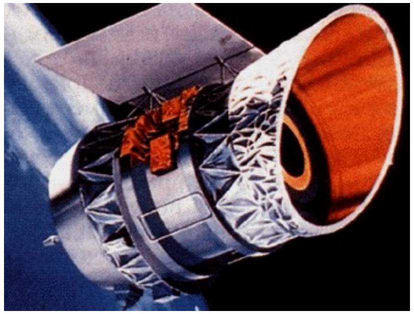
Much of our original knowledge of interstellar dust comes from a 0.60 m telescope dubbed IRAS, the Infrared Astronomical Satellite (1983).

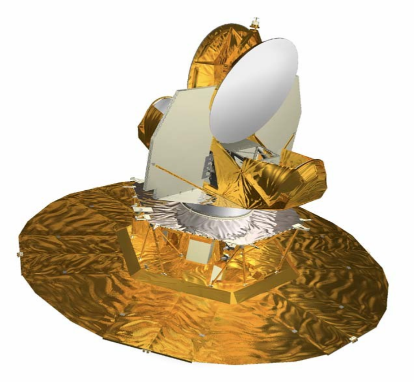


- -covered over 96% of the sky at 12, 25, 60, and 100 μm
- -provided our first view of the extragalactic sky at far-IR wavelengths
- -had uniform sensitivity limits: 0.5 Jy at 12, 25, 60 μm; 1.5 Jy at 100 μm
- -experienced negligible Galactic extinction

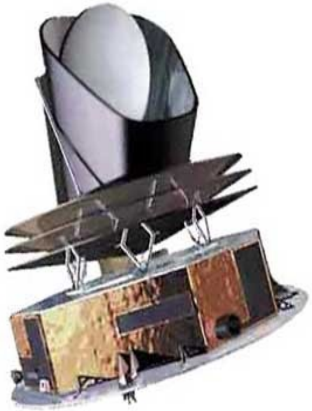
In ½ hour, IRAS obtained more $\lambda > 5\mu m$ data than all previous efforts combined. The mission lasted 10 months.

In addition to cataloging ~250,000 point sources, IRAS detected 20,000 extended sources and diffuse emission from the entire sky. The COBE, WMAP, and Planck satellites subsequently studied the latter in more detail the 1990s, 2000s, and 2010s.

COBE



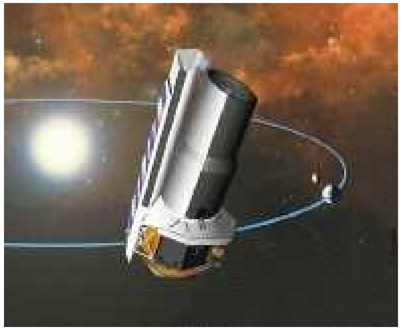
WMAP



Planck

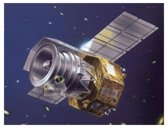
Our legacy of infrared telescopes (plus ground-based 2MASS):

Infrared Space Observatory
0.60 m
mid-/far-IR imaging & spectroscopy

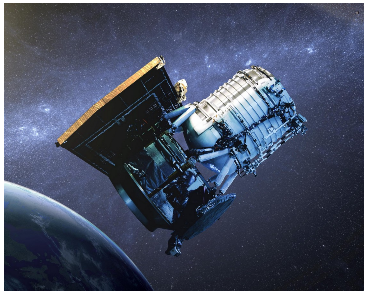


It's big!

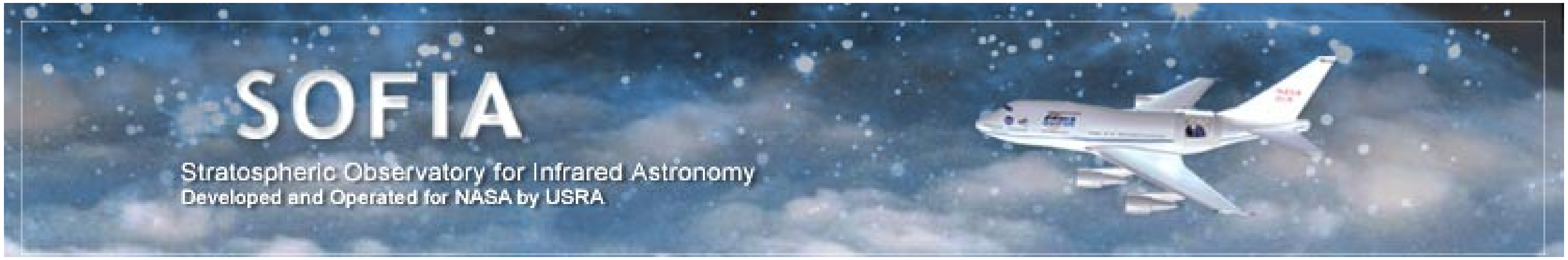
Spitzer Space Telescope
0.85 m
mid-/far-IR imaging
mid-IR spectroscopy



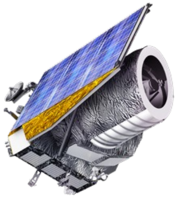
Akari
0.67 m
near-/mid-/far-IR imaging



WISE
0.40 m
mid-IR imaging

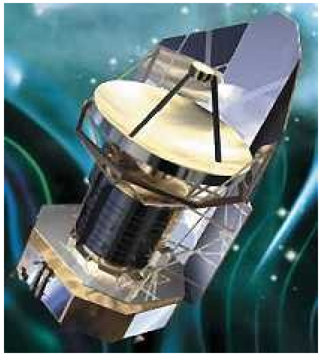


SOFIA
2.5 m
mid-/far-IR imaging
IR/submm spectroscopy



Euclid
1.2 m
optical/near-IR imaging

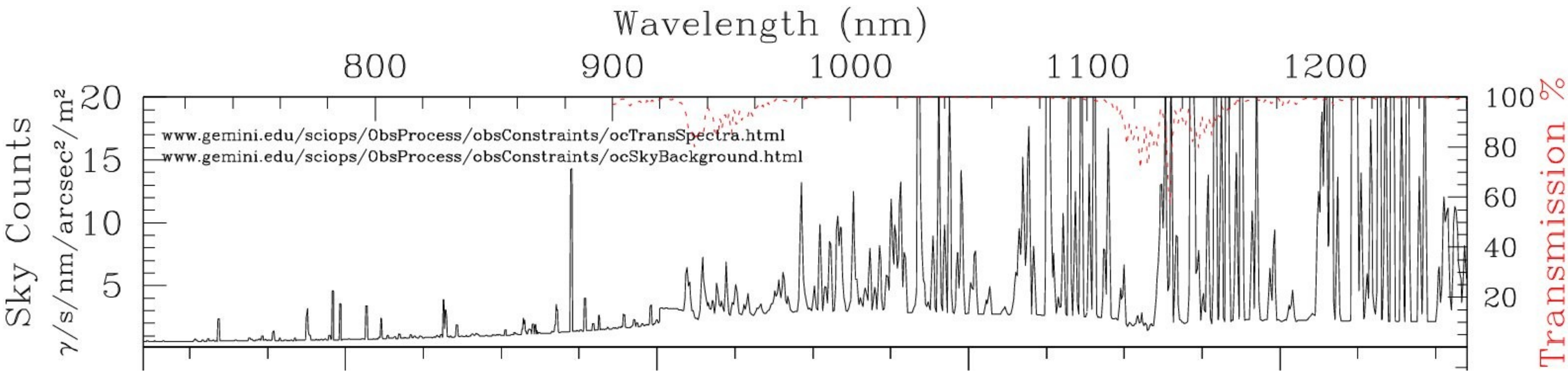
JWST
6.5 m
near-/mid-IR imaging & spectroscopy

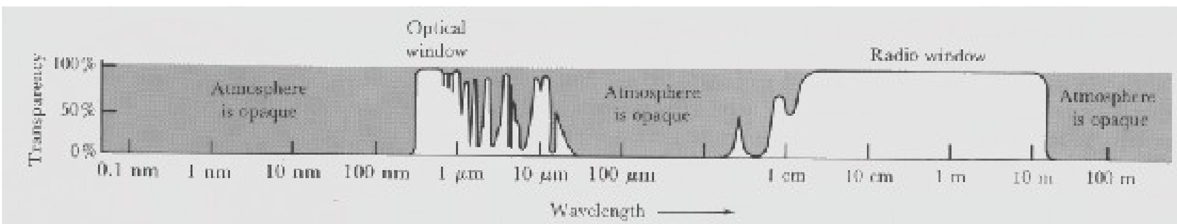


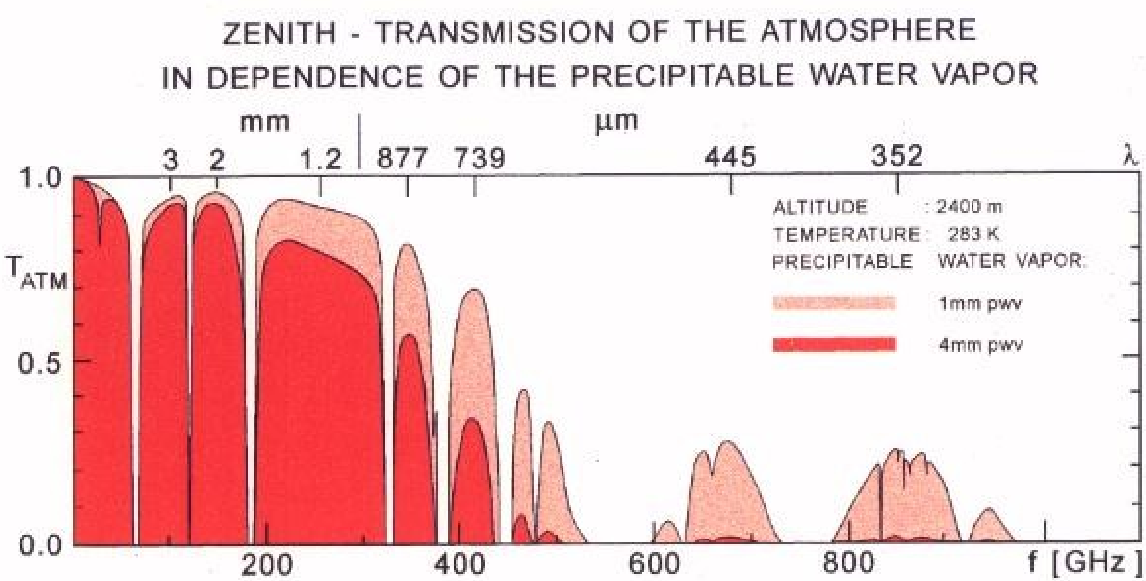
Herschel Space Observatory
3.5 m
far-IR/submm imaging & spectroscopy

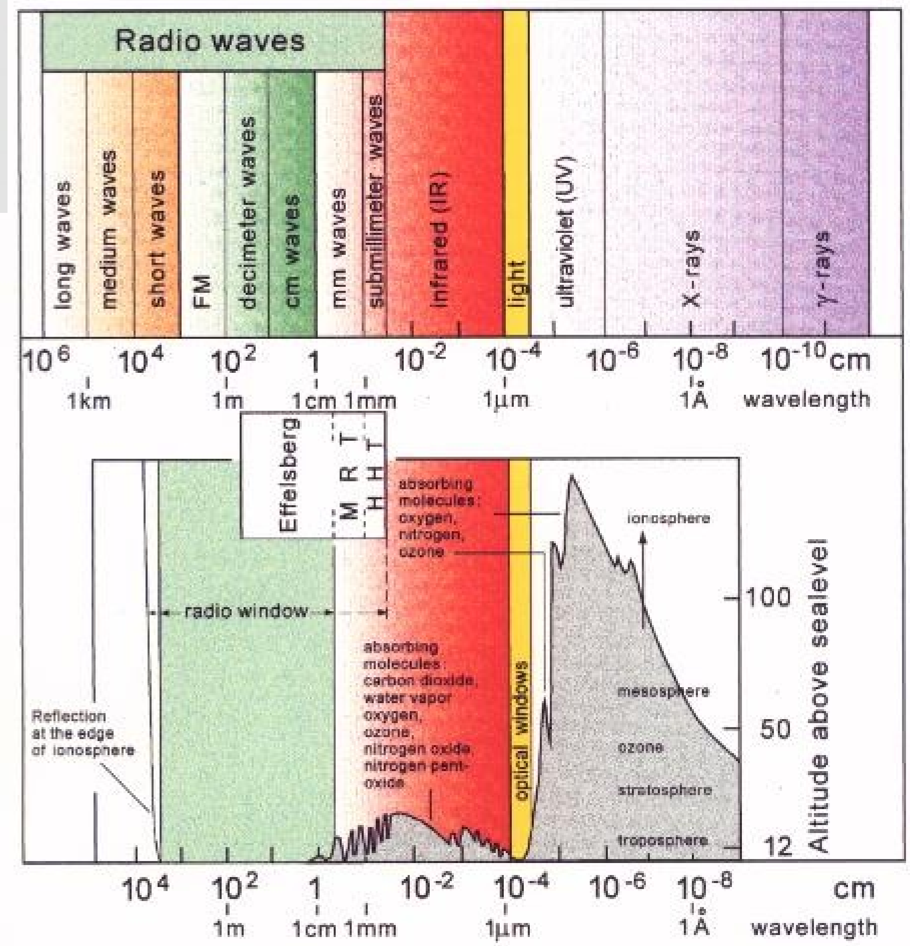
Nancy Grace Roman
2.4 m
opt/NIR imaging
launch: 2026

Why (stratosphere- and) space-based? The atmosphere both _____ and _____ in the infrared.

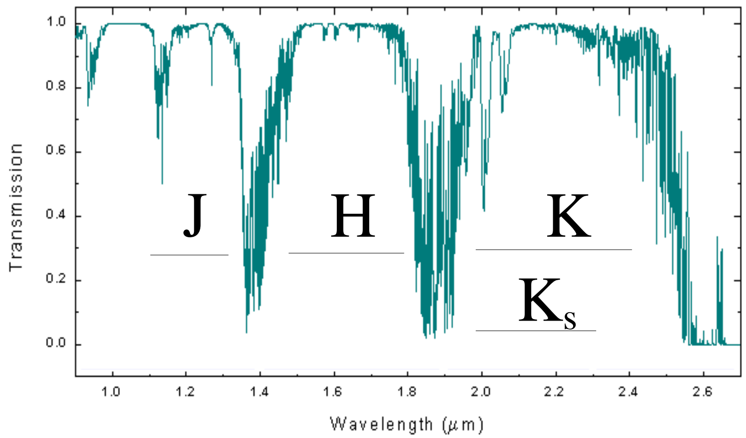


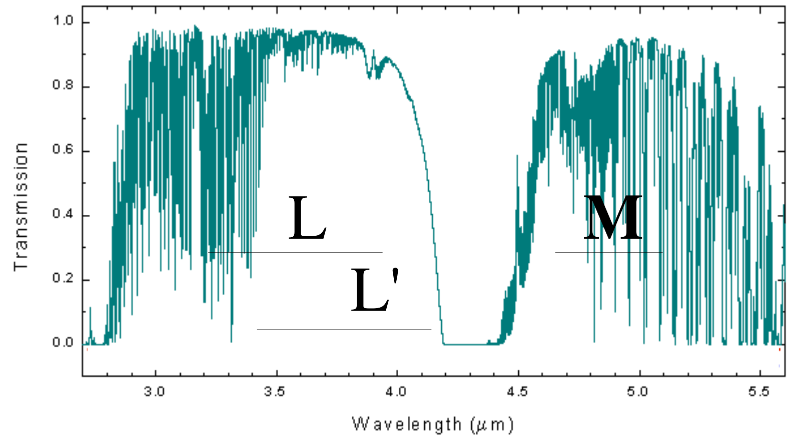




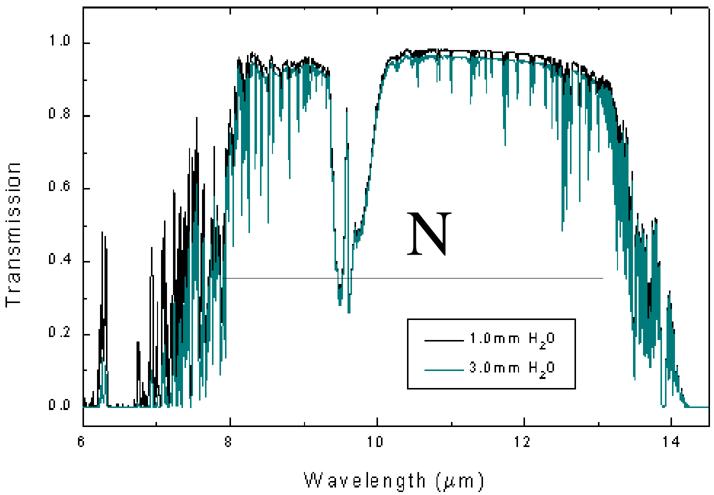


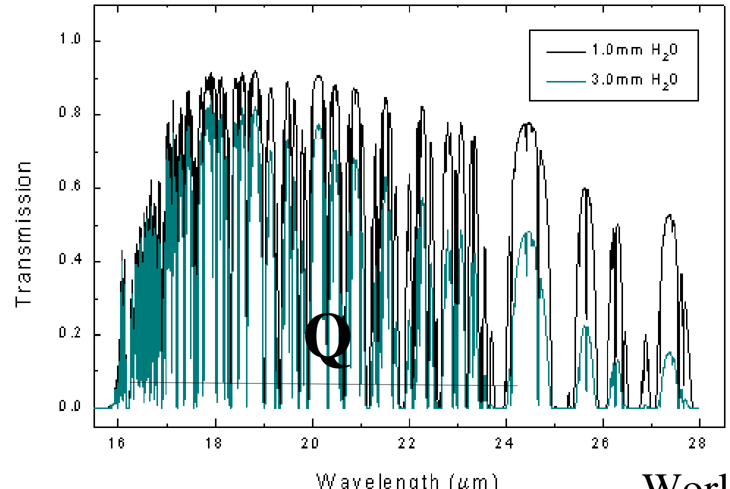
Why (stratosphere- and) space-based? The atmosphere both absorbs and emits in the infrared.



