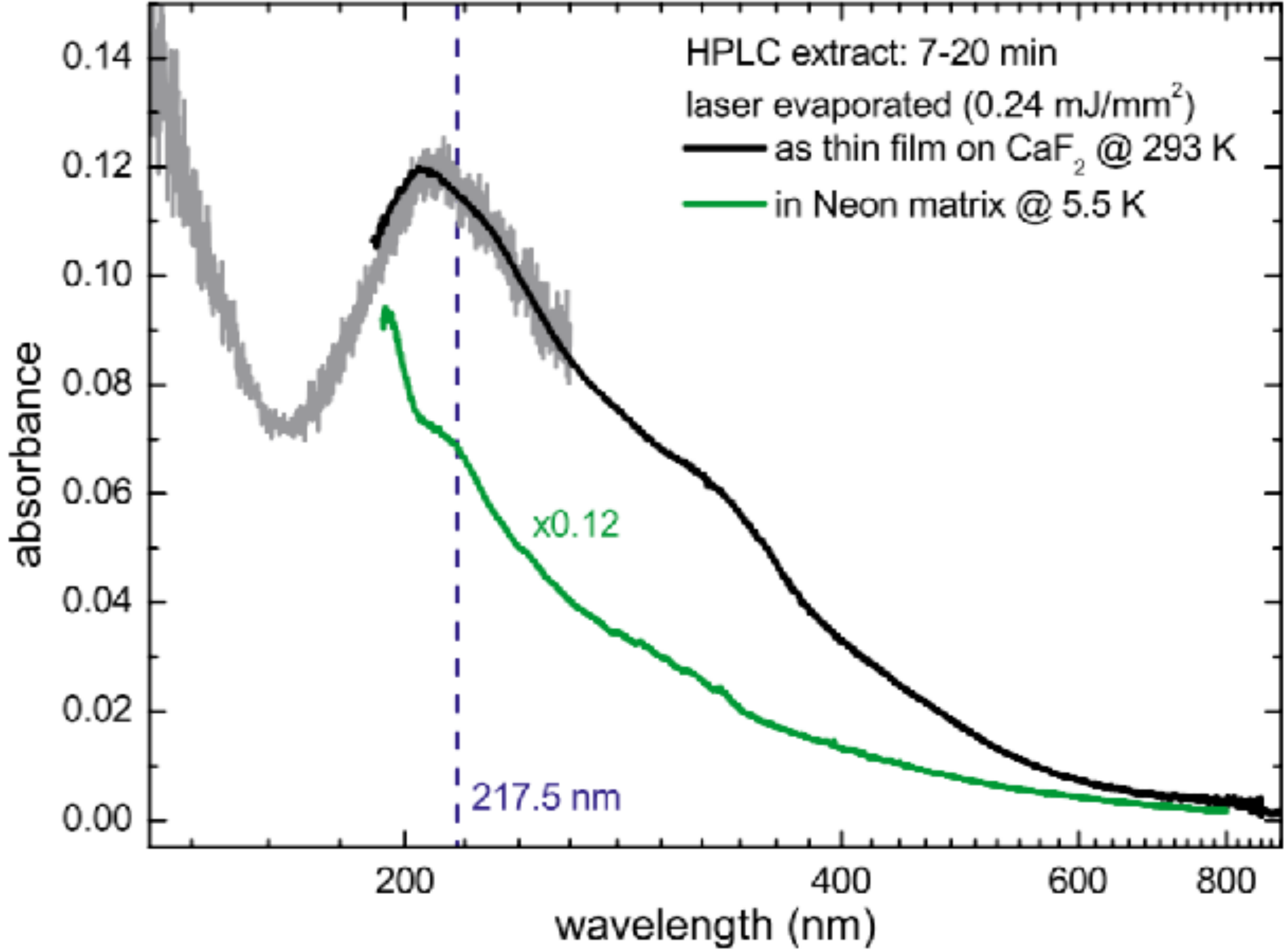


2175 Å bump:

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

Dust Composition

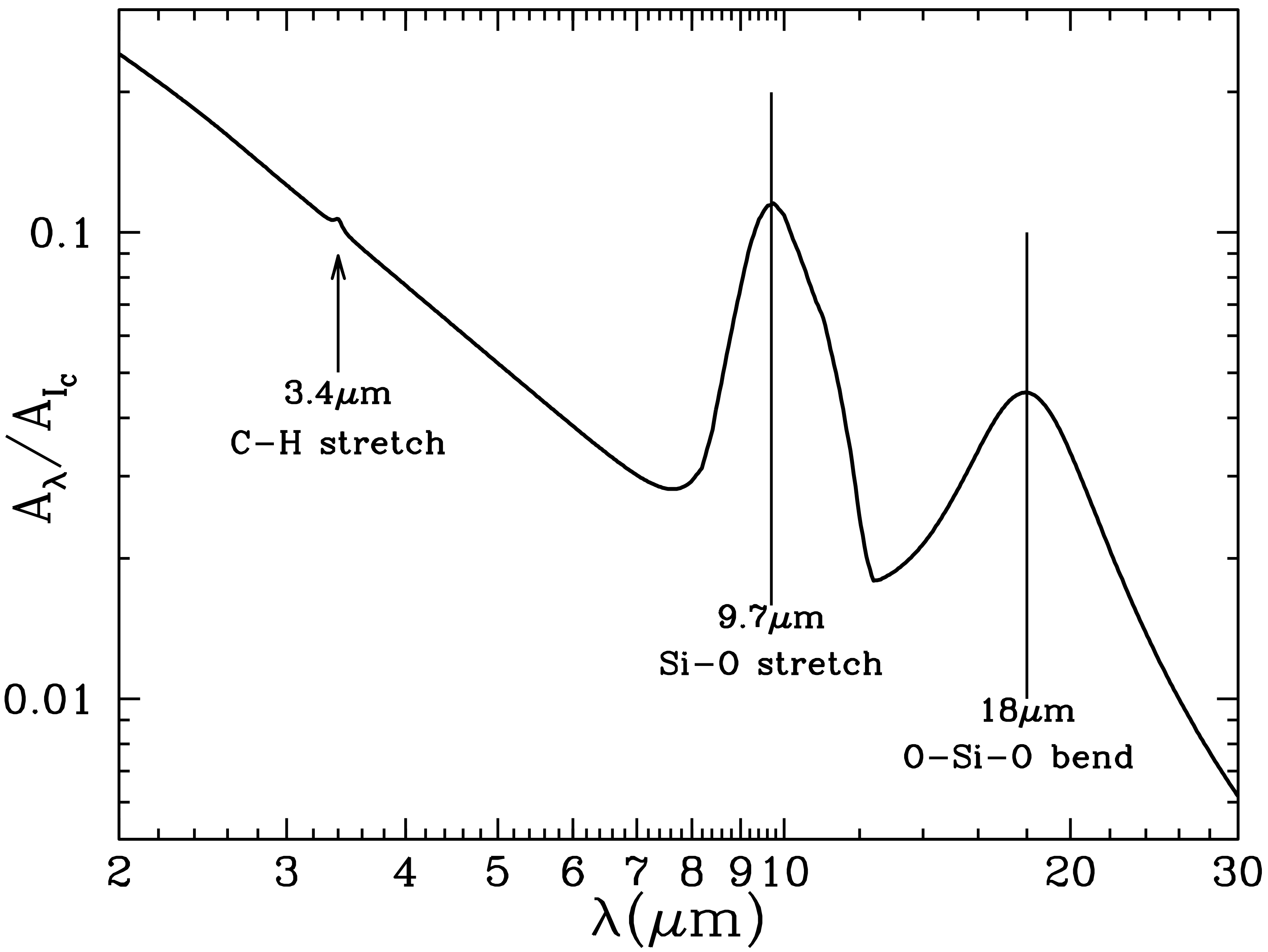
Steglich et al. 2010



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

Dust Composition

Spectroscopic features in absorption

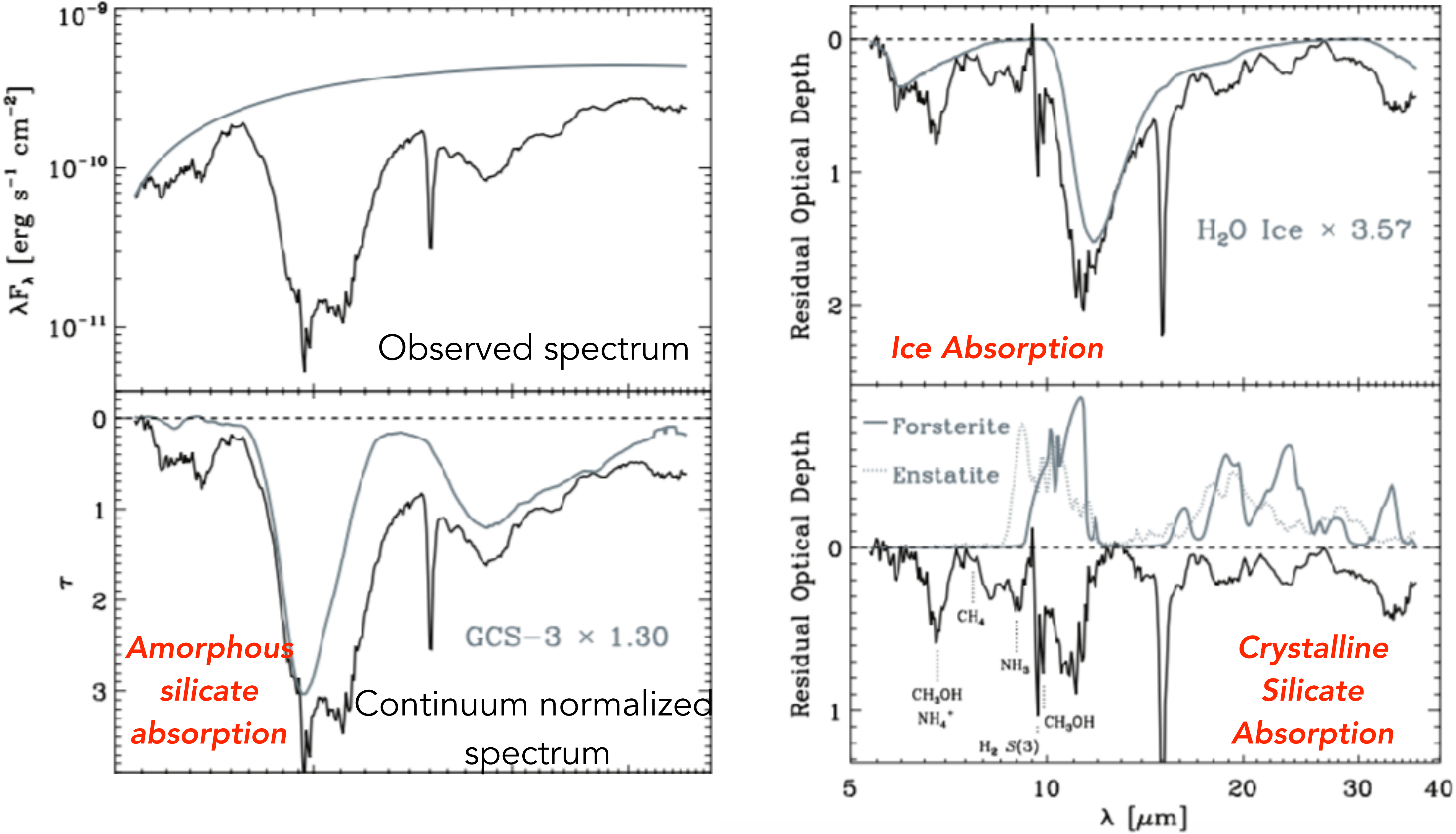


Silicate bending/ stretching modes at 9.7 and 18 μm.