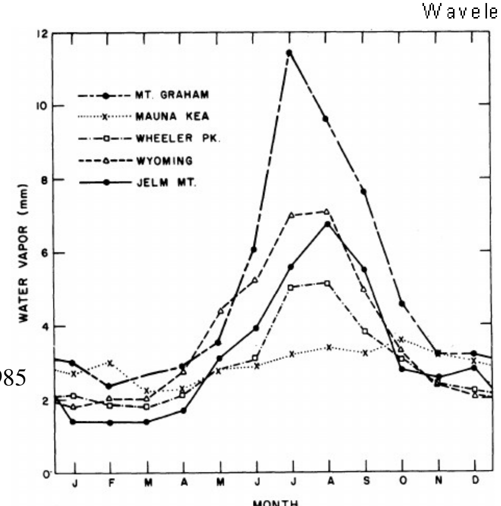


http://gemini.edu

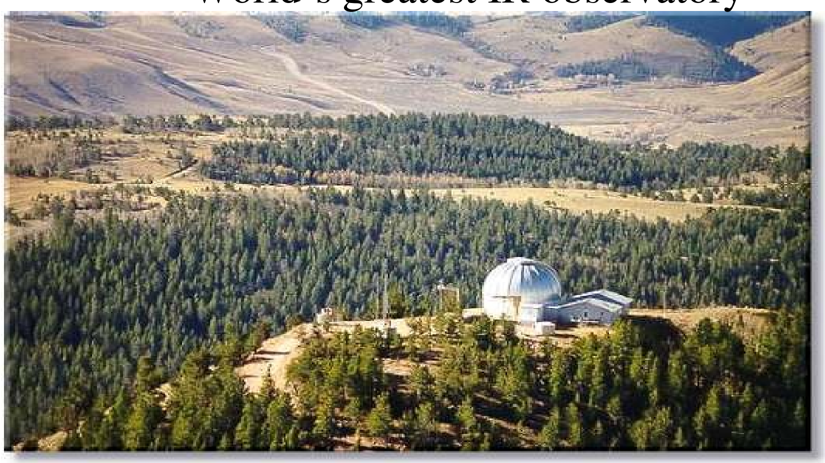




Grasdalen+1985

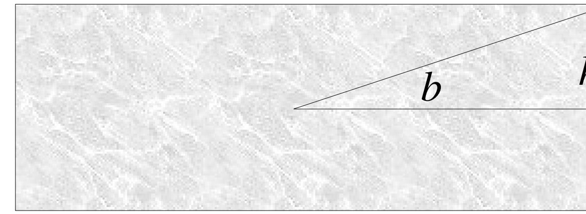


World's greatest IR observatory



Interstellar Grains

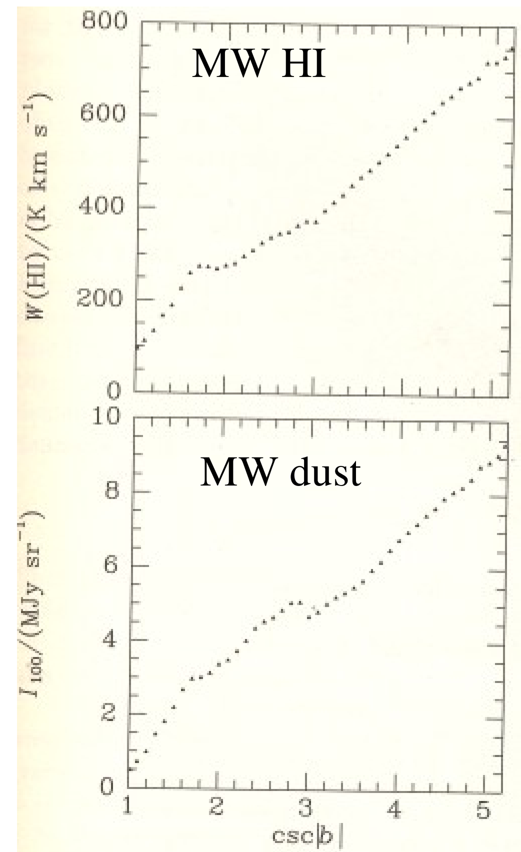
If we model the dust distribution in the Milky Way as a uniform slab of thickness $2h$, then we'd expect the dust emission to be proportional to the cosecant of the Galactic latitude b: $f_\nu(\mathrm{IR}) \propto h\csc(b)$. This is consistent with observations (below schematic).



- -Interstellar dust is composed of clumps of atoms and molecules, much like common smoke, soot, chalk dust, ...
- -Interstellar dust is typically of size ~0.01-1μm
  ⇒ good scatterer of optical light
- -Emission by dust is often fit by a single Planck function times a ν-dependent emissivity (aka 'modified blackbody')

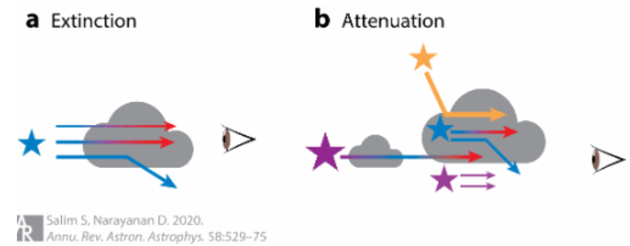
$$f_\nu \propto \varepsilon_\nu B_\nu(T_{dust}) \text{ where } \varepsilon_\nu \propto \nu^\beta$$

- -Dust can polarize light
  ⇒ elongated and aligned
- -30-50% of a galaxy's luminosity is stellar light reprocessed by dust (and 50% for the entire Universe)
- -Interstellar space is 10^6 times 'dirtier' than Earth's atmosphere
- -1 Earth volume = 1 pair of dice



Binney & Merrifield 1998

Consistent with dust coming from the ISM!



The Milky Way is patchy ⇒ extinction by dust

$I_\lambda = I_\lambda^o e^{-\tau}$

for $a << \lambda$, $\tau_\lambda \propto \lambda^{-4}$ (Rayleigh)

for $a >> \lambda$, $\tau_\lambda \propto \lambda^0$ (geometrical) what does this mean?

Reddening: extinction is higher towards the ____ ⇒ stars appear _______.

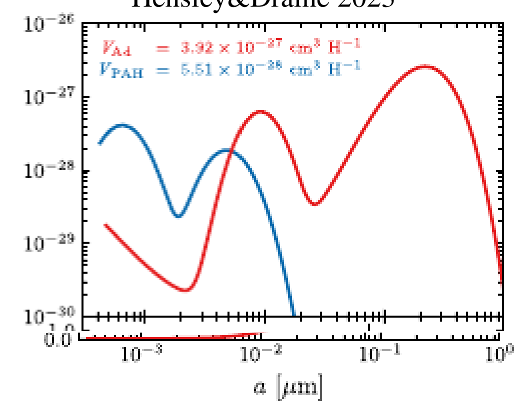
What about the 'blueing' of reflection nebulae?!

a ~0.01-1μm (particles are ~size of visual photons)

Extinction is ~ 1 mag/kpc in solar neighborhood

Early references: Struve 1847; van de Hulst 1957

Hensley&Draine 2023



Definitions

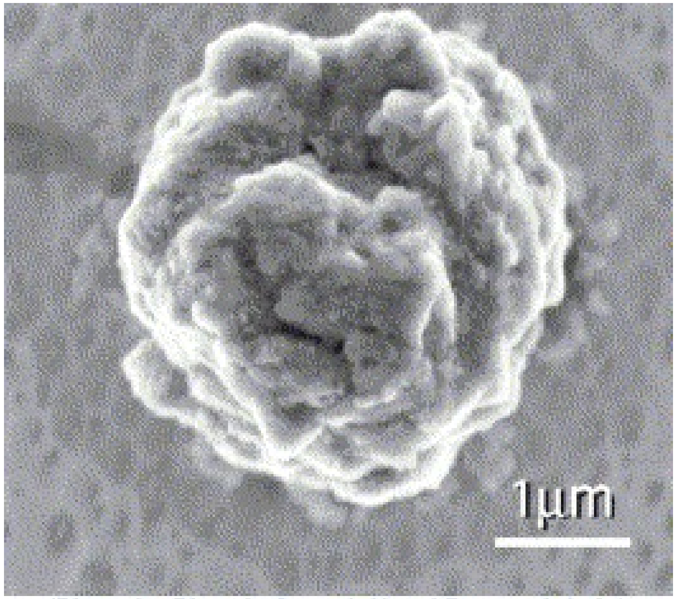
Q	=	$\sigma_{opt}/\sigma_{geom}$	extinction efficiency	$= \sigma_{opt}/\pi a^2$ (for spheres)
Q_s	=	$\sigma_{scat}/\sigma_{geom}$	scattering efficiency	
Q_a	=	$\sigma_{abs}/\sigma_{geom}$	absorption efficiency	
Q	=	$Q_s + Q_a$	total extinction efficiency	

A_λ = extinction at wavelength λ

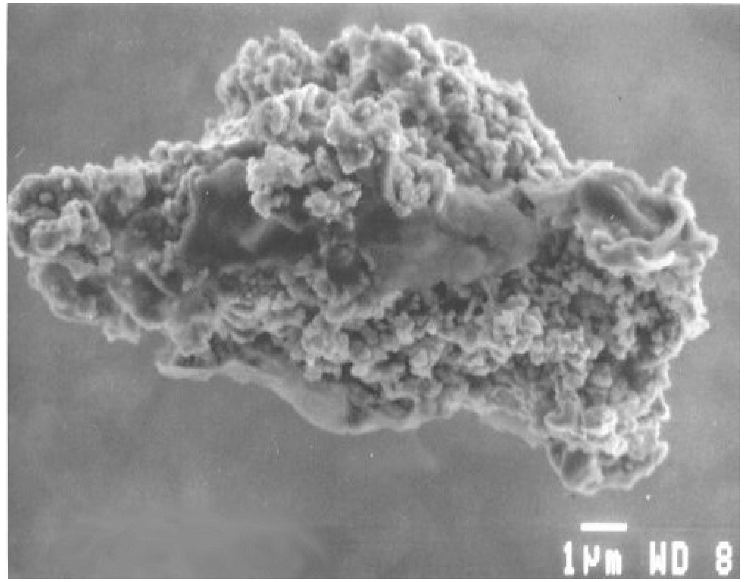
A_λ/N_{Htotal} ~ dust/gas ratio

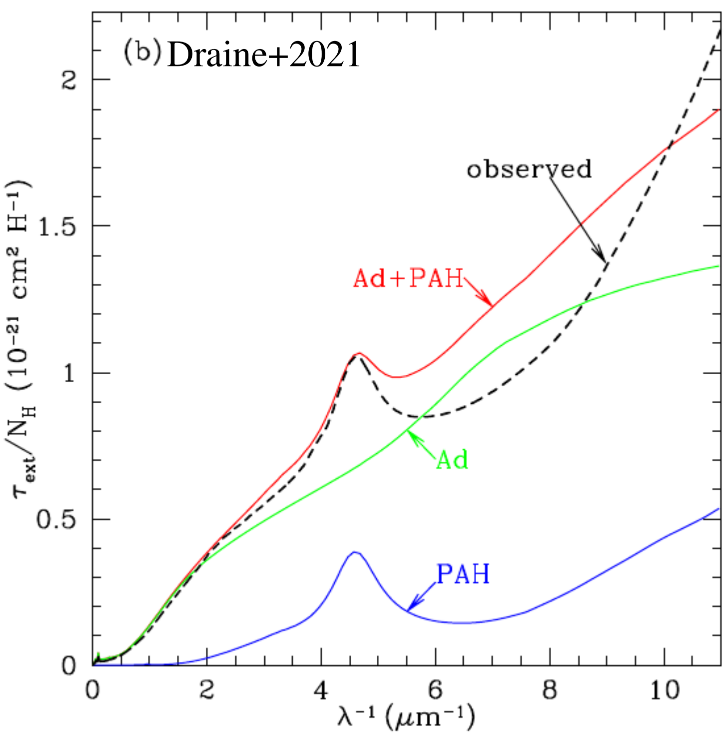
It is found that A_I/N_{Htotal} ~ _____ mag cm^2 ⇒ a given mass of gas contains a characteristic amount of dust, irrespective of whether the hydrogen is in the form of H or H_2.

Interstellar Grains



(Photo by Rhonda Stroud, Naval Research Lab.)

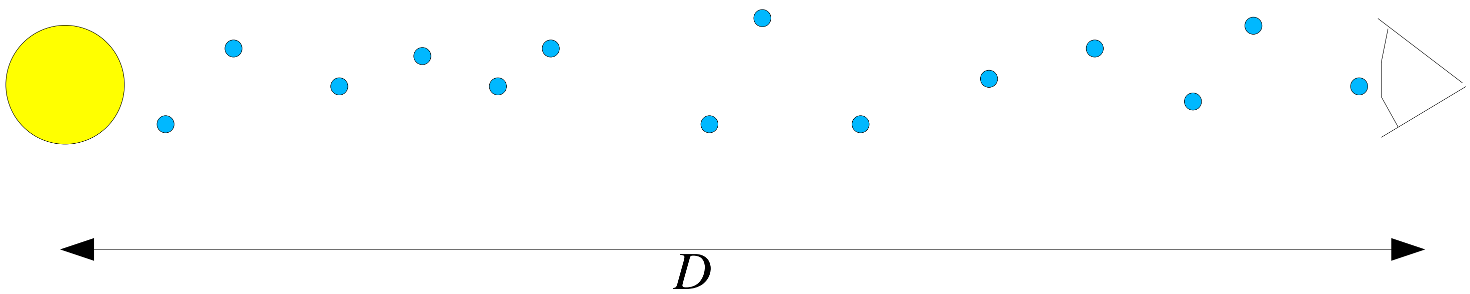




Galactic extinction curve shows peak characteristic of tiny dust 'grains' called PAHs (see Slide 22).