Smooth profile = amorphous silicate

Silicate Absorption in a protostar in Orion

Poteet et al 2011



Observed spectrum

Amorphous silicate absorption

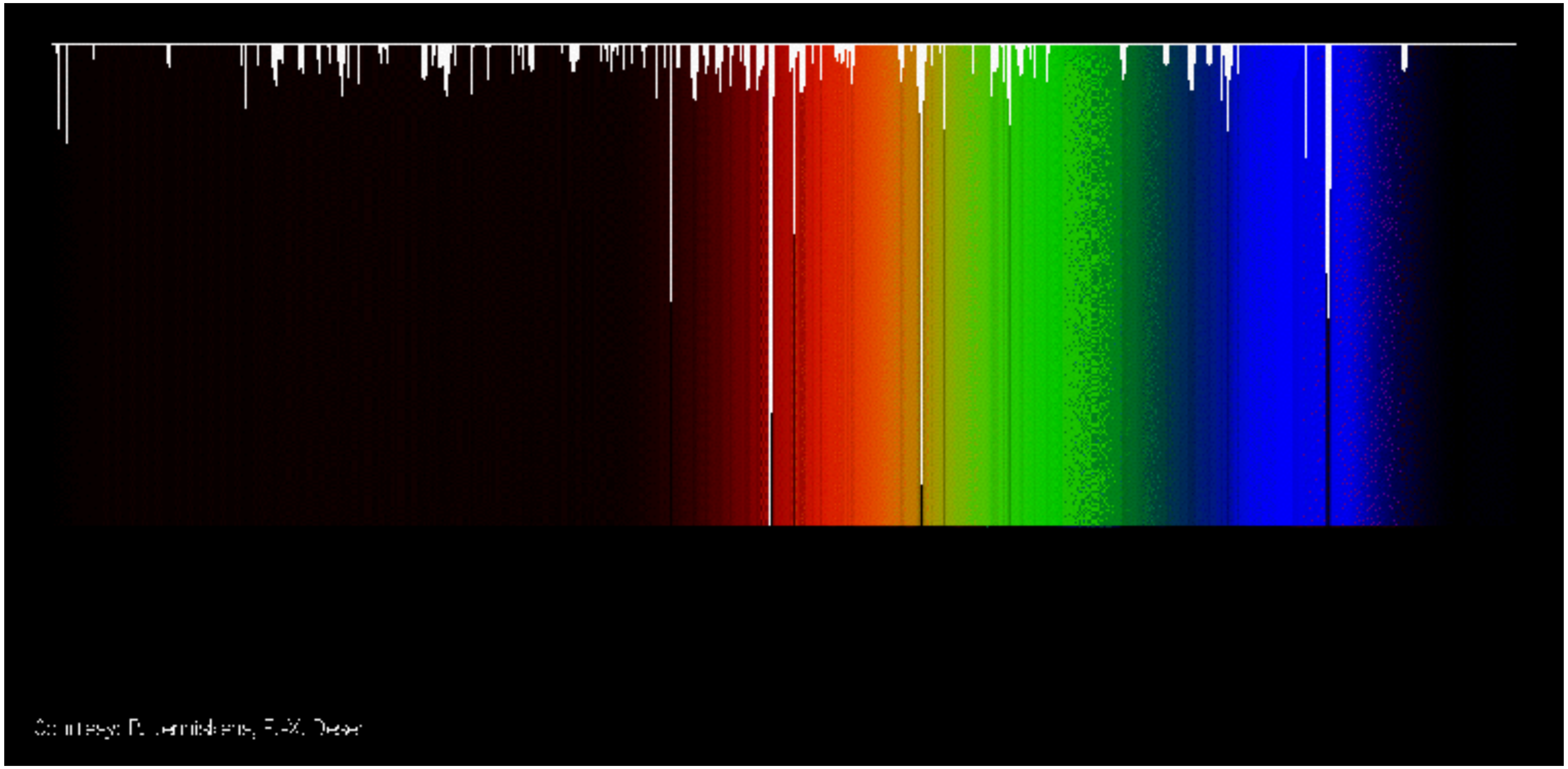
Continuum normalized spectrum

Ice Absorption

Crystalline Silicate Absorption

Dust Composition

Spectroscopic features in absorption



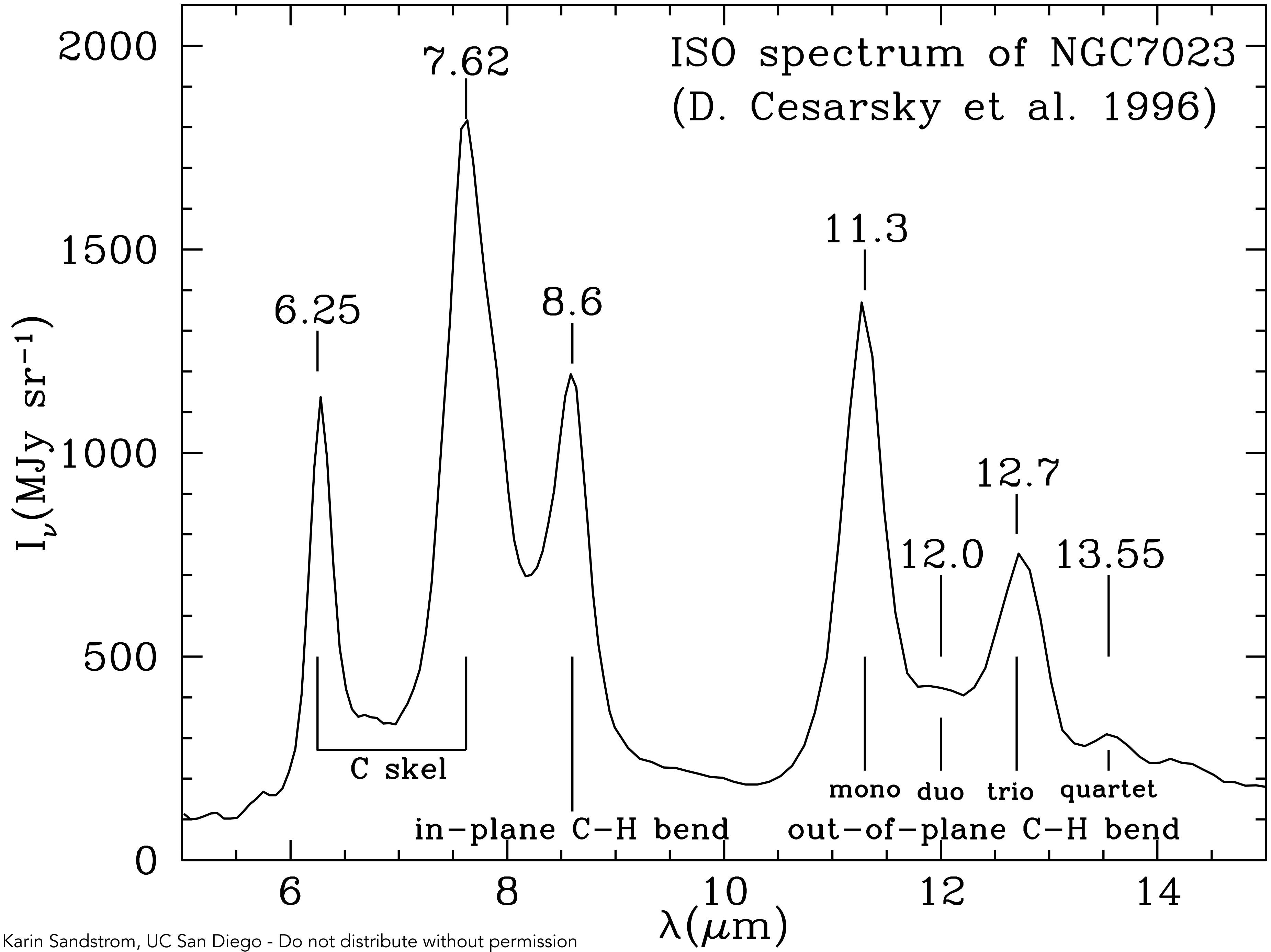
Two bands identified with C_{60}^{+}

Campbell et al. 2015

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

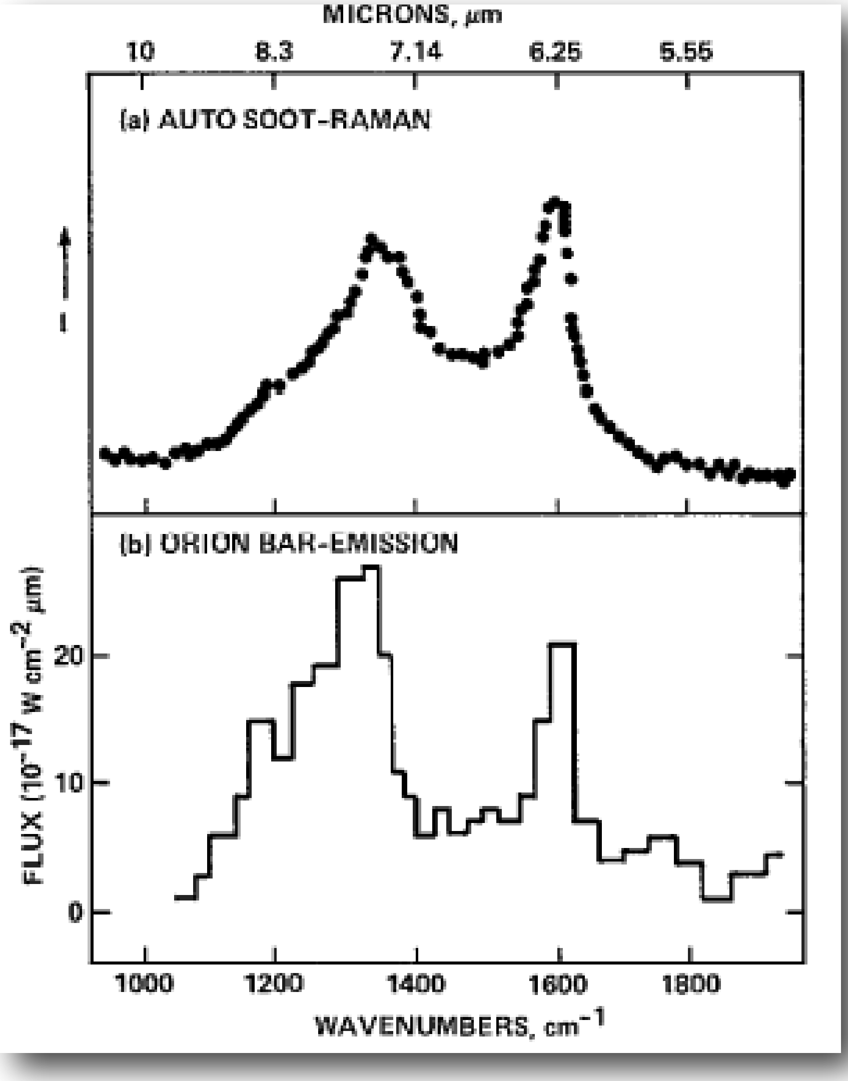
Dust Composition

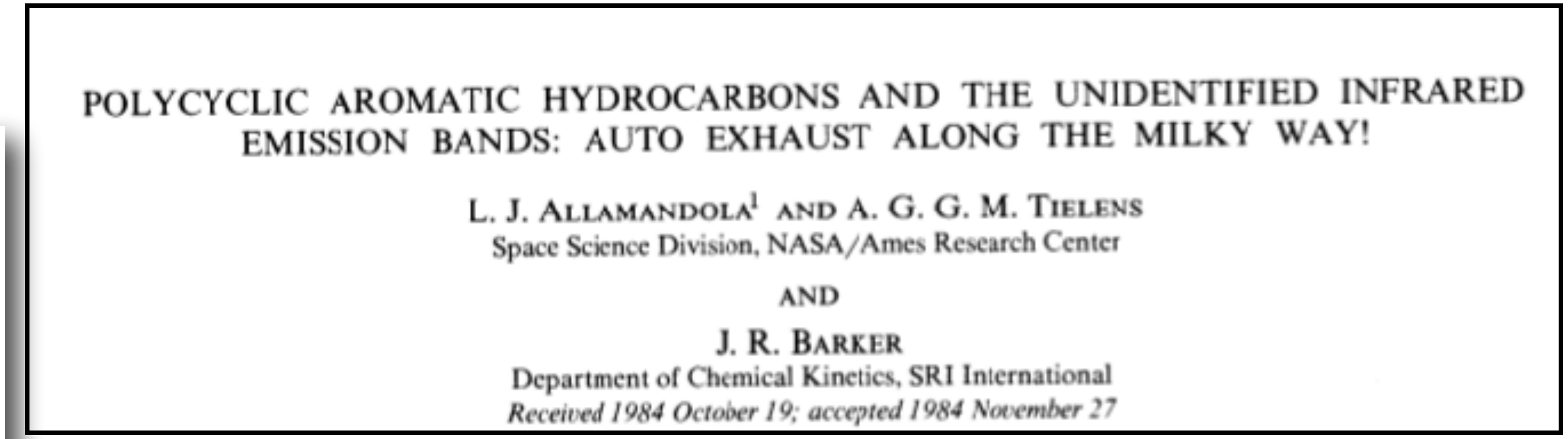
Spectroscopic features in emission



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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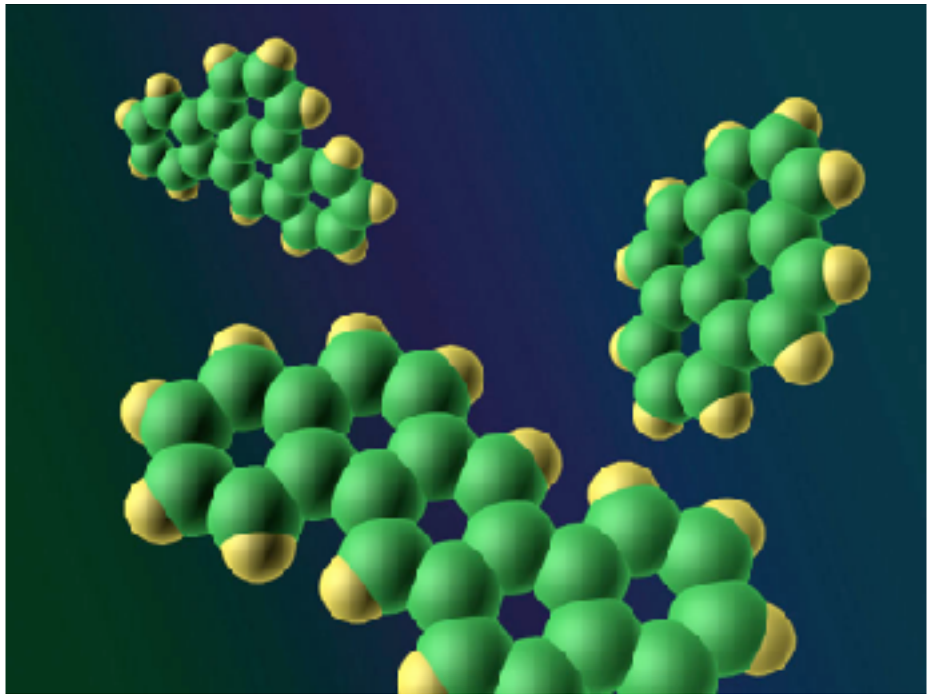
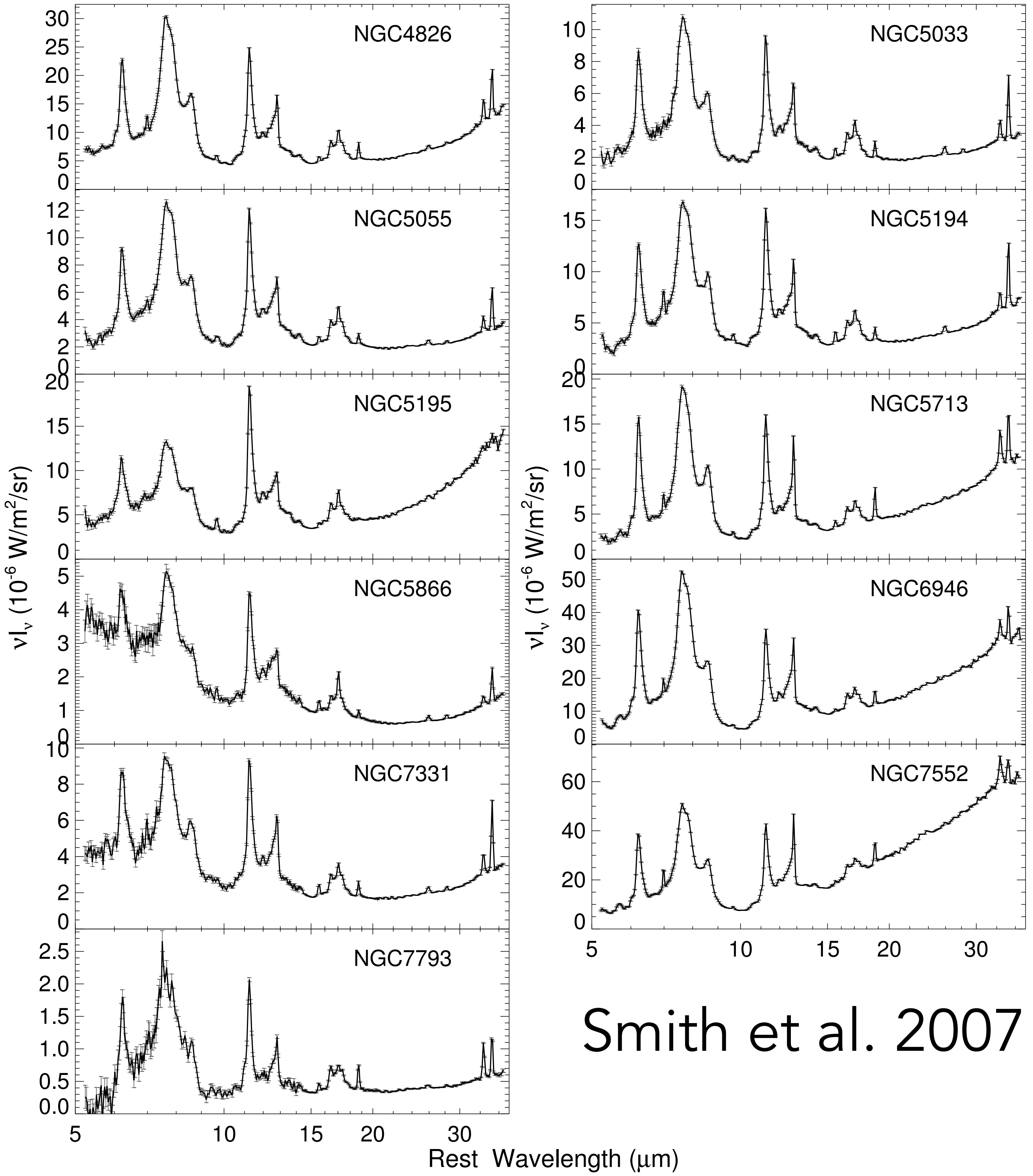
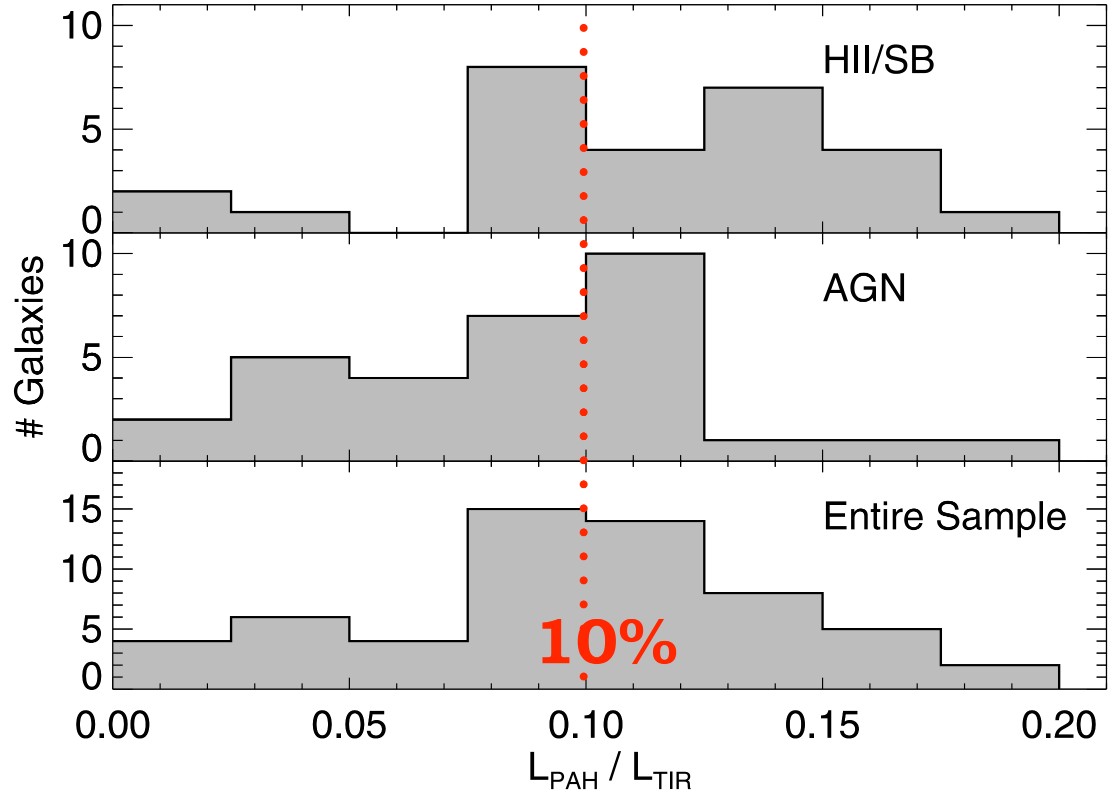