Classical grains of size ______ are primarily responsible for The diffuse Galactic emission at long wavelengths

$I_V = I_V^{o} 10^{-Av/2.5}$, $N_H = \int n_H ds = n_H D$ for uniform density



$I_\lambda = I_\lambda^{o} e^{-\tau} \Rightarrow \tau_V = A_V \ln(10)/2.5 = A_V 2.303/2.5 = A_V 0.9210 = A_V/1.086$

and $\tau_V = Q\pi a^2 n_d D = \sigma_{opt} n_d D$

and $N_H = n_H D$

Now we can estimate the **gas-to-dust ratio**

$\tau_V/N_H = Q\pi a^2 n_d/n_H \Rightarrow n_H/n_d = Q\pi a^2 N_H/\tau_V$

$\rho_{dust} = 4/3\pi a^3 \rho_{grain} n_d$ = dust mass/volume

$\rho_{gas} = m_H n_H$

$\Rightarrow \rho_{gas}/\rho_{dust} = \quad = ¾\, m_H/(\pi a^3 \rho_{grain})\, Q\pi a^2 N_H/\tau_V = 1.086\ ¾\, m_H/a\, Q/\rho_{grain}\, N_H/A_V$

Take a~0.1μm, ρ_{grain}~ 2 g cm^{-3}, m_H = 1.67 10^{-24} g

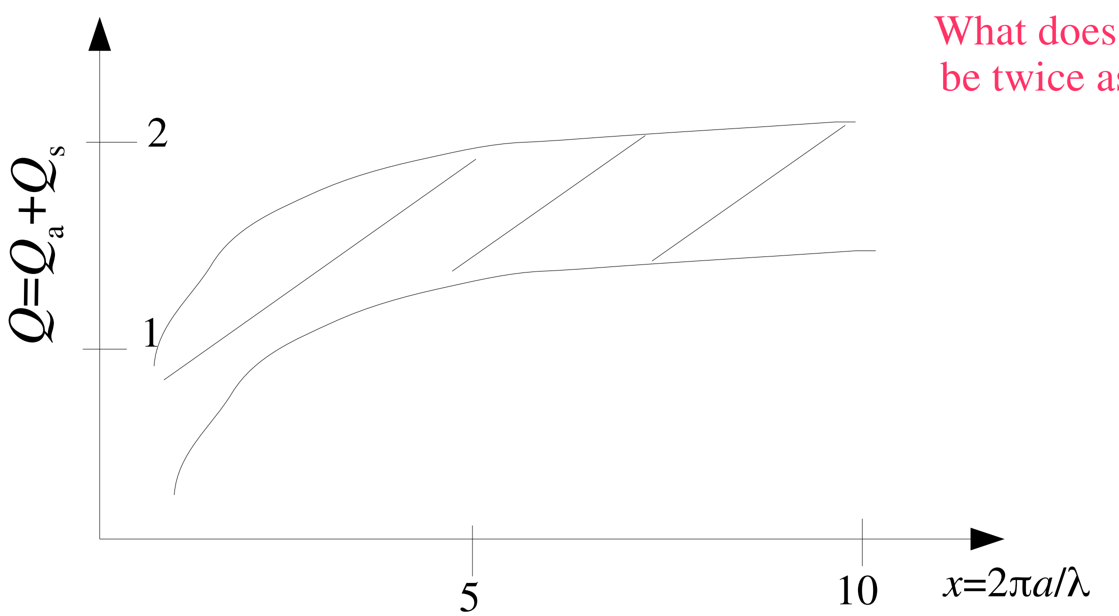
Q varies with λ, but for optical λ and typical grain size, Q is of order 10^{0}.

$$\Rightarrow \boxed{\rho_{gas}/\rho_{dust} = 130 \sim 10^2}$$

Reference for gas-to-dust ratios in spiral galaxies: Mayya & Rengarajan 1997, Remy-Ruyer+2014

This ratio is roughly what one gets by summing metal-to-hydrogen ratios for the solar neighborhood abundances (see table from Ch. 2&3&4 Slide 2).

$\{\Sigma(n_i/n_H)\ \text{A.W.}_i\}^{-1} \sim 10^2$



What does this mean plot mean, and how can a cross-section be twice as large as the geometrical value (Tielens Fig 5.1)?

Extinction

The dimming of light $A_\lambda = (m - m_0)_\lambda$ p.133 Binney & Merrifield 1998

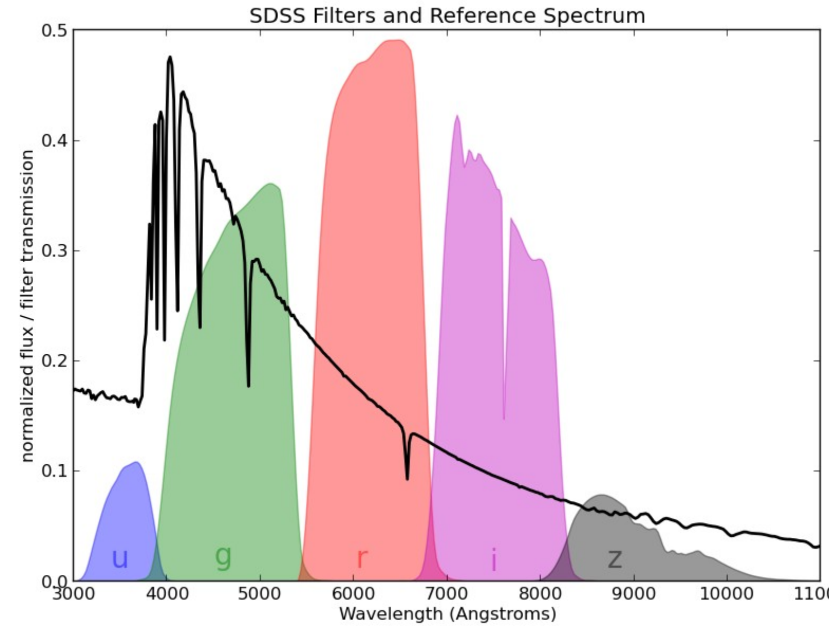
Reddening, or a general color excess, is the difference between observed and intrinsic color

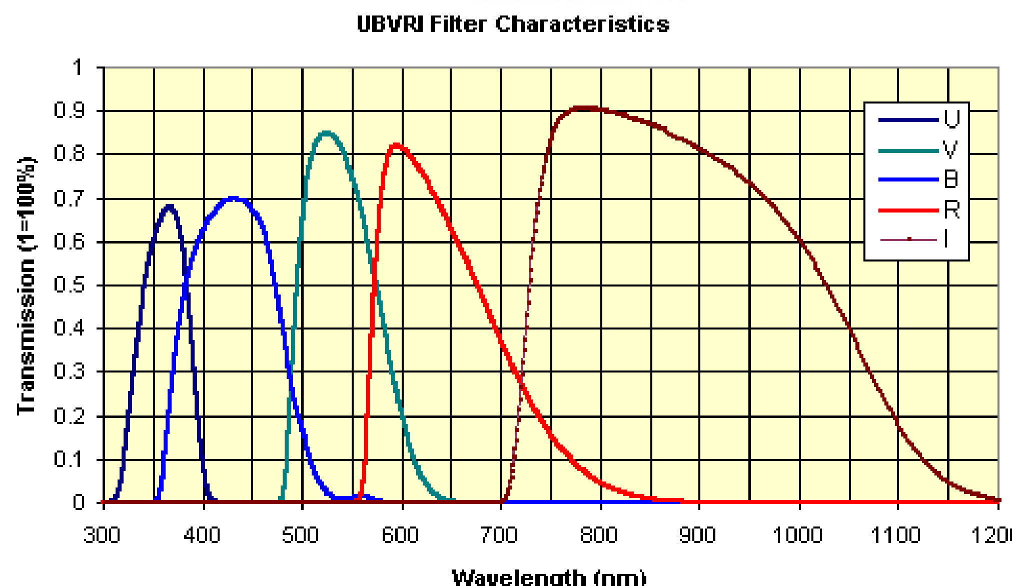
$$E(\mathrm{X-Y}) = [m(\mathrm{x}) - m(\mathrm{y})] - [m_0(\mathrm{x}) - m_0(\mathrm{y})] = A_\mathrm{x} - A_\mathrm{y}$$

Some standard filters for optical astronomy

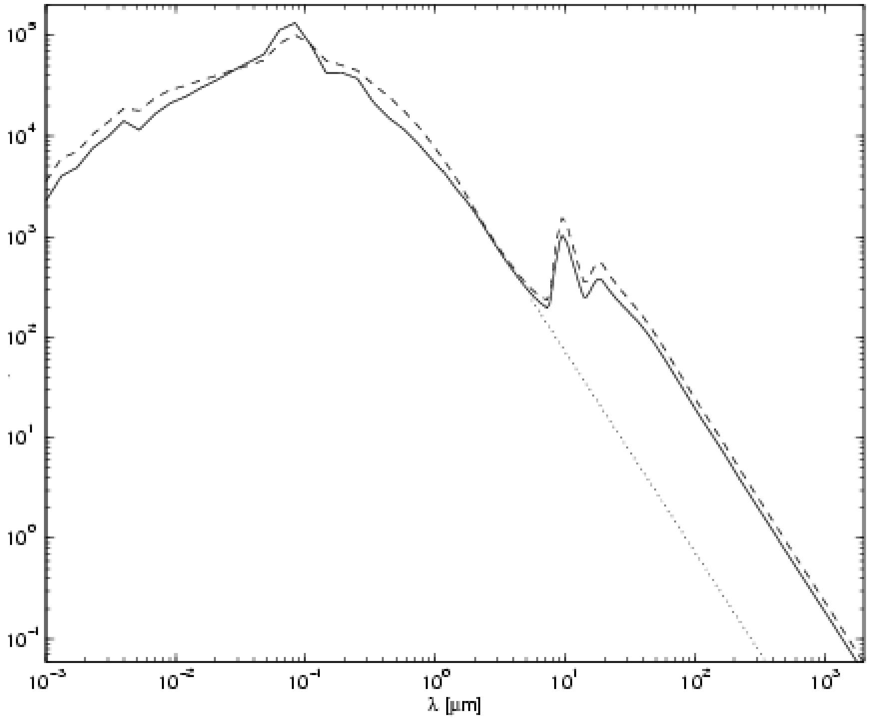
	λ	Δλ(nm)		λ	Δλ(nm)
U	365	66	u	356	60
B	445	94	g	483	138
V	551	88	r	626	138
R	658	138	i	767	153
I	806	149	z	910	137

The frequently-quoted color excess is E(B-V).
For much of the ISM, $A_\mathrm{V} \sim 3.1 E(\mathrm{B-V})$
(→ Slide 12).

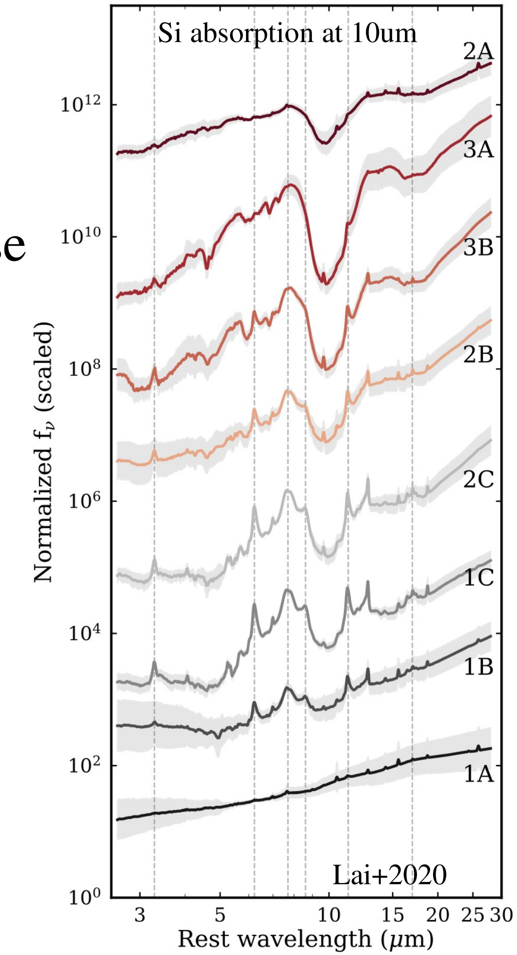




Extinction curve



The extinction curve broadly maximizes near 0.1μm because there are many dust grains in the ISM of this size. The sharper features arise from absorption by other particular dust grain types.



Does A_V scale with any parameter in this listing?

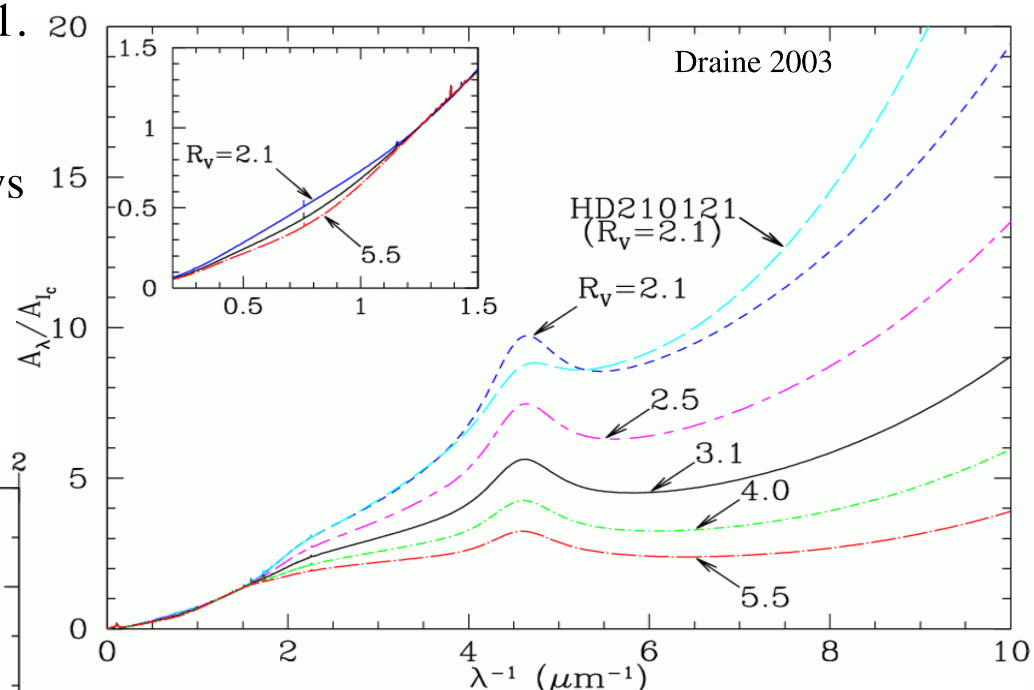
Why doesn't this table obey the canonical 1 mag/kpc we learned about on Slide 6?