Dust Composition



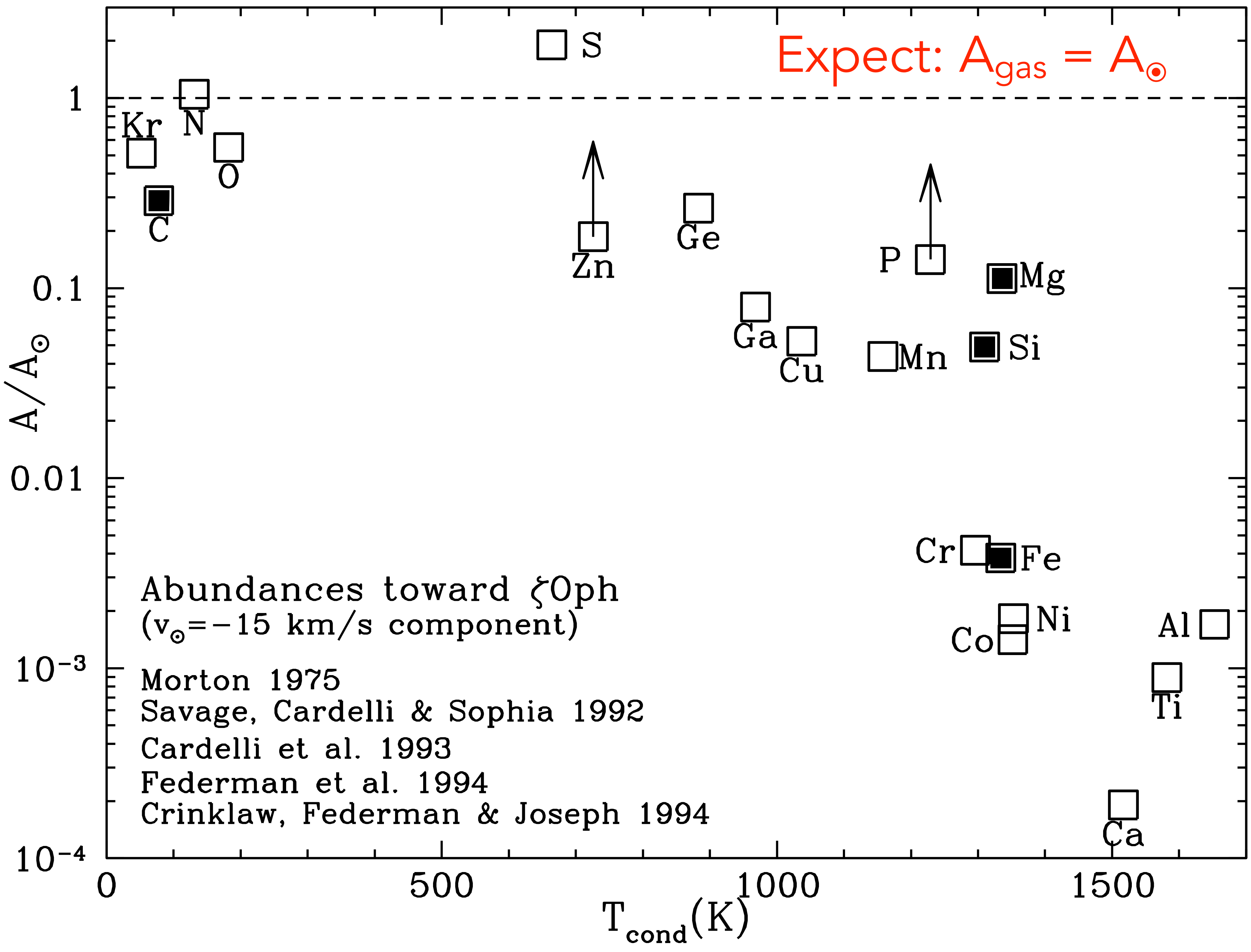
Smith et al. 2007



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

Depletions

Abundance in gas relative to Solar

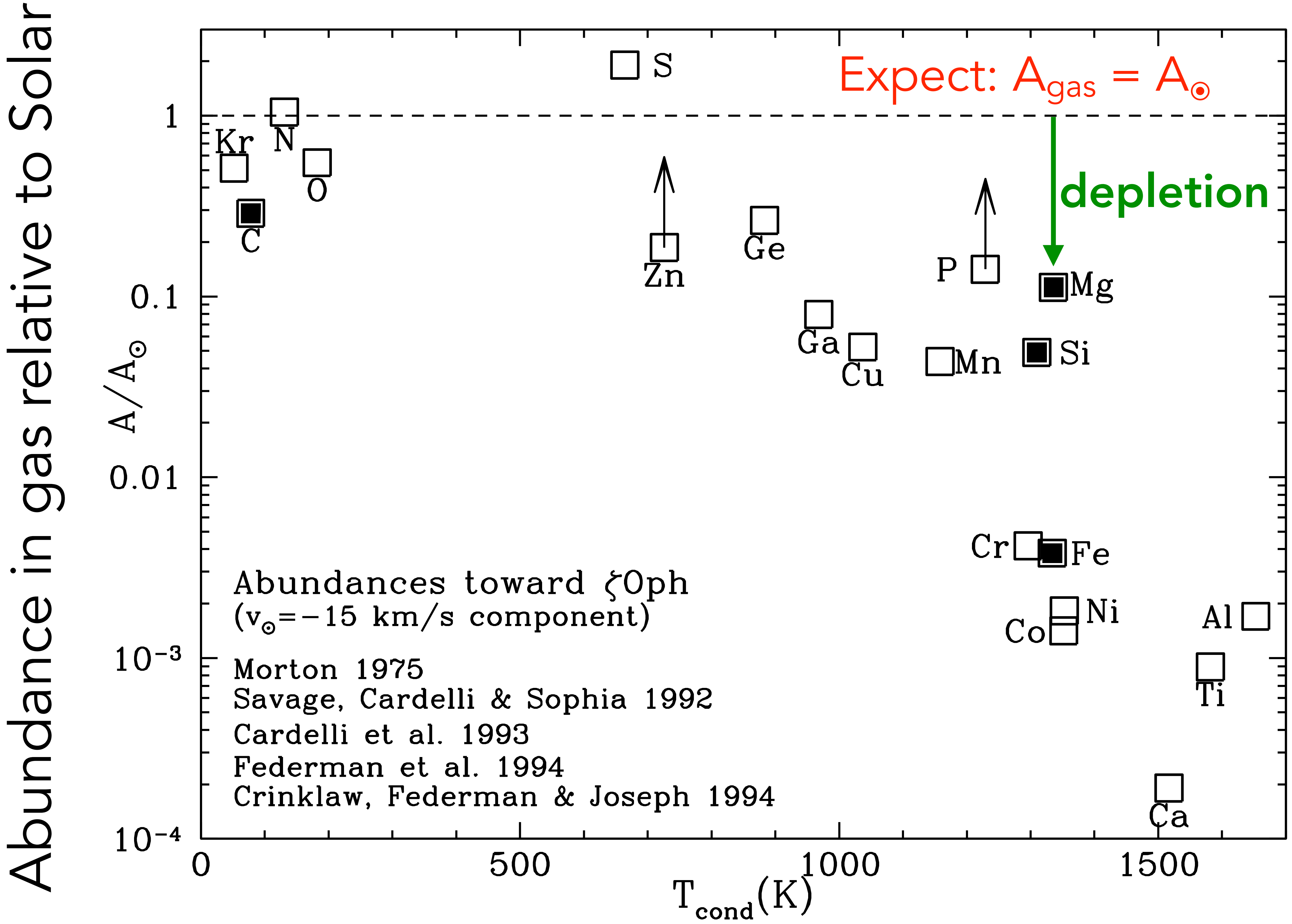


Expect: $A_{gas} = A_{\odot}$

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


Abundance in gas relative to Solar
A/A⊙
Expect: A_gas = A⊙
depletion
S
Kr
N
O
C
Zn
Ge
P
Mg
Ga
Cu
Mn
Si
Cr
Fe
Ni
Co
Al
Ti
Ca
1
0.1
0.01
10⁻³
10⁻⁴
0
500
1000
1500
T_cond(K)
Abundances toward ζOph
(v⊙=−15 km/s component)
Morton 1975
Savage, Cardelli & Sophia 1992
Cardelli et al. 1993
Federman et al. 1994
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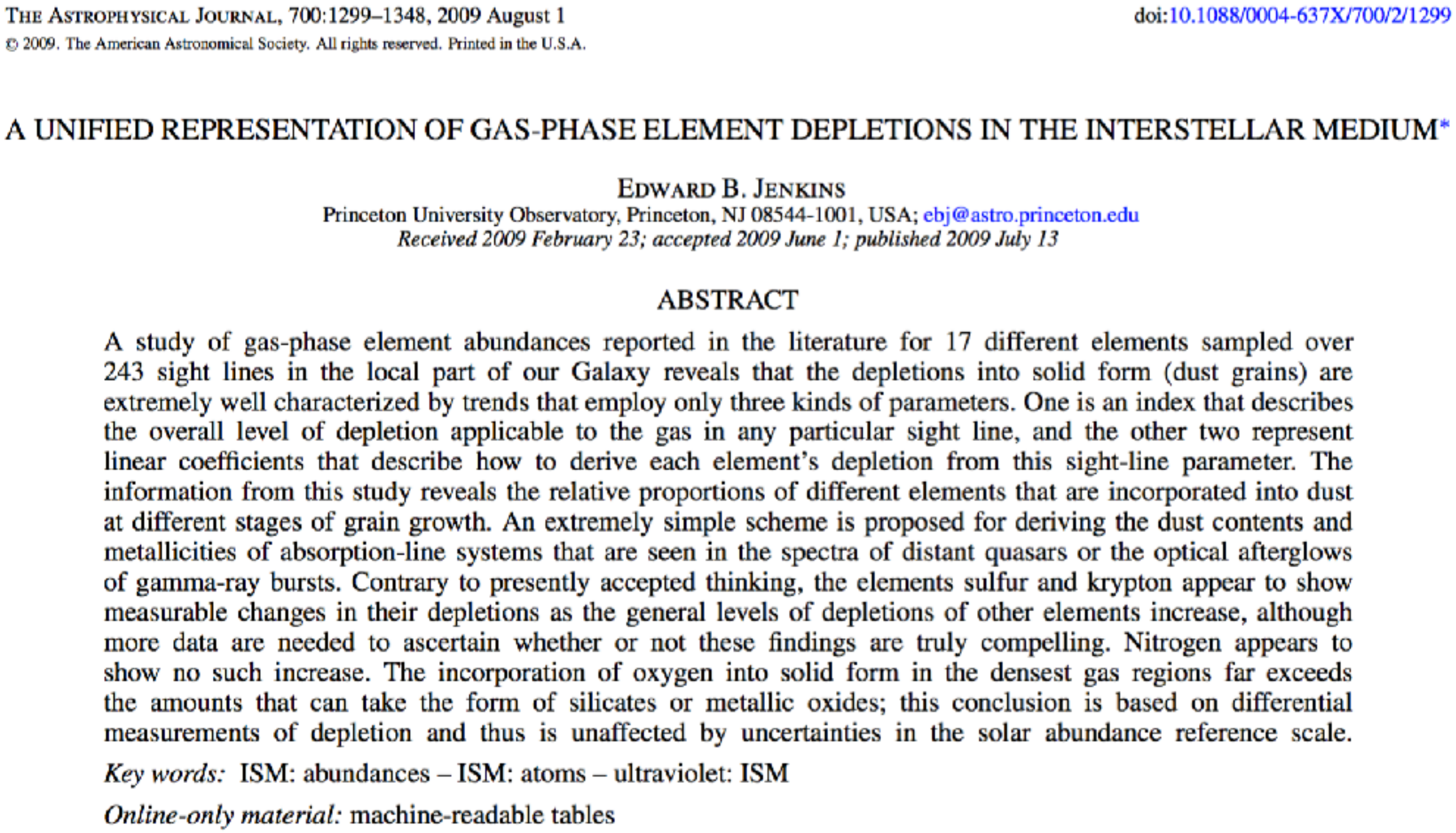
Depletions



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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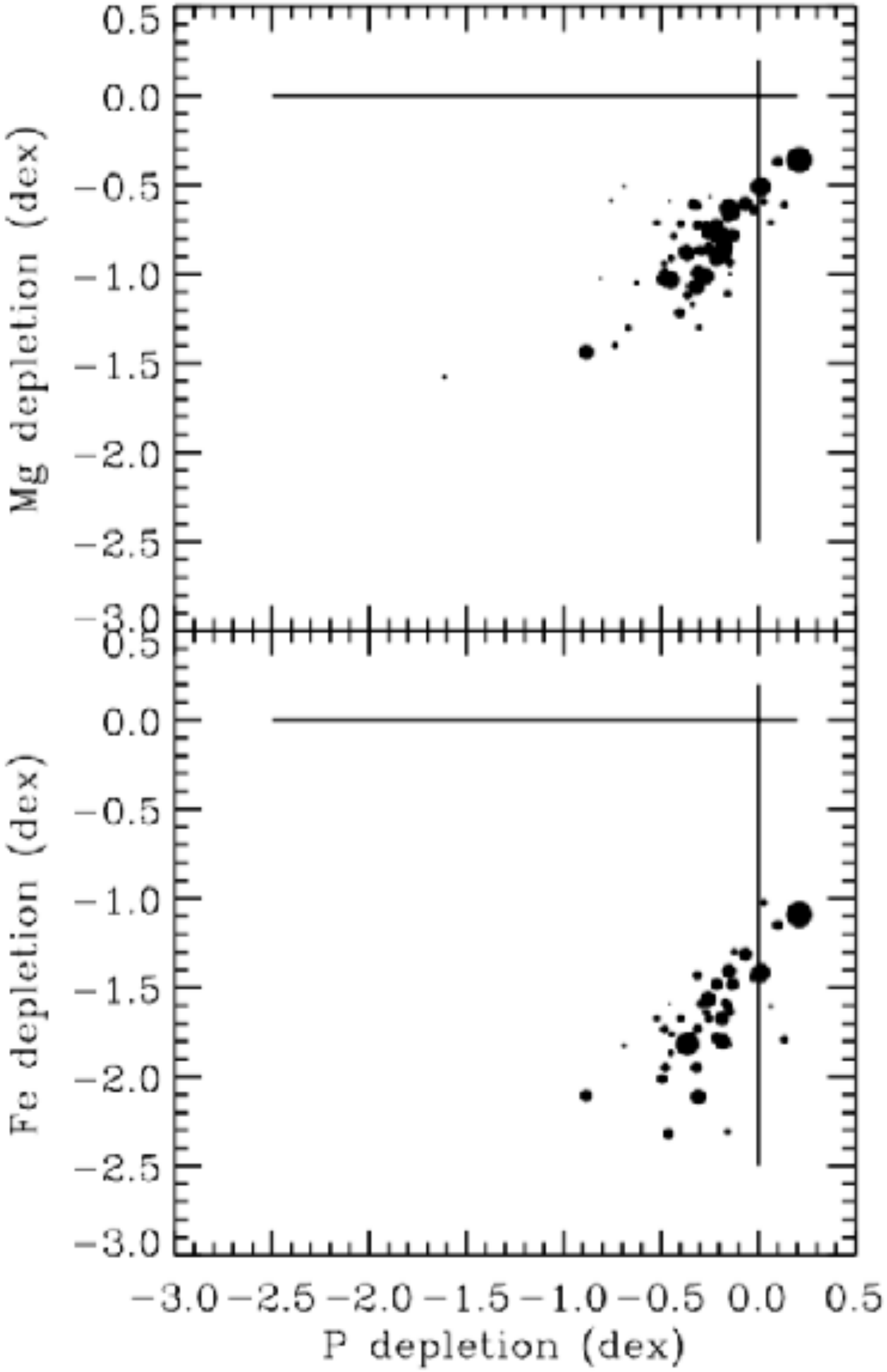
ABSTRACT

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:

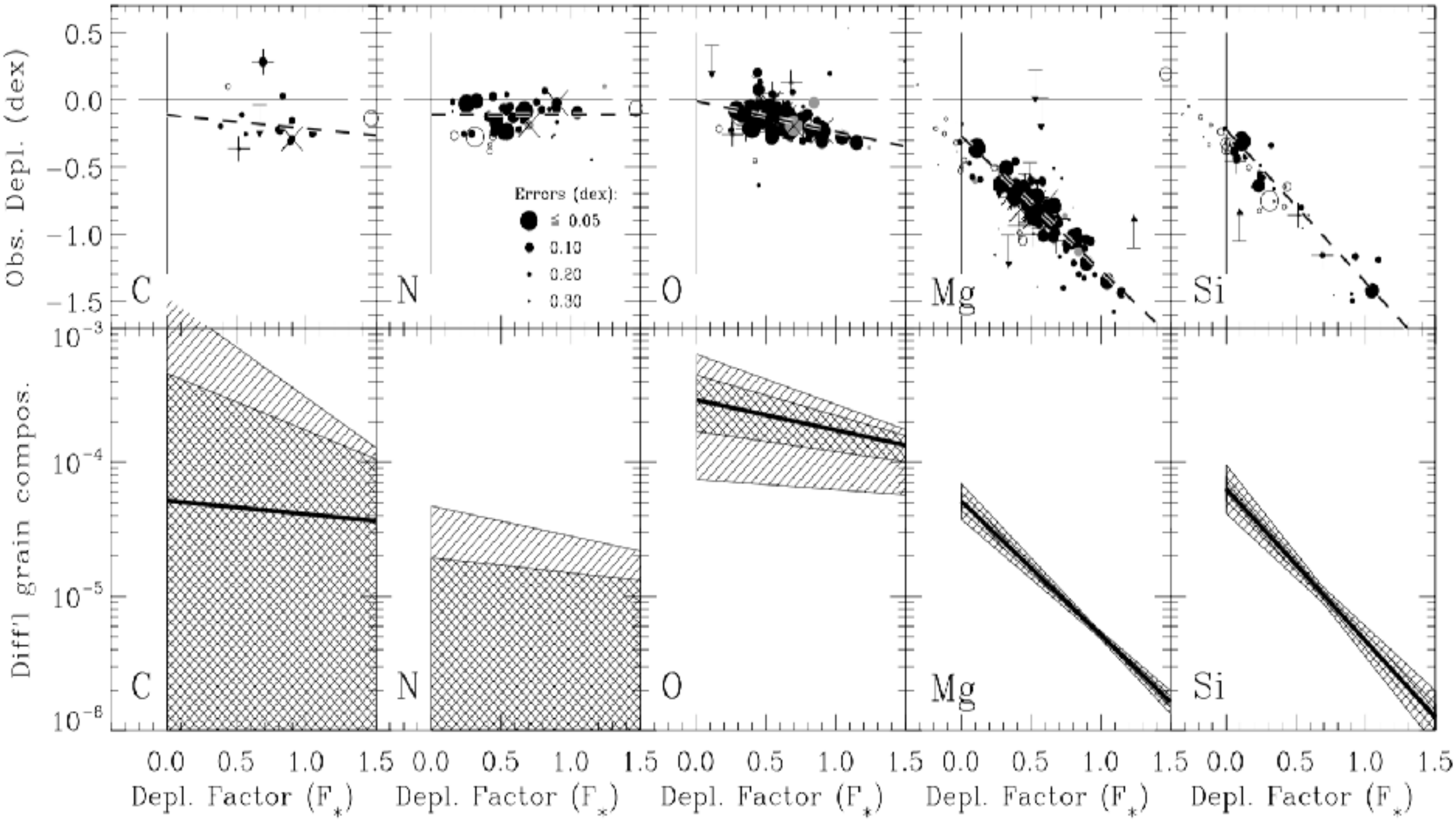
F_* = parameterization of overall depletion

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

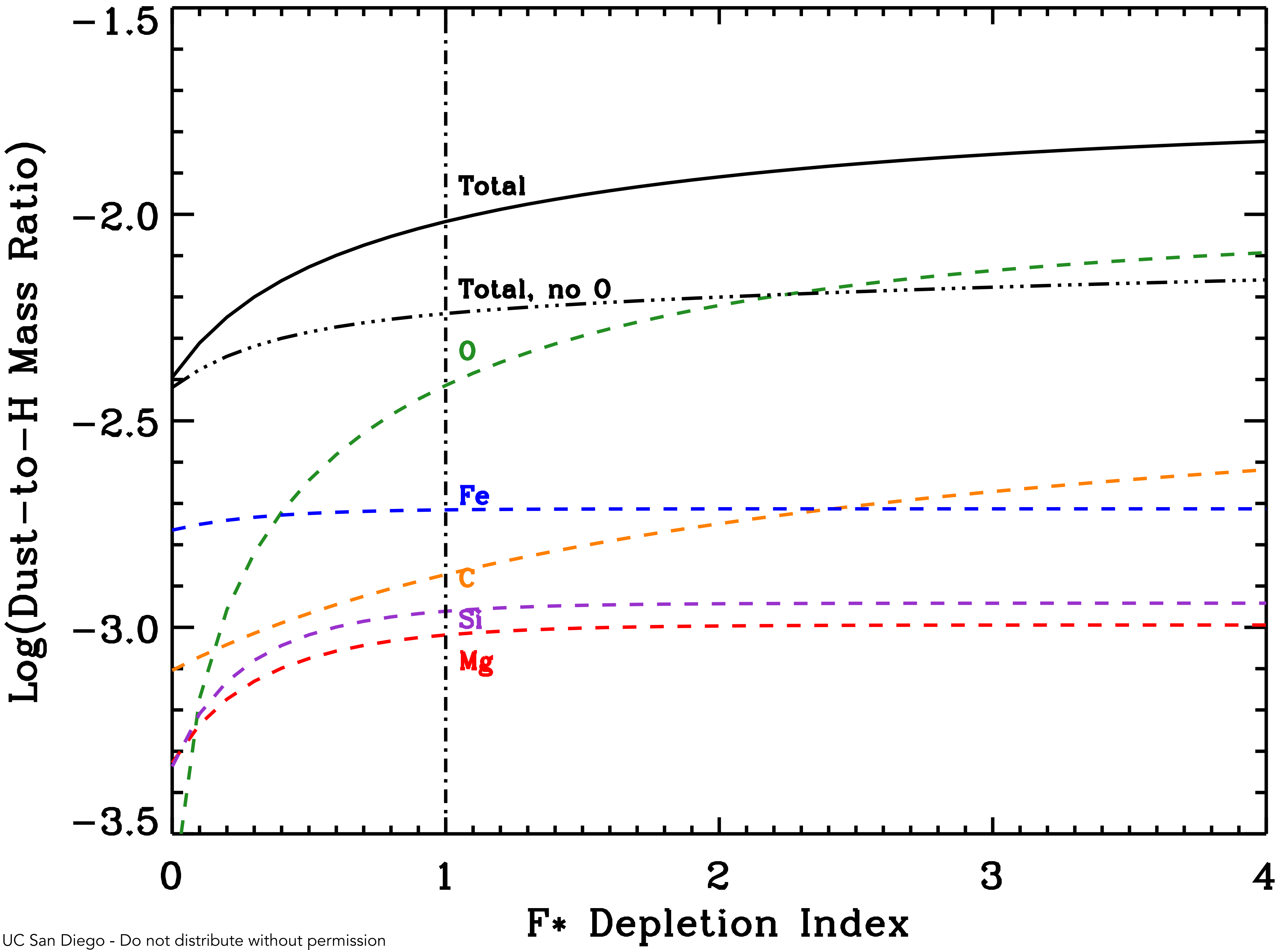
A_X = depletion rate for element X
as a function of F_*

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

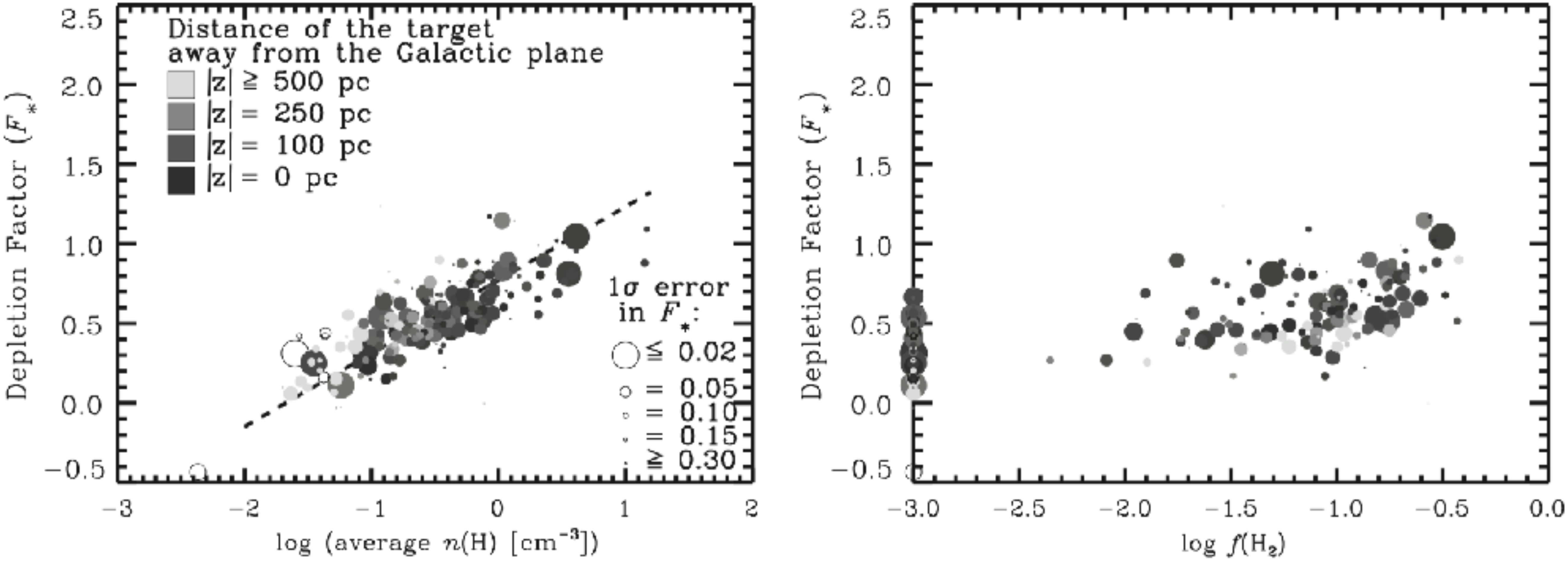
Depletions


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

Dust Composition



Dust Composition



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

Next Up: ISM Phases

- Part I: “ISM Phases”
- Part II: Neutral Gas Heating & Cooling
- Part III: Neutral Gas Observations

What are “ISM Phases”?