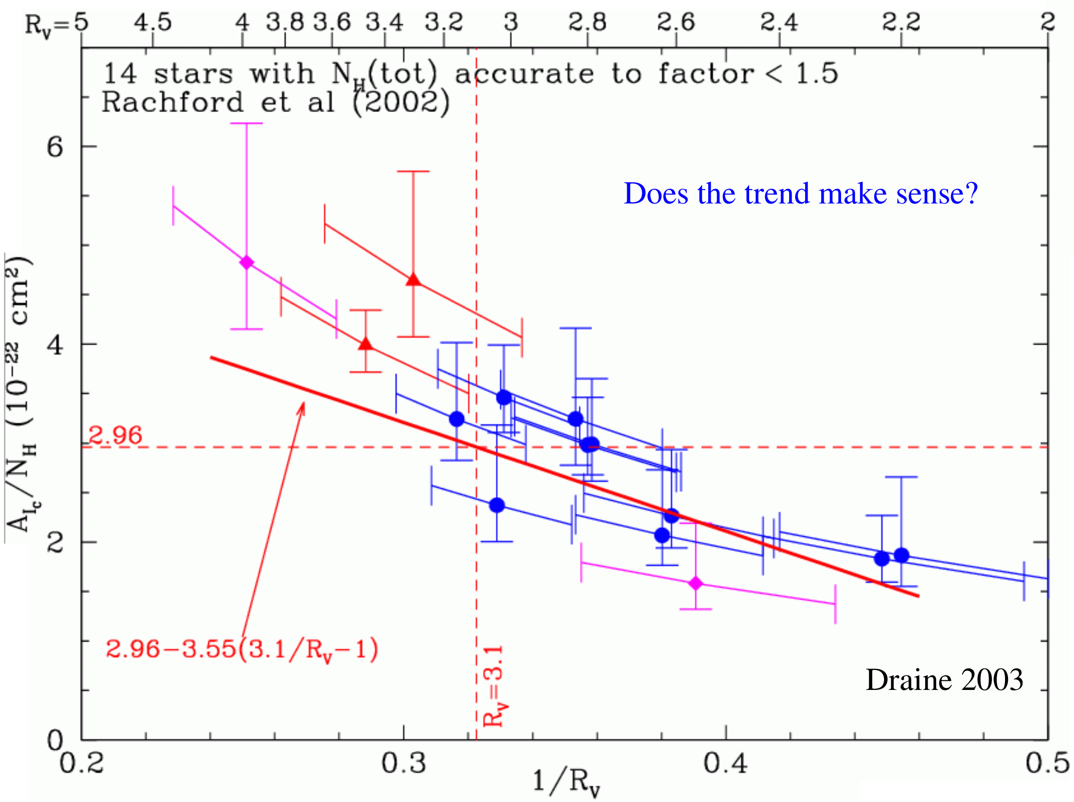
	Globule	IR Cloud	Dark Cloud	Diffuse Cloud	Cloud Complex
A_V (mag)	4	30	4	0.2	4
N_H (cm-2)	8e21	6e22	8e21	4e20	8e21
n_H (cm-3)	7000	40000	2000	20	200
R (pc)	0.3	0.4	1	5	10
T (K)	10	50	10	80	10
M (Msun)	30	400	300	400	30000

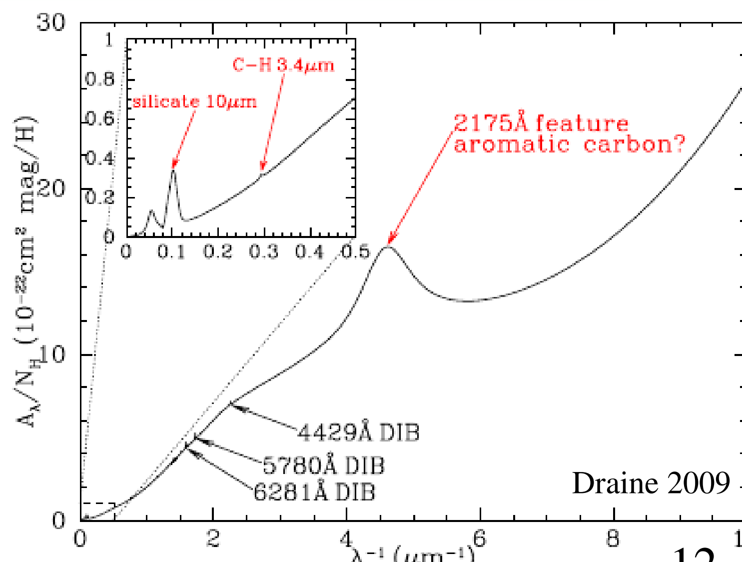
Milky Way Extinction (Draine 2003; 2009)

$R_V \equiv A_V/(A_B - A_V)$ characterizes the slope of the extinction curve over optical wavelengths. Very large grains would produce $R_V \rightarrow \infty$ (why?), whereas Rayleigh scattering ($A_\lambda \propto \lambda^{-4}$) would produce very steep extinction with $R_V \approx 1.2$. A 'standard' Milky Way value: $R_V \approx 3.1$.

We discussed how A_V/N_H was essentially constant for every line-of-sight. Work by a UWyo PhD shows that this is true to within a factor of 2 (below).

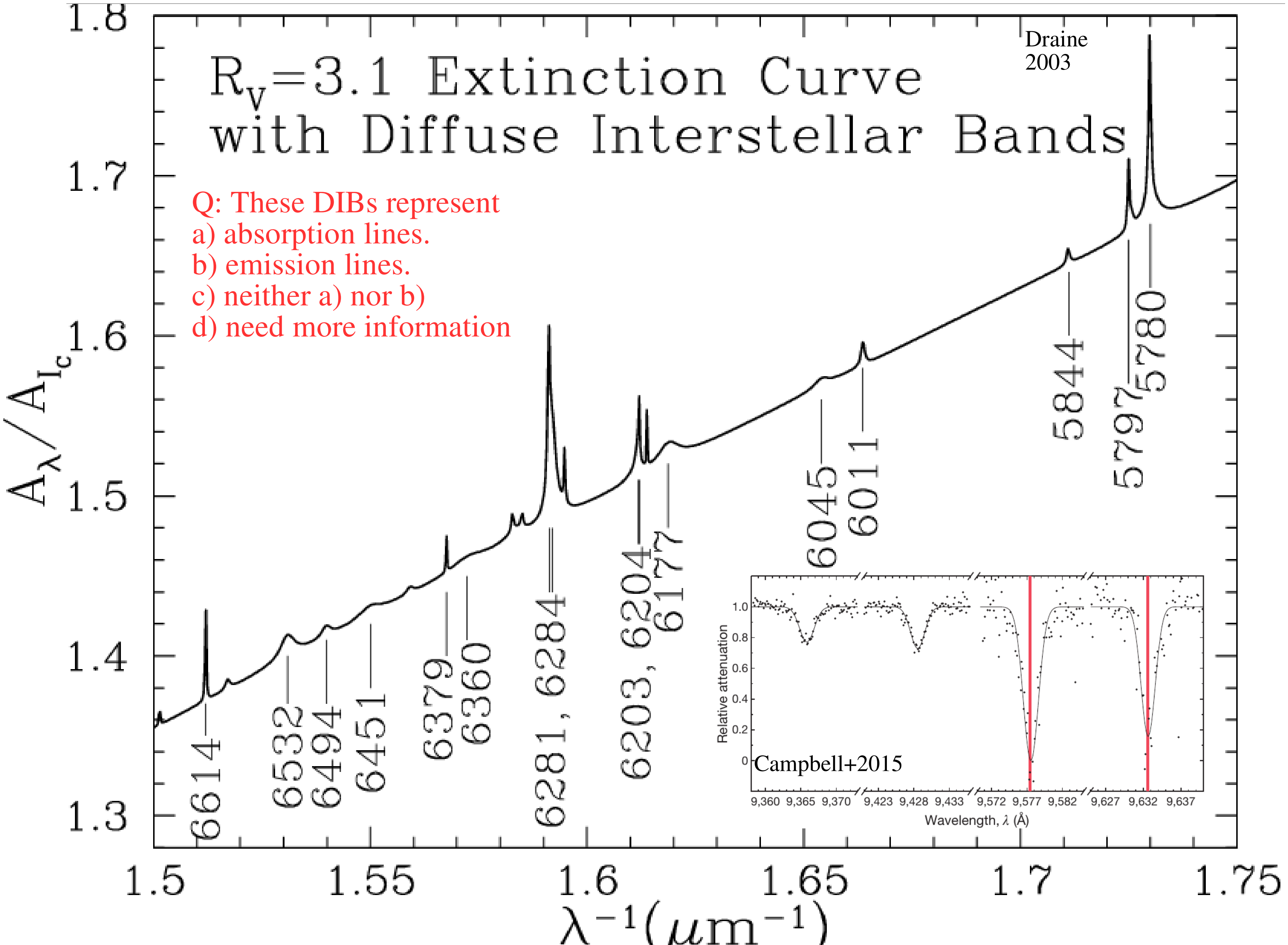






<u>Milky Way Extinction</u> (Draine 2003)

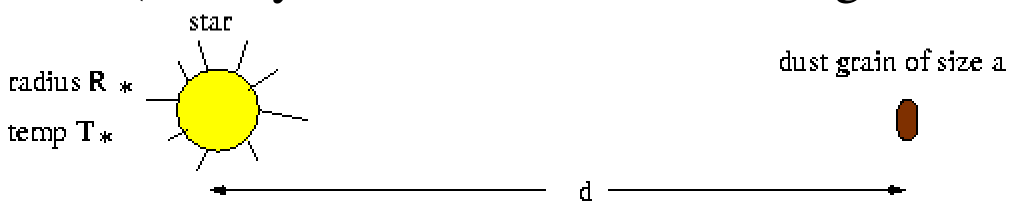
There are over 150 'diffuse interstellar bands' that are probably due to PAHs. They were discovered in 1922, but the first convincing identification occurred in 2015!



Q: These DIBs represent
a) absorption lines.
b) emission lines.
c) neither a) nor b)
d) need more information

Thermal Emission from Large Interstellar Dust Grains

Dust absorbs photons, typically in the UV or visible since the cross-section is higher there, and then radiates (usually in the infrared — a dust grain cannot get too hot or it will evaporate!).



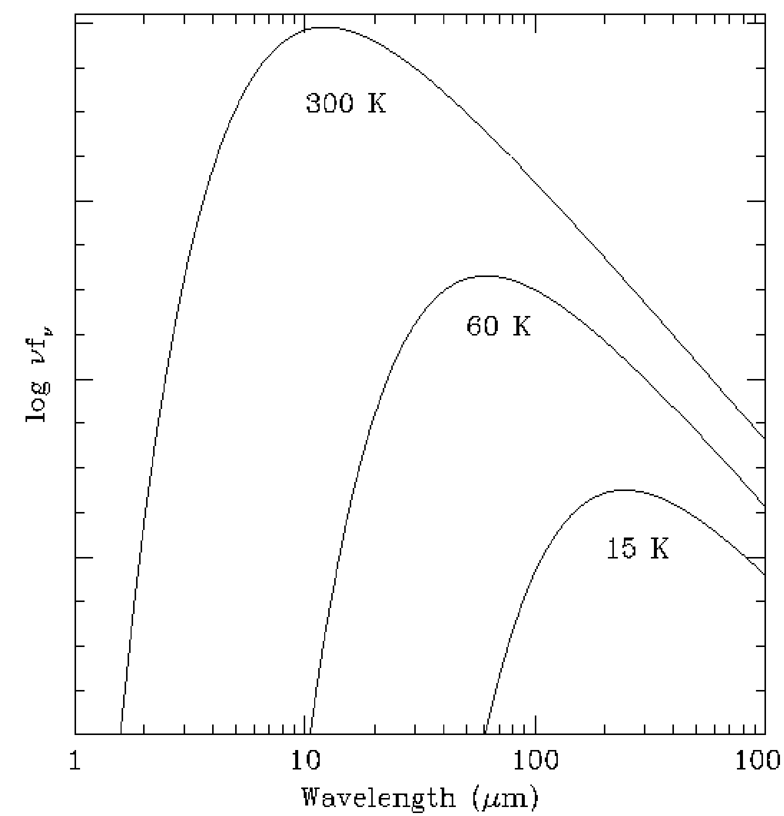
The flux from the star at a distance d is $f_\nu = R_*^2 F_\nu / d^2 = R_*^2 \pi B_\nu / d^2$

if the star radiates as a blackbody.

The dust absorbs energy at a rate $P_{\rm abs} = \int_0^\infty d\nu Q_{\rm abs} \pi a^2 R_*^2 \pi B_\nu(T_*)/d^2$

and will emit radiation at a rate $P_{\rm em} = \int_0^\infty d\nu Q_{\rm em} 4\pi a^2 \pi B_\nu(T_{\rm d})$

where $T_{\rm d}$ is the dust temperature and $4\pi a^2$ is the spherical area of the grain.



If the dust grain is in thermal equilibrium, the radiative rates balance and

$P_{\rm abs} = P_{\rm em}$, or $\int_0^\infty d\nu Q_{\rm abs} \pi a^2 R_*^2 \pi B_\nu(T_*)/d^2 = \int_0^\infty d\nu Q_{\rm em} 4\pi a^2 \pi B_\nu(T_{\rm d})$

$\Rightarrow \frac{4\pi}{4\pi} \int_0^\infty d\nu Q_{\rm abs} R_*^2 \pi B_\nu(T_*)/d^2 = 4 \int_0^\infty d\nu Q_{\rm em} \pi B_\nu(T_d)$

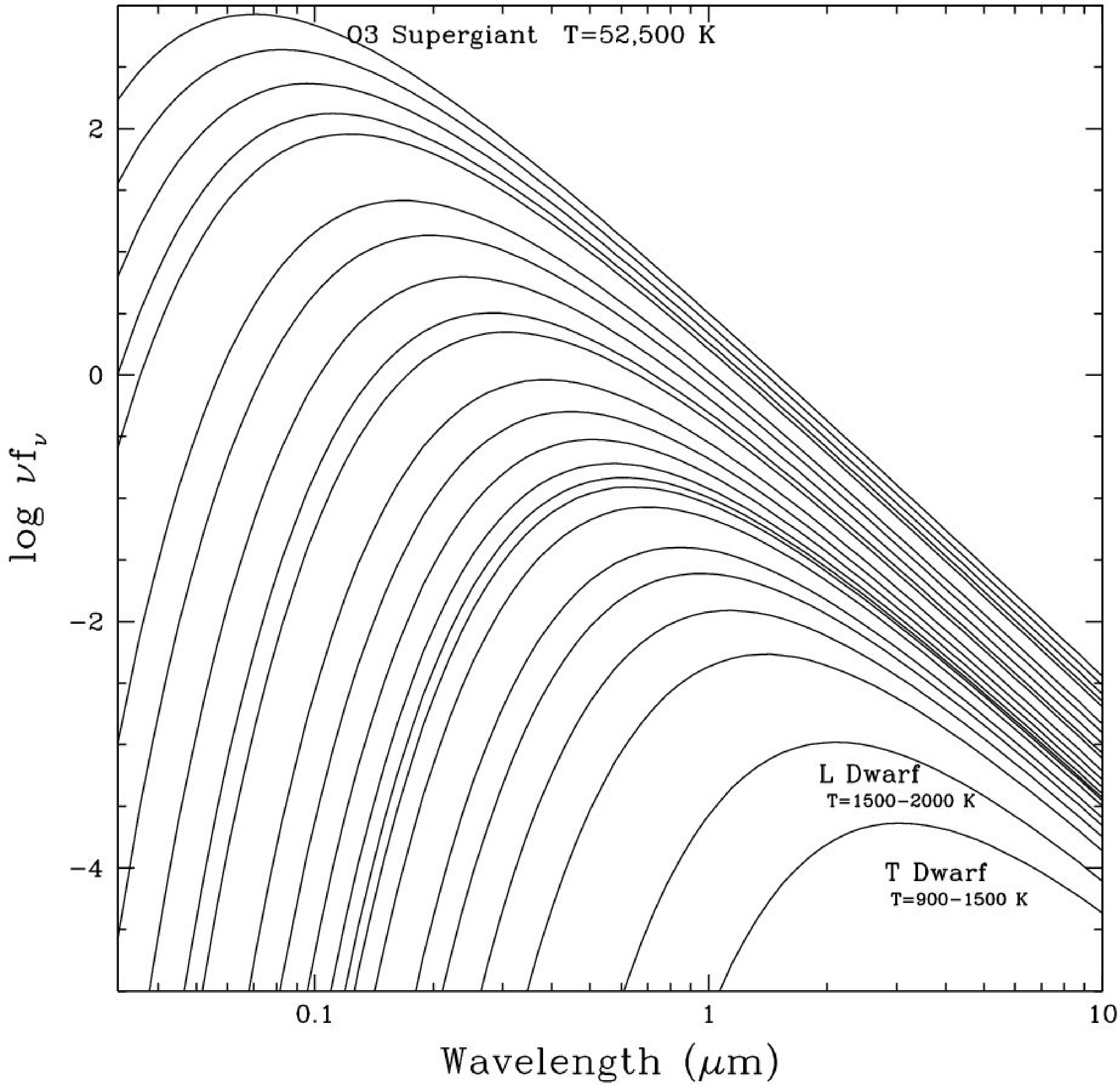
$\Rightarrow \frac{Q_{\rm abs}}{Q_{\rm em}} \cdot \frac{1}{16\pi d^2} \int_0^\infty d\nu 4\pi R_*^2 \pi B_\nu(T_*) = \int_0^\infty d\nu \pi B_\nu(T_d)$

$\Rightarrow \frac{Q_{\rm abs}}{Q_{\rm em}} \cdot \frac{1}{16\pi d^2} \cdot L_* = \sigma T_d^4$

$\Rightarrow T_{\rm d} = \left(\frac{L_* Q_{\rm abs}}{16\pi d^2 \sigma_{\rm SB} Q{\rm em}}\right)^{\frac{1}{4}} = 279K \left(\frac{Q_{\rm abs}}{Q_{\rm em}}\right)^{\frac{1}{4}} \left(\frac{1{\rm A.U.}}{d}\right)^{\frac{1}{2}} \left(\frac{L_*}{L_\odot}\right)^{1/4}$

Blackbody reminder

If the stars radiate as blackbodies, the main sequence profiles are defined by the effective stellar temperatures



where emissivity per unit area per steradian $= Q_{em} B_\nu$

$= Q_{abs} B_\nu$ (by Kirchoff's Law)

Suppose we have very big particles, e.g., planets or asteroids. Now in general, the l.h.s. of the radiative balance is dominated by optical/UV photons and the r.h.s. by the emission of infrared photons. Let us take the average visual albedo to be *A*, implying Q_{abs}=1-*A*, and the average emissivity in the infrared to be Q_{em}. Assume rapid rotation, like for an isothermal planet or asteroid.

Using Wien's Law ($\lambda_{peak} T \sim 0.29$ cm K) gives $\lambda_{peak} \sim$ __µm for T=279 K (in the mid-infrared)

Note that if the object were not rotating (and not thermally conductive), we have

$$\Rightarrow T_{\rm d} = \left(\frac{L_* Q_{\rm abs}}{4\pi d^2 \sigma_{\rm SB} Q{\rm em}}\right)^{\frac{1}{4}} = 395K \left(\frac{Q_{\rm abs}}{Q_{\rm em}}\right)^{\frac{1}{4}} \left(\frac{1{\rm A.U.}}{d}\right)^{\frac{1}{2}} \left(\frac{L_*}{L_\odot}\right)^{1/4}$$

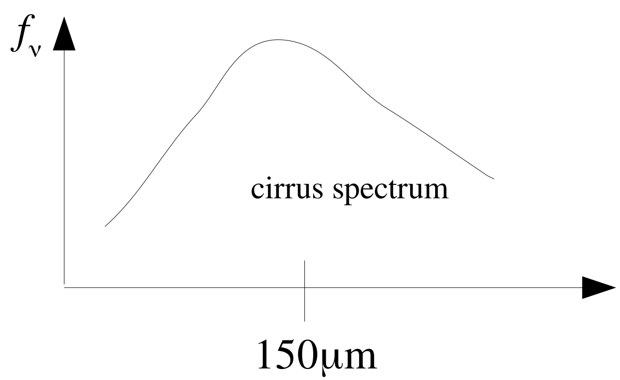
In other words, the effective radiating area is ___ rather than ___ for the subsolar point (i.e., at 'noon'). The moon could be an example.

For a large object like an asteroid we would have Q_{em}~1. However, for a dust particle in the infrared $Q_{em}=Q_{abs} << 1$ in general because the particle is much smaller than the wavelength. In the visible Q_{abs}~1. All this means that small particles will be <u>hotter</u> than larger ones because they do not radiate very efficiently in the infrared.

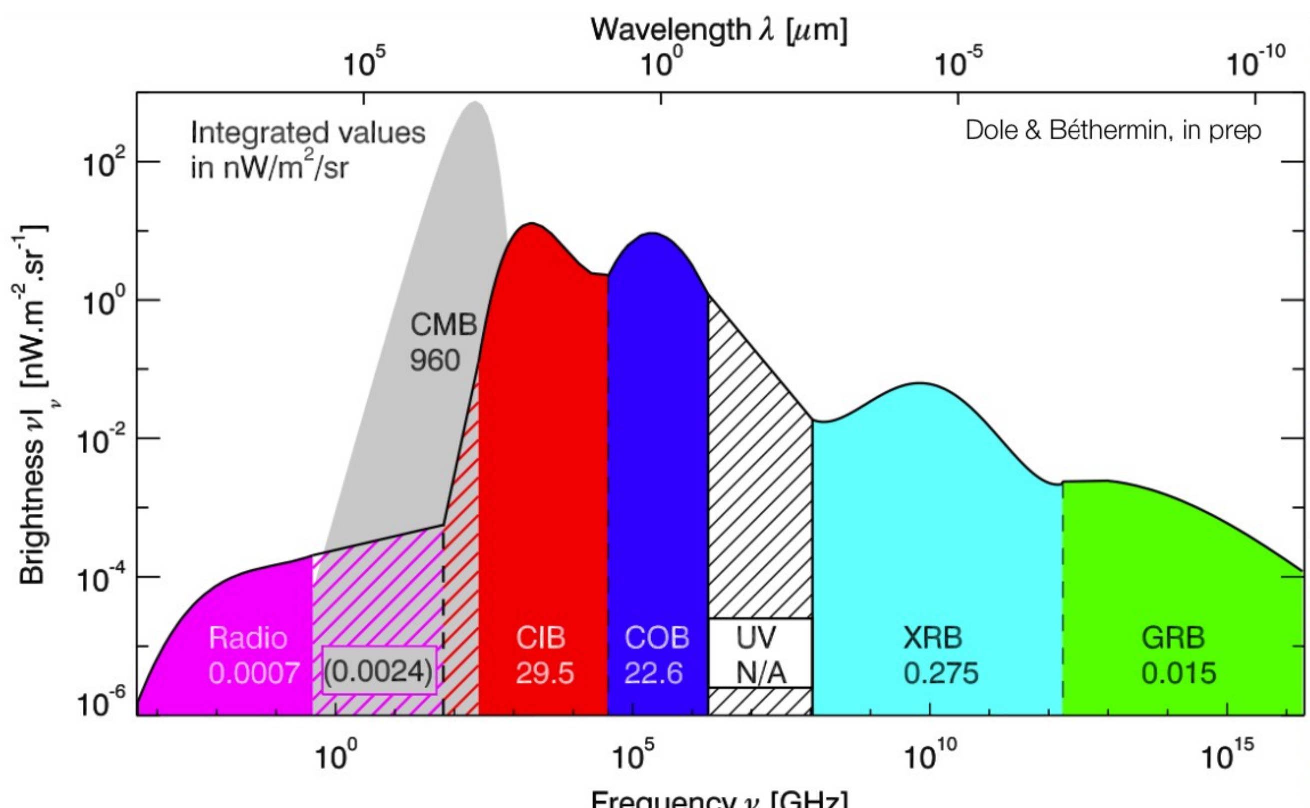
What do we see emitted from dust?

As we've already seen, the extinction curve toward stars is fairly smooth and exhibits a peak near 217.5nm, which is attributed to large PAH clusters. The bulk of the absorbed starlight heats large dust grains to temperatures ~20K, grains that are thinly spread throughout the ISM. These grains are responsible for the 'diffuse cirrus' emission (see Slide 6; of course those dust particles very near hot stars will be heated to much higher *T*). According to Wien's Law, the characteristic wavelength of emission is ~150μm.

In fact, up to 50% of the energy radiated in the Universe is emitted at IR wavelengths.



Galaxy formation & evolution processes contribute ~5% of the electro-magnetic content of the Universe, with about half from starlight and half from dust.



All is not rosy with this simple picture of dust emission, however. In some cases dust is found which is much hotter than you would expect to find on the basis of thermal equilibrium calculations, e.g., the case of the reflection nebula NGC 7023.

$L_{*}=10^4\ L_{sun}$ $\qquad$ d=0.15 pc

$\Rightarrow \quad T_d =$ ___ K $(Q_{UV}/Q_{IR})^{1/4}$ where Q_{UV} and Q_{IR} are average UV and IR absorption and emissivity.

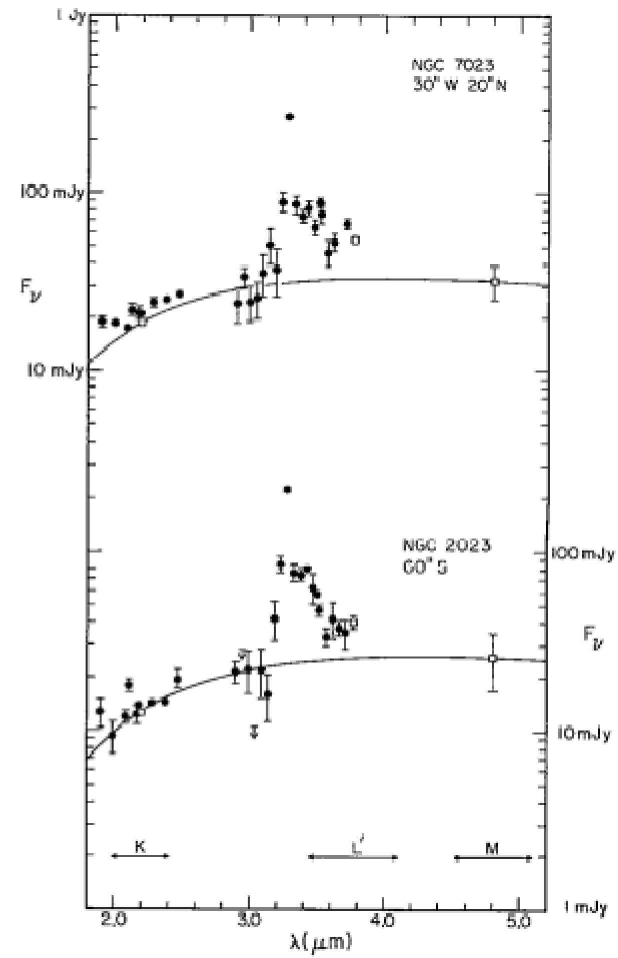
For a plausible range of Q_{UV} and Q_{IR}, we'd expect T_d = 70-150 K.

But this is <u>not</u> what is observed! If dust grains near NGC7023 are in thermal equilibrium with the surrounding interstellar radiation field, then the observations indicate T_d >1000 K !!

One possible explanation is that the observations are of reflected starlight — that light should be bluer than the stellar spectrum, but observations do not support this explanation (it isn't bluer).

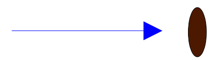
What is the answer? **Stochastically-heated small grains**

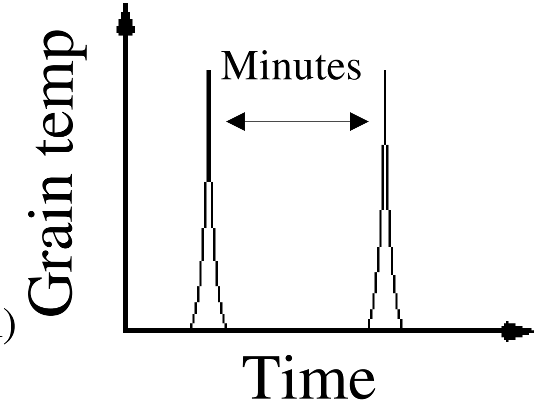
If an energetic photon strikes a very small particle, one composed of maybe 50 atoms (e.g., polycyclic aromatic hydrocarbons), the particle may significantly heat up.



Sellgren, Werner, & Dinerstein 1983

Stochastic Heating of Small Interstellar Aromatic Grains





For low T_d we have the Debye law: $C_v \propto T_d^{\,3}$

For high T_d $C_v = 3Nk_B$ why? $(6N$ = # degrees of freedom)

The dividing line between low and high temperatures is the 'Debye Temperature' which is 200-500 K for typical grain material. It is usually indicated by θ_D.

Suppose the dust becomes very warm when a photon hits it, so that $T_d > \theta_D$. The main contribution to the heat capacity will be the high T component, so $C_v = 3Nk_B$. Then $h\nu = 3Nk_B\Delta T_d$.

In NGC 7023, color temperatures of ~1000 K are seen from the dust.
Supposing λ~2000Å (near the peak of a moderately warm star),

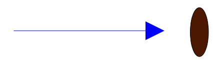
$N = h\nu / 3k_BT_d \sim$ ___

A couple dozen 'atoms' are present in the particle! A more careful analysis gives N=70-90 atoms for silicate or graphite grains. Thus the physics of very small grains was born.

Note that if we assume a lattice spacing of 3Å: $N = 4/3\pi a^3 (3Å)^{-3}$

$\Rightarrow a = 3(¾\, N / \pi)^{1/3} \sim 3(¾\; 80 / \pi)^{1/3} \sim 8$Å for the particle size

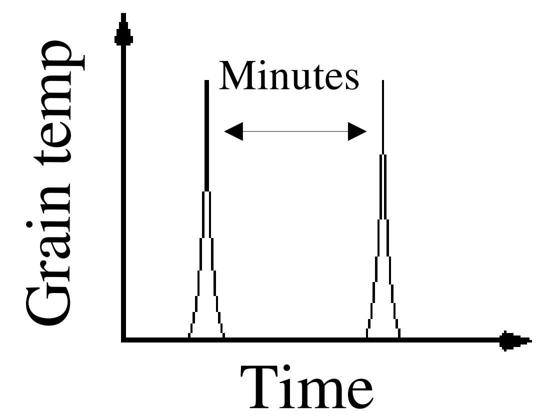
Stochastic Heating of Small Interstellar Aromatic Grains – back of the envelope



The absorption of an energetic photon causes an N-atom grain to heat up:

$$\Delta E = \int dT \frac{\partial E}{\partial T} \rightarrow h\nu = \int dT C_{\rm v},$$

where $2C_{\rm v}/k$ = number degrees of freedom $\sim 6N$



Rate at which photons hit the grains: (e.g. NGC 7023)

$$\begin{aligned} \Re &= \text{star photon rate} \times \frac{\text{projected grain surface area}}{4\pi d^2} \\ &\approx \frac{L_*}{h\nu} \times \frac{\pi a^2}{4\pi d^2} \times Q_{\rm abs} \\ &\sim 10^{-3}\ \text{sec}^{-1} \end{aligned}$$

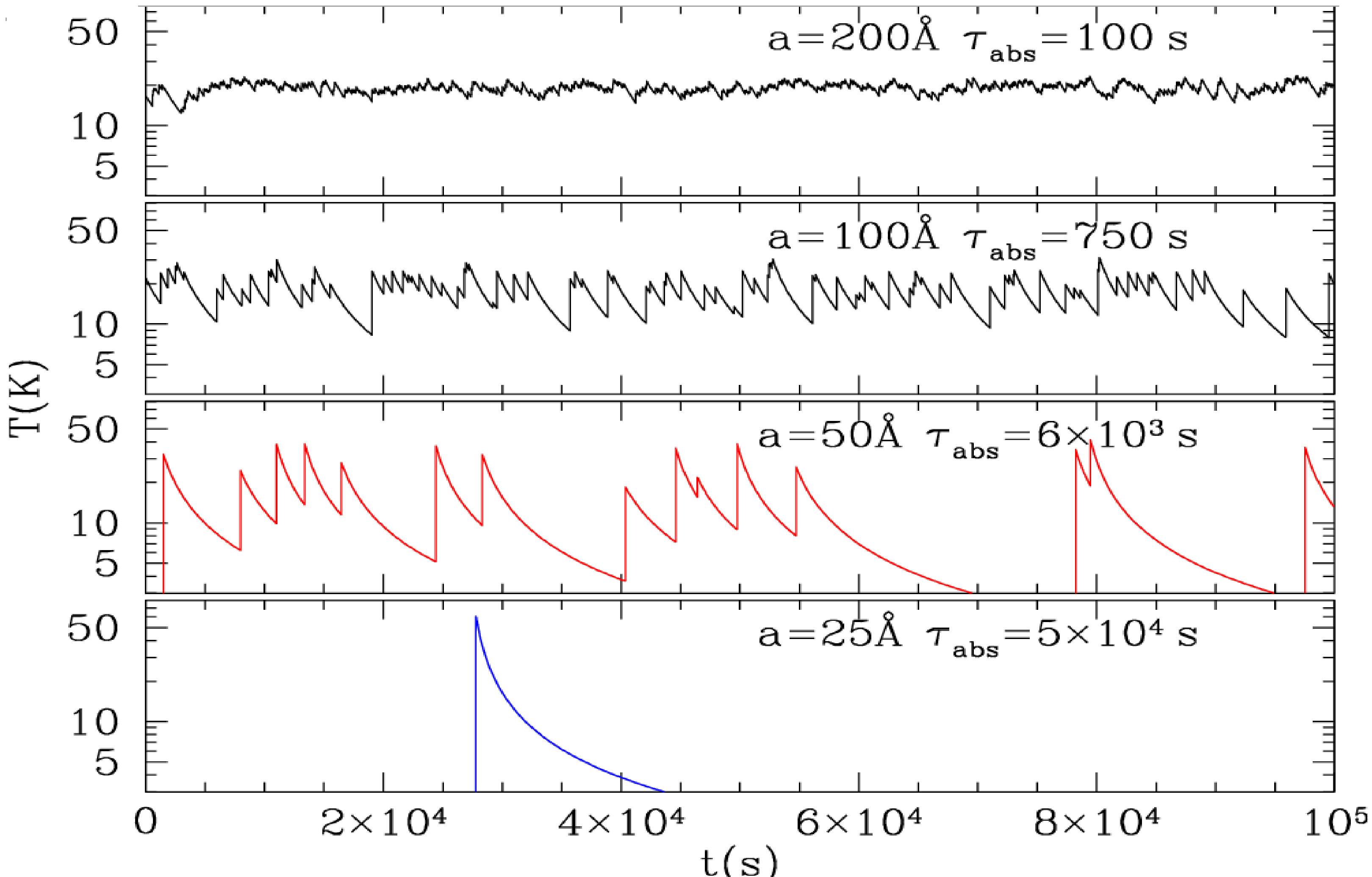
Rate at which the grains cool:

$$\begin{aligned} \Delta t^{-1} &= \frac{\partial E/\partial t}{E} \\ &\approx \frac{\text{grain luminosity}}{\frac{1}{2}kT \times \text{number degrees of freedom}} \\ &\approx \frac{4\pi a^2 \sigma T_{\rm d}^4}{3NkT} \times Q_{\rm em} \\ &\sim 10^3\ \text{sec}^{-1} \end{aligned}$$

$\Rightarrow$**Grains will cool down before another photon strikes!!**

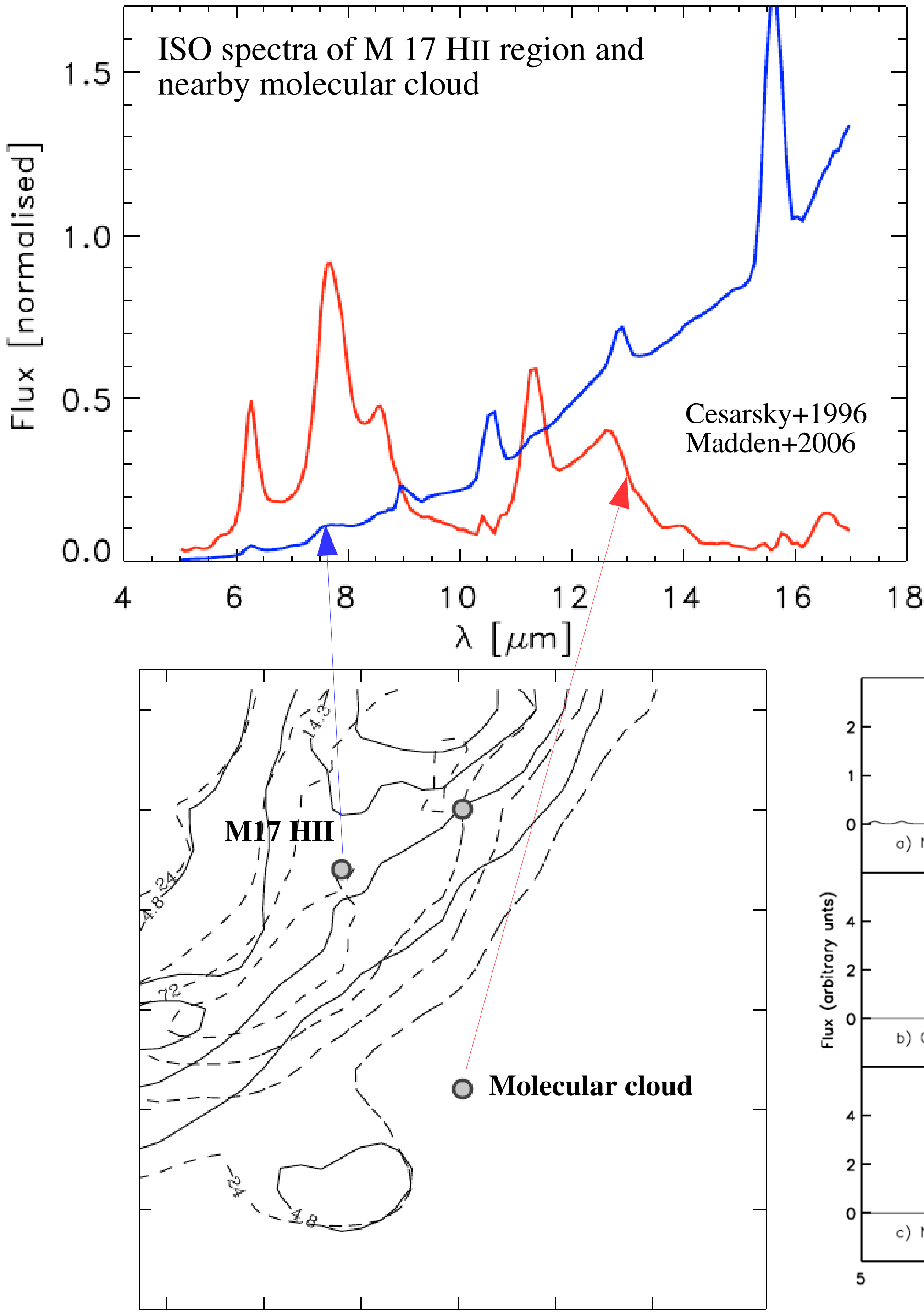
Stochastic Heating of Small Interstellar Aromatic Grains – a realistic model

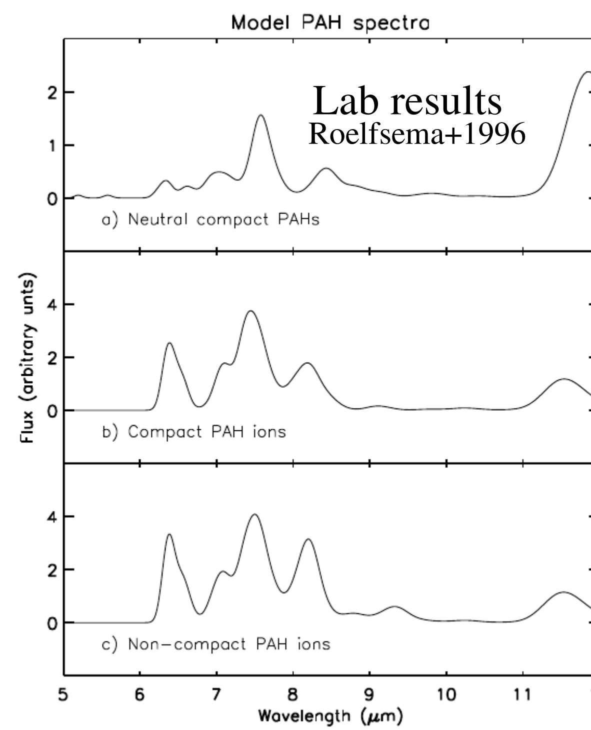
A day in the life of 4 carbonaceous grains, heated by the local interstellar radiation field. τ_{abs} is the mean time between photon absorptions (Draine 2003; Draine & Li 2001).

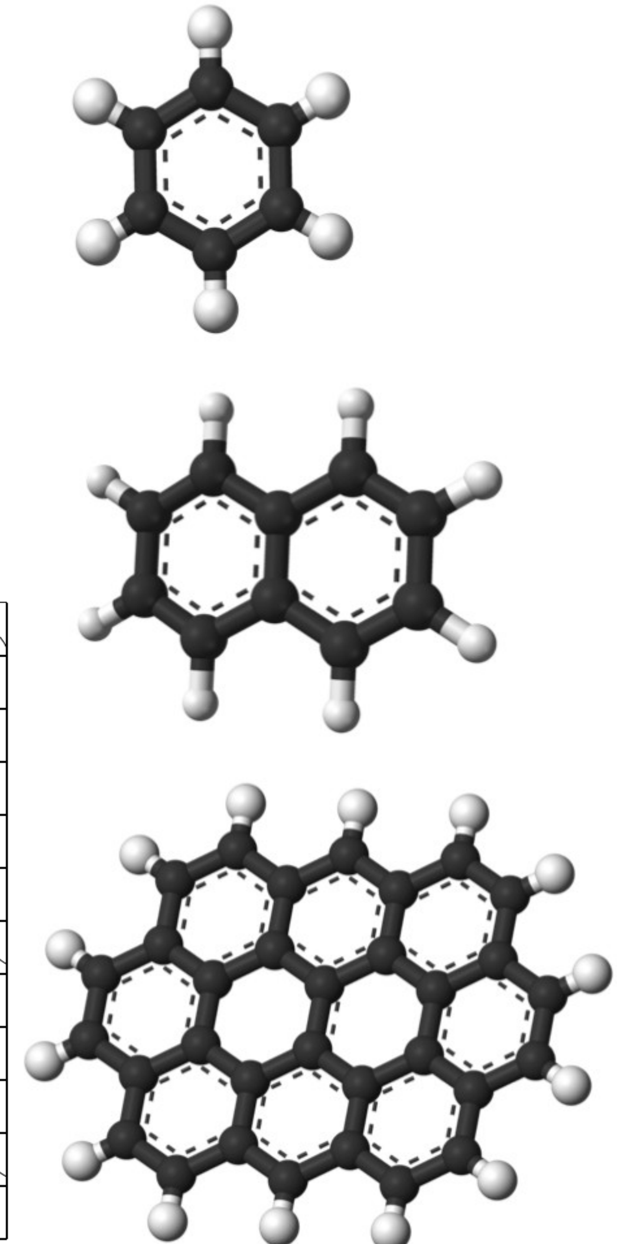


Recall from our notes that PAHS smaller than 15Å are responsible for half of the heating of the neutral ISM, and grains between 15 and 100Å are responsible for the other half. Recall also that the diffuse cirrus is caused by 'classical' large grains of size ~2000Å.

Polycyclic Aromatic HydroCarbons:
C planar structures with H appendages







Mid-Infrared Emission Features Are Ubiquitous

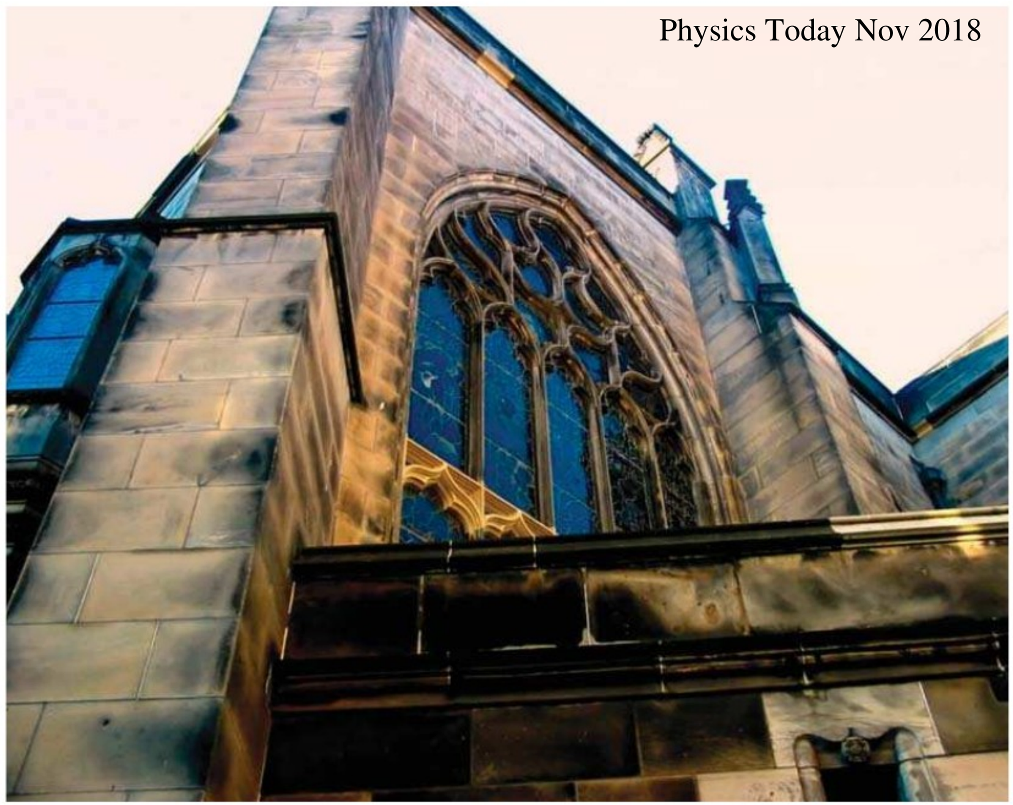
Seen in planetary nebulae, proto-planetary nebulae, reflection nebulae, H II regions, circumstellar envelopes, Galactic diffuse cirrus, external galaxies, Chevrolets, ...

Soot formation: A new mechanism for an old problem

Gaseous hydrocarbons may cluster into sooty particles through a chain reaction.

When they are burned, diesel, kerosene, firewood, and other carbonaceous fuels produce black and brown carbon particles known as soot. Humans have used soot as a pigment since prehistoric times and still use it in tires, inks, and plastics. But soot generally is not humanity's friend. Unregulated coal-burning led to soot-blackened buildings, like Edinburgh's St Giles' Cathedral in figure 1. Airborne soot particles absorb solar energy and act as condensation nuclei for cloud droplets; soot is also a pollutant that can lead to lung cancer and respiratory diseases. To help engineers design combustion systems that produce less black carbon, researchers have long wanted to better understand the process by which soot forms.

On Earth, no natural processes besides combustion produce soot. In interstellar space, similar high-temperature conditions may produce similar carbonaceous dust (see the article by Alessandra Candian, Junfeng Zhen, and Alexander G. G. M. Tielens on page 38). During combustion, gas-phase fuels and volatile



Physics Today Nov 2018

evolve during combustion, they grow into a layered structure that resembles graphite. But how the precursors can stick together to make large soot particles has remained a mystery.

FIGURE 1. ST GILES' CATHEDRAL IN EDINBURGH. Unregulated coal burning from the Industrial Revolution up to the 1950s led to many soot-blackened buildings in the UK. (Photograph by Rachelle Burnside/ Shutterstock.com.)

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

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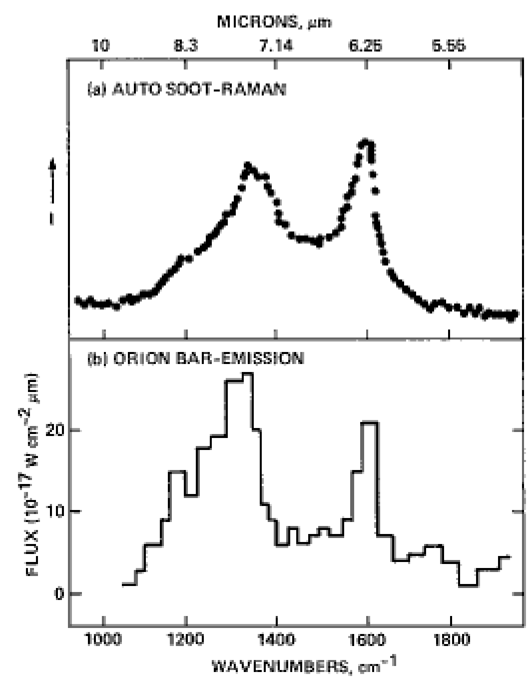
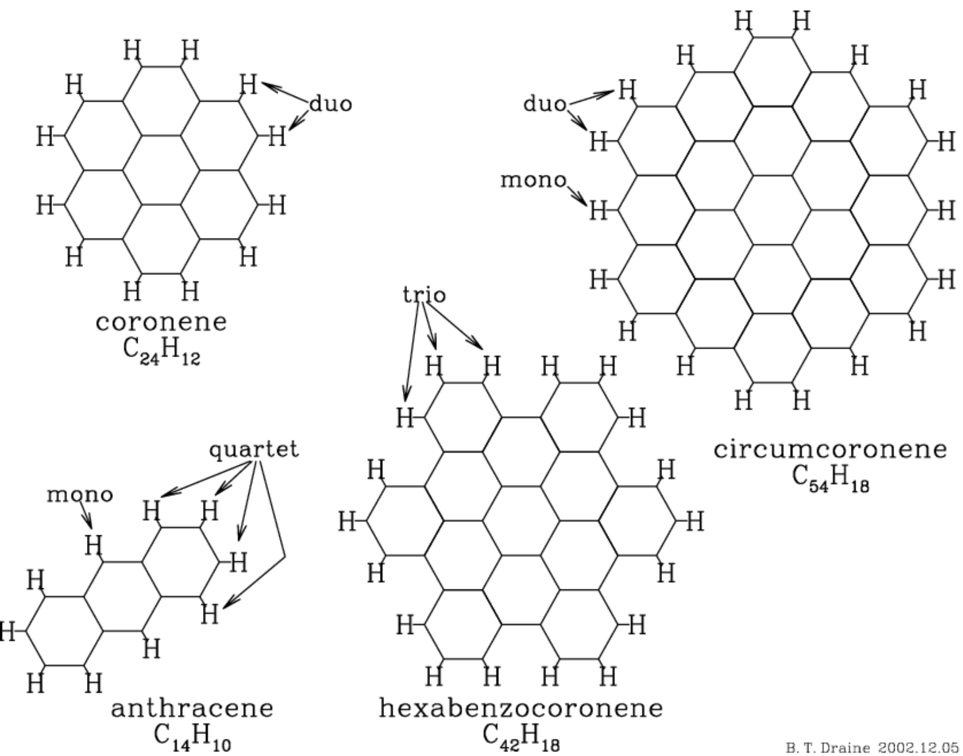
and
J. R. Barker
Department of Chemical Kinetics, SRI International
Received 1984 October 19; accepted 1984 November 27

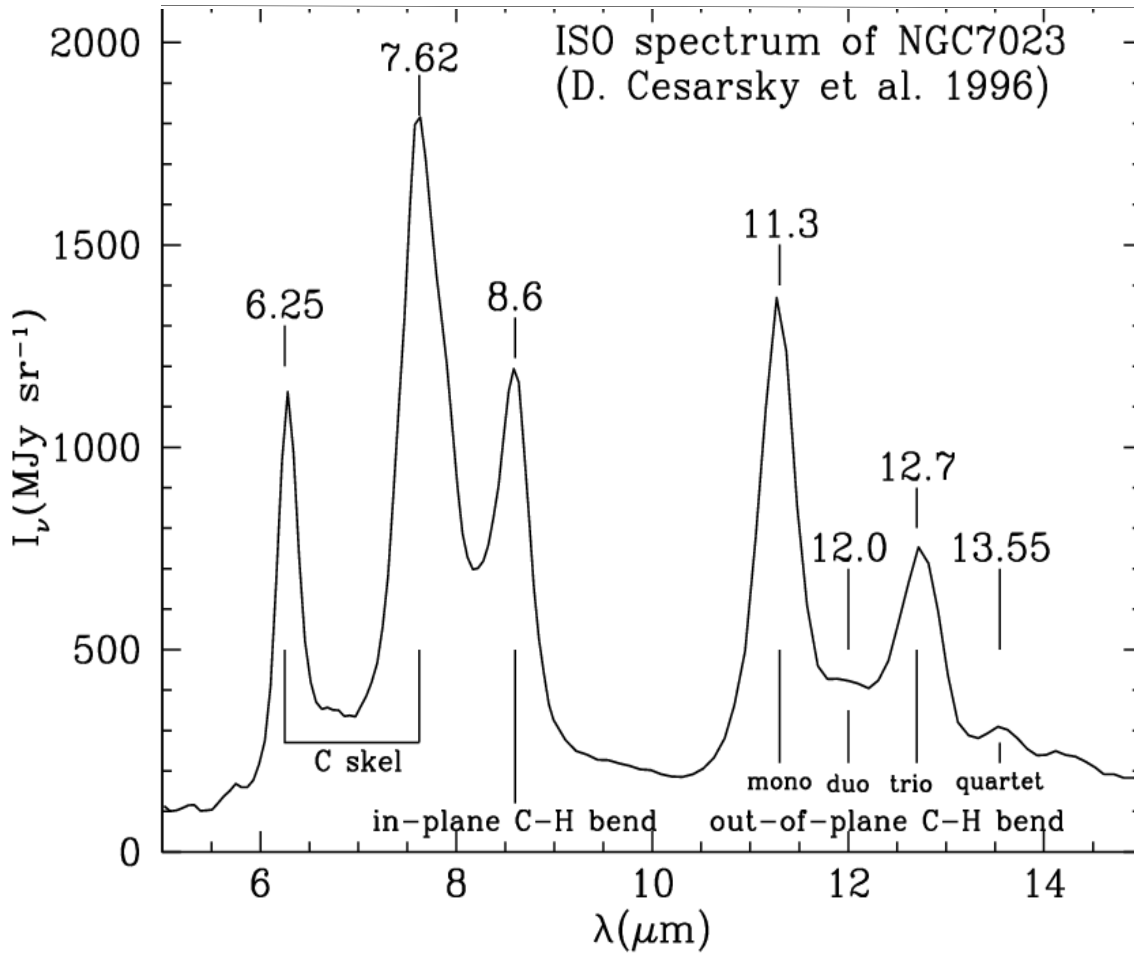


Mid-Infrared PAH Features (Draine 2003)

The mid-infrared features are attributed to vibrational modes (bending, stretching) of PAHs (e.g., Leger & Puget 1984). When H atoms are attached to the edge of an aromatic ring skeleton, the system will vibrate if triggered by an optical or UV photon.

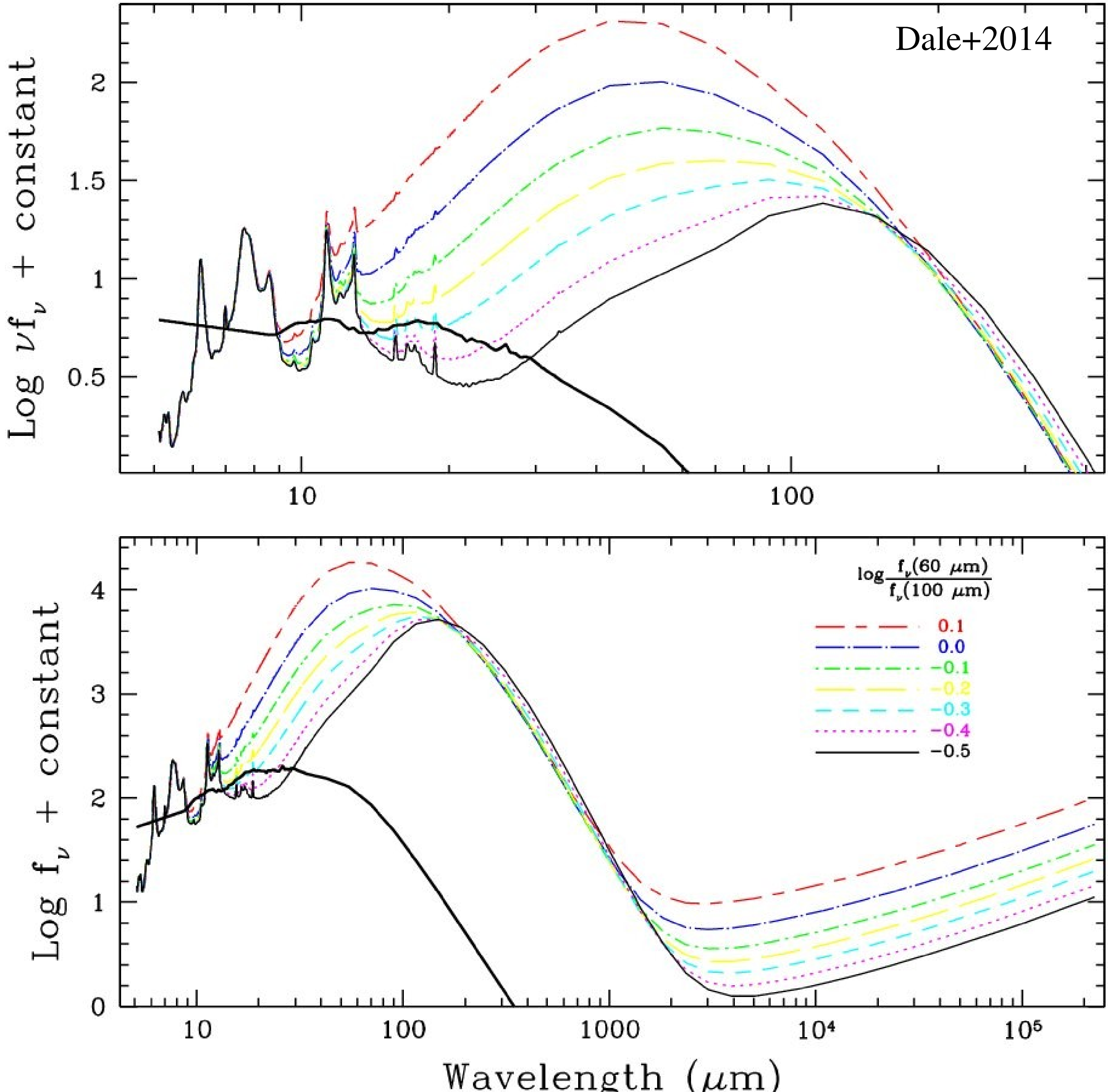
The bending modes can be 'mono' (no adjacent H), 'duo' (2 contiguous H), 'trio' (3 contiguous), or 'quartet' (4 contiguous).





The Infrared Spectral Energy Distribution for normal galaxies of different star formation activity levels. Note the presence of mid-infrared features (in addition to the far-infrared thermal emission).

λ(μm)	identification
3.0	ice (absorption)
9.7	silicate (emiss/abs)
18.0	silicate (emiss/abs)
11	SiC
20	silicate
3.3,6.2,7.7	PAH
8.6,11.3	PAH
12.6,17	PAH



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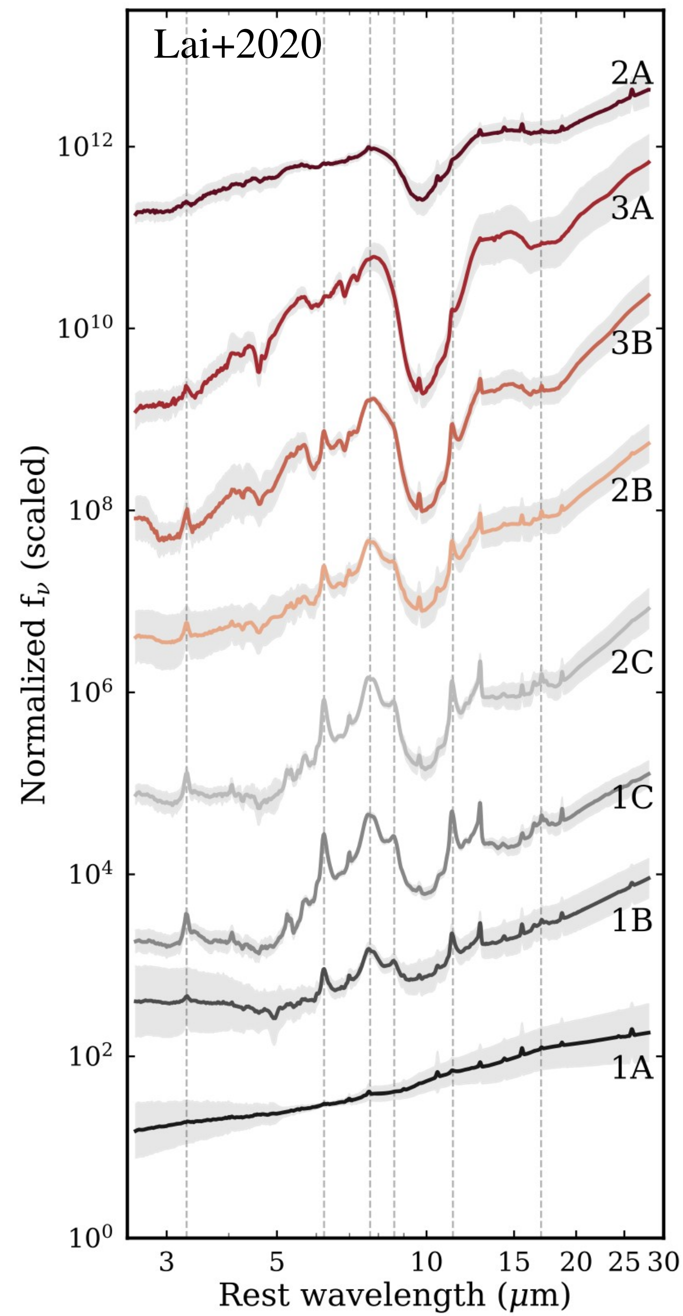
18.0	silicate (emiss/abs)
11	SiC
20	silicate
3.3,6.2,7.7	PAH
8.6,11.3	PAH
12.6,17	PAH

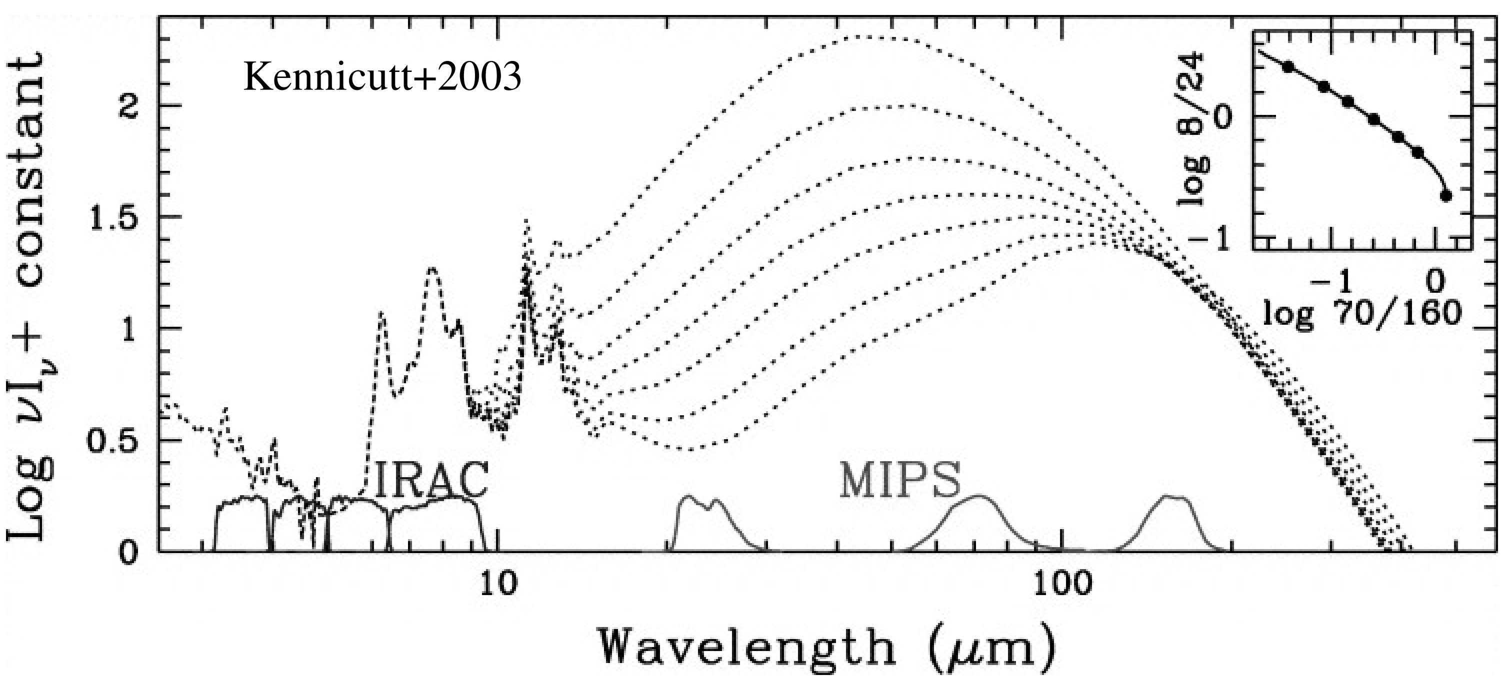


Q: What is the physical significance of the different far-infrared shapes below?

Q: Can you make a quantitative prediction for the characteristics of the far-infrared hump?

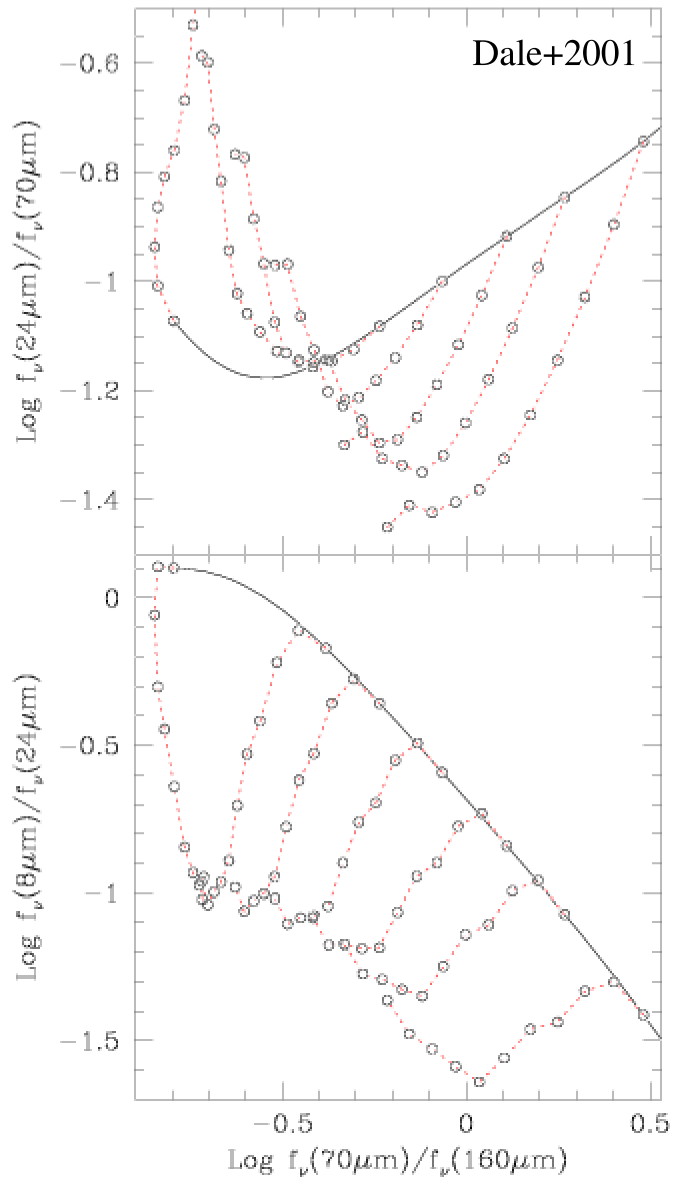
Q: Why don't the mid-infrared features change in wavelength as well?

Q: Do you think the infrared spectrum helps or hinders photometric redshift efforts?

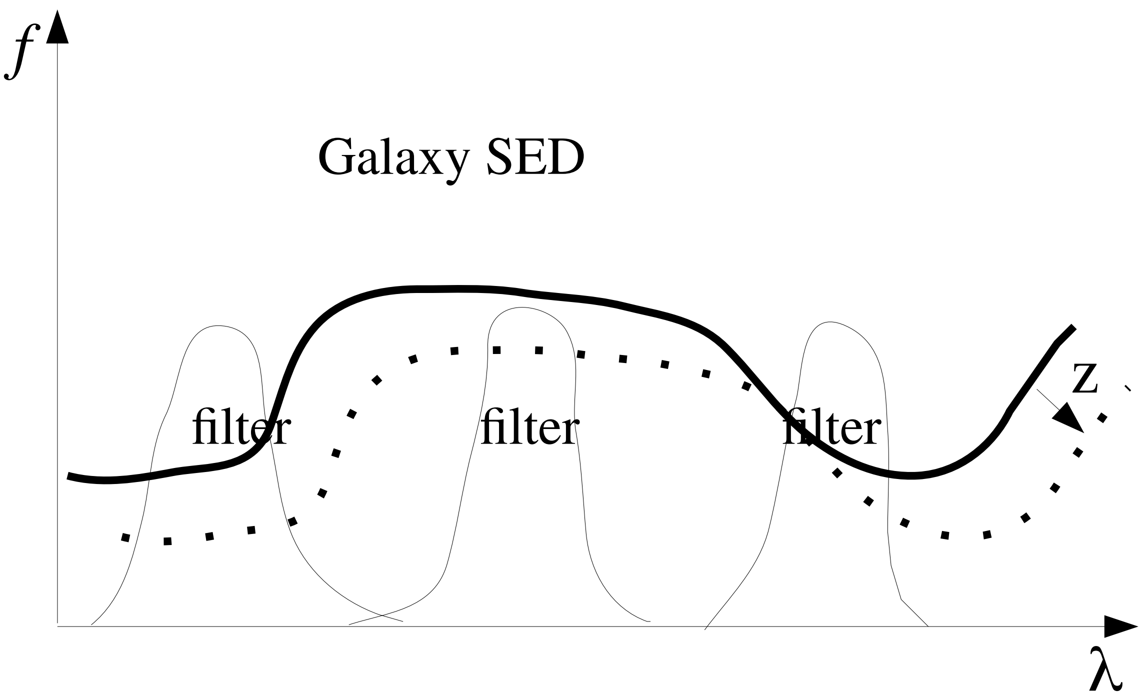


Q: Do you think the infrared spectrum helps or hinders photometric redshift efforts?

Spitzer infrared color tracks from z=0 to1



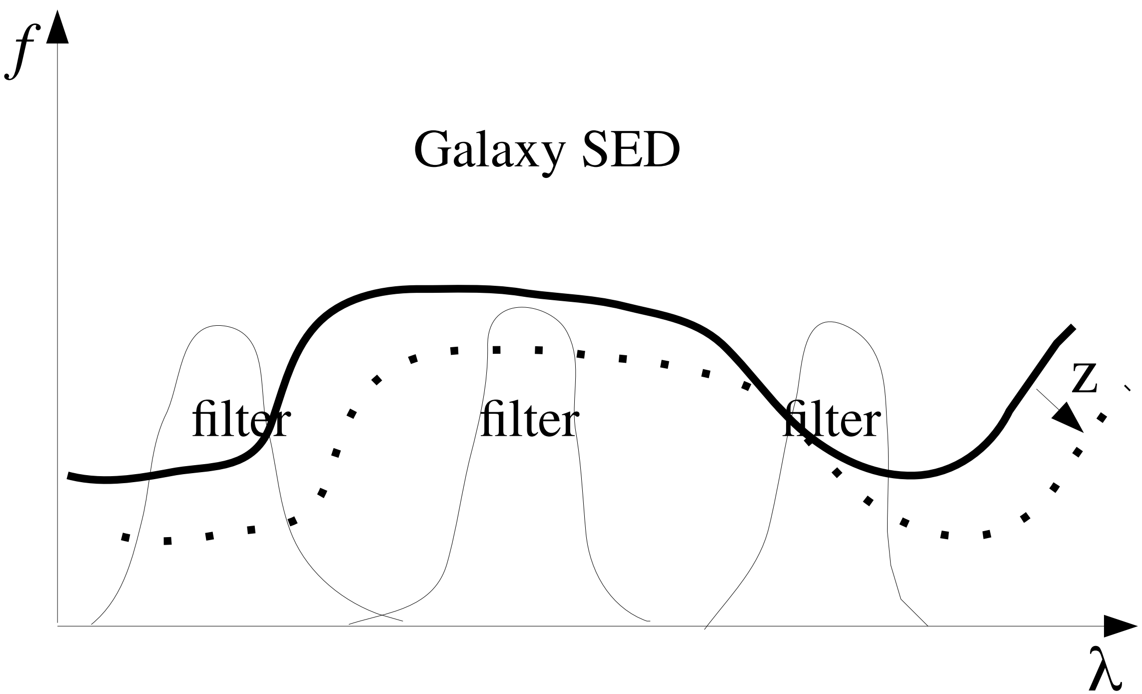
A photometric redshift is the redshift of the best-matched SED template to the observed broadband data. Ideally, a single template at a single redshift will be the unique solution. In practice, different templates at different redshifts can provide equally reasonable fits. The quantification of the matching, for all applicable z, is known as a probability distribution function (PDF).



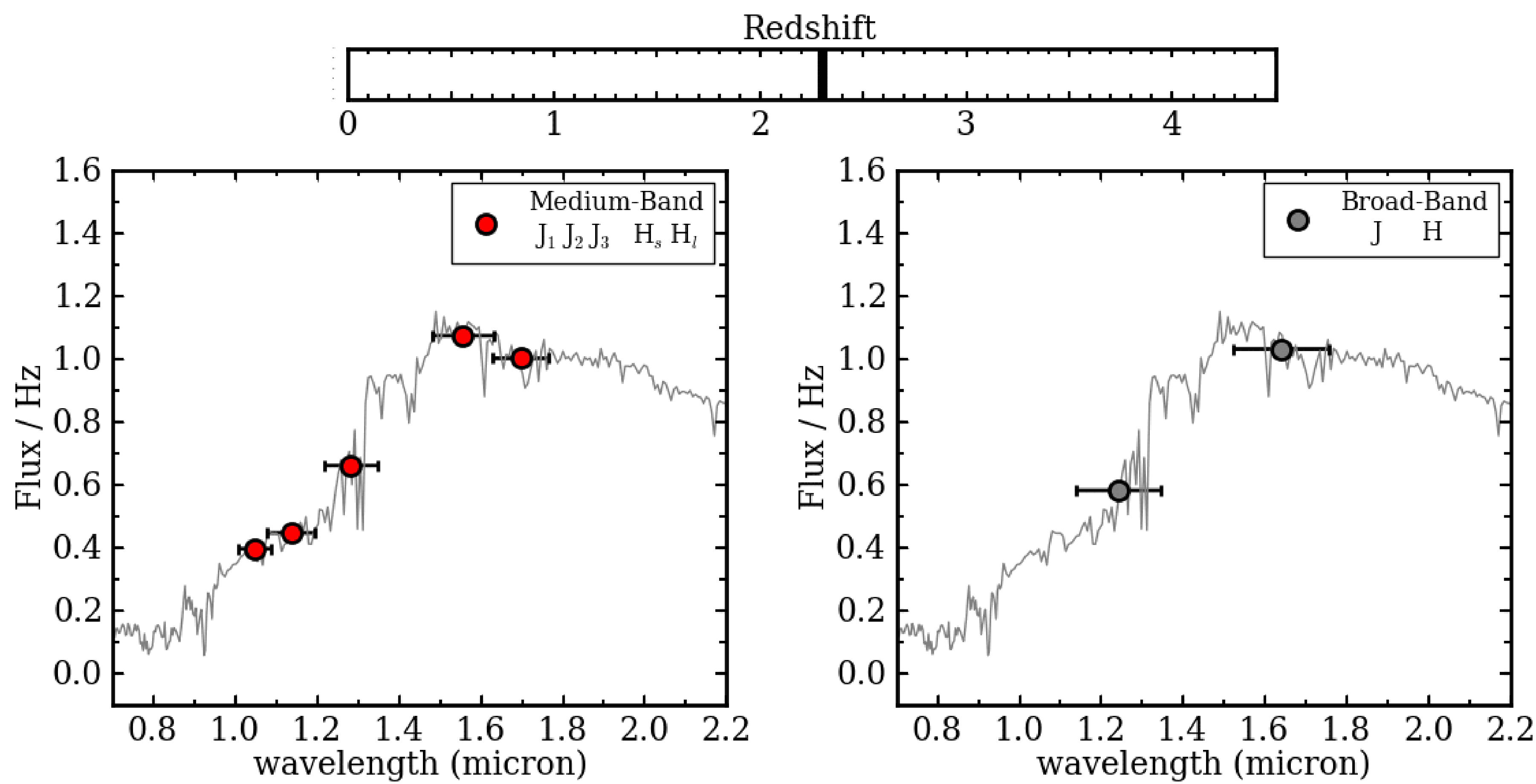
Challenges to photometric redshift efforts:

-optical spectrum is variable according to star formation history and metallicity
-optical spectrum can be reddened and attenuated due to dust extinction
-having the proper suite of template SEDs (e.g., AGNs add additional confusion)
-far-infrared peaks at different wavelengths for different dust temperatures
-mid-infrared feature (PAHs) can be minimal/absent for particularly hard radiation fields

Thus, ideally one will have photometry from a large number of wavelengths, in order to have the best chance of constraining the redshift.



Photometric Redshifts: Templates & Broadband Data



https://zfourge.tamu.edu/

Photometric Redshifts & Probability Distribution Functions

Fotopoulou & Paltani 2018

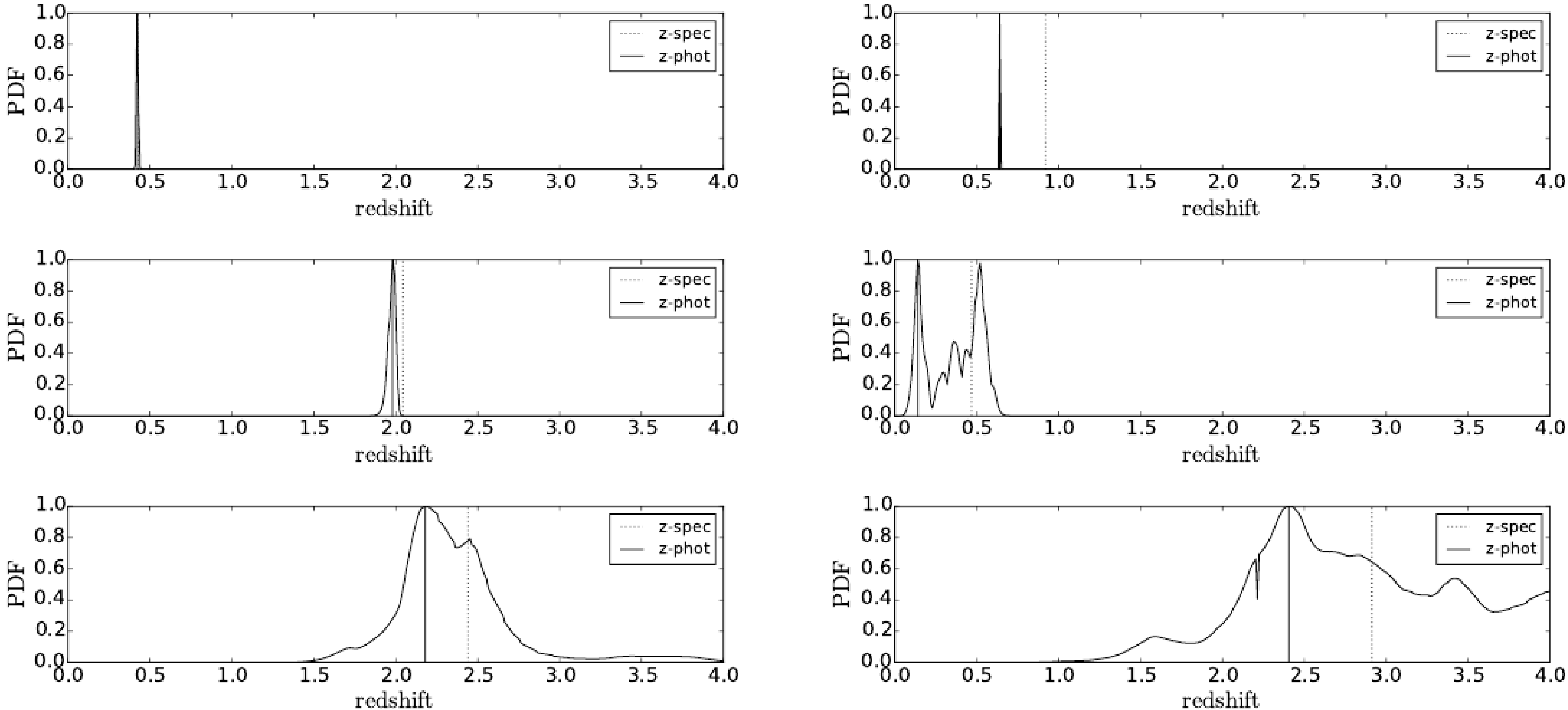