Characteristic states of gas in a galaxy:
defined by ionization, chemical, density, temperature state

Possibly the result of some sort of equilibrium:
pressure, chemical, thermal, etc

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Characteristic states of gas in a galaxy:
defined by ionization, chemical, density, temperature state

Possibly the result of some sort of equilibrium:
pressure, chemical, thermal, etc

Questions:

- What are the dominant processes that set these phases and how do they change from galaxy to galaxy?
- To what degree is the idea of “phases” an accurate representation of the ISM?

Phases in the Milky Way

Name	T (K)	Ionization	frac of volume	density (cm^{-3})	P ~ nT (cm^{-3} K)
hot ionized medium	10^6	H^+	0.5(?)	0.004	4000
ionized gas (HII & WIM)	10^4	H^+	0.1	$0.2\text{-}10^4$	$2000 - 10^8$
warm neutral medium	5000	H^0	0.4	0.6	3000
cold neutral medium	100	H^0	0.01	30	3000
diffuse molecular	50	H_2	0.001	100	5000
dense molecular	10-50	H_2	10^{-4}	$10^3\text{-}10^6$	$10^5 - 10^7$

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cold neutral medium	100	H^0	0.01	30	3000
diffuse molecular	50	H_2	0.001	100	5000
dense molecular	10-50	H_2	10^{-4}	10^3-10^6	$10^5 - 10^7$

Pressure equilibrium

What we are going to do next:

Understand what sets the properties of various ISM phases:

Neutral gas

Molecular gas

Ionized gas

Neutral Gas

~60% of gas in MW is in “HI regions”
where hydrogen is atomic (not ionized, not molecular)

Heating:

- Cosmic Ray Ionization
- Photoionization of H & He
- Photoionization of metals
- Photoelectric effect from dust
- Shocks, turbulent dissipation, MHD phenomena

Cooling:

- Collisionally excited fine structure lines
- Lyman α at $T>10^4$ K
- recombination of e- and grains

Γ heating rate per volume $\sim n_H X_H n_{coll} v_{coll} \sigma Y(E)$

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density of whatever
is being ionized
X_H = abundance
relative to H

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Γ heating rate per volume $\sim \boxed{n_H\ X_H}\overset{\text{interaction rate}}{\boxed{n_{coll}\ v_{coll}\ \sigma}}\ Y(E)$

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interaction rate

Γ heating rate per volume $\sim \boxed{n_H X_H}\,\boxed{n_{coll}\, v_{coll}\, \sigma}\,\boxed{Y(E)}$

density of whatever is being ionized
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energy yield per interaction

Heating:

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interaction rate

$$\Gamma \quad \text{heating rate per volume} \sim \boxed{n_H X_H}\boxed{n_{coll}\, v_{coll}\, \sigma}\boxed{Y(E)}$$

density of whatever is being ionized
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energy yield per interaction

* Integrate this over the distribution of collider energies

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interaction rate

$$\Gamma \quad \text{heating rate per volume} \sim \boxed{n_H X_H}\boxed{n_{coll}\, v_{coll}\, \sigma}\boxed{Y(E)}$$

density of whatever is being ionized
X_H = abundance relative to H

energy yield per interaction

* Integrate this over the distribution of collider energies

Heating:

Cosmic Ray Ionization	H & He
Photoionization of H & He	H & He
Photoionization of metals	C, O, Ne, Mg, Si (IP < 13.6 eV)
Photoelectric effect from dust	Dust
Shocks, turbulent dissipation, MHD phenomena	

$$\Gamma \quad \begin{matrix}\text{heating rate} \\ \text{per volume}\end{matrix} \sim \underbrace{\boxed{n_H \, X_H}}_{\text{density of whatever is being ionized}} \overbrace{\boxed{n_{coll} \, v_{coll} \, \sigma}}^{\text{interaction rate}} \underbrace{\boxed{Y(E)}}_{\text{energy yield per interaction}}$$

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Heating:

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interaction rate

Γ heating rate per volume $\sim \boxed{n_H X_H}\boxed{n_{coll} v_{coll} \sigma}\boxed{Y(E)}$

density of whatever is being ionized
X_H = abundance relative to H

energy yield per interaction

* Integrate this over the distribution of collider energies

Heating:

- Cosmic Ray Ionization	- ζ_{CR}
- Photoionization of H & He	- $(u_\nu/h\nu)\ c\ \sigma_{H,He}(E)$
- Photoionization of metals	- $(u_\nu/h\nu)\ c\ \sigma_Z(E)$
- Photoelectric effect from dust	- $(u_\nu/h\nu)\ c\ \langle Q_{abs,*}\rangle\ \pi a^2$ (integrate over a)
- Shocks, turbulent dissipation, MHD phenomena	

interaction rate

$$\Gamma \quad \text{heating rate per volume} \sim \boxed{n_H\, X_H}\boxed{n_{coll}\, v_{coll}\ \sigma}\boxed{Y(E)}$$

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• Shocks, turbulent dissipation, MHD phenomena	

Depend on CR flux and radiation field strength.

interaction rate

$$\Gamma \quad \text{heating rate per volume} \sim \boxed{n_H X_H}\boxed{n_{coll}\, v_{coll}\, \sigma}\boxed{Y(E)}$$

density of whatever is being ionized
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density of whatever is being ionized

X_H = abundance relative to H

energy yield per interaction

* Integrate this over the distribution of collider energies

Depends on ionization state of gas, energy of collider & “work function”

Heating:

- Cosmic Ray Ionization
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- Photoionization of metals
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- Shocks, turbulent dissipation, MHD phenomena

interaction rate

$$\Gamma \quad \begin{matrix}\text{heating rate} \\ \text{per volume}\end{matrix} \quad \sim \boxed{n_H \, X_H}\boxed{n_{coll} \, v_{coll} \, \sigma}\boxed{Y(E)}$$

density of whatever
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X_H = abundance
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energy yield
per interaction

* Integrate this over the distribution of collider energies

Heating:

- Cosmic Ray Ionization
- Photoionization of H & He
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Common theme:
interaction rate is set by
external radiation field
or cosmic ray flux so…

$$\Gamma \sim n_H \, \zeta \, E$$

$$\Lambda \quad \frac{\text{cooling rate}}{\text{per volume}} \sim n_C\, n_X\, k_{10}\, E_{10}$$

In the case where $n_c \gg n_{crit}$, i.e. every collision leads to radiative transition.

where n_c = collider density
n_X = collisionally excited species density
k_{10} = collisional rate coefficient
E_{10} = energy difference of levels

Cooling:

- Collisionally excited fine structure lines
- Lyman α at $T>10^4$ K
- recombination of e- and grains

Λ cooling rate per volume $\sim n_C \, n_X \, k_{10} \, E_{10}$

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n_X = collisionally excited species density
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Recall “collision strength” Ω_{ul}

$$k_{u\ell} = \frac{h^2}{(2\pi m_e)^{3/2}} \frac{1}{(kT)^{3/2}} \frac{\Omega_{u\ell}}{g_u}$$

separates gas temperature from atomic properties

Cooling:

- Collisionally excited fine structure lines
- Lyman α at $T>10^4$ K
- recombination of e- and grains

Λ cooling rate per volume $\sim n_C\, n_X\, k_{10}\, E_{10}$

In the case where $n_c >> n_{crit}$, i.e. every collision leads to radiative transition.

note that different colliders have different k values

Important point:
cooling rate ~ n^2

$\Lambda \sim n^2\, \lambda(T)$ const

function of gas temperature

quantum mechanics

Cooling:

- Collisionally excited fine structure lines
- Lyman α at $T>10^4$ K
- recombination of e- and grains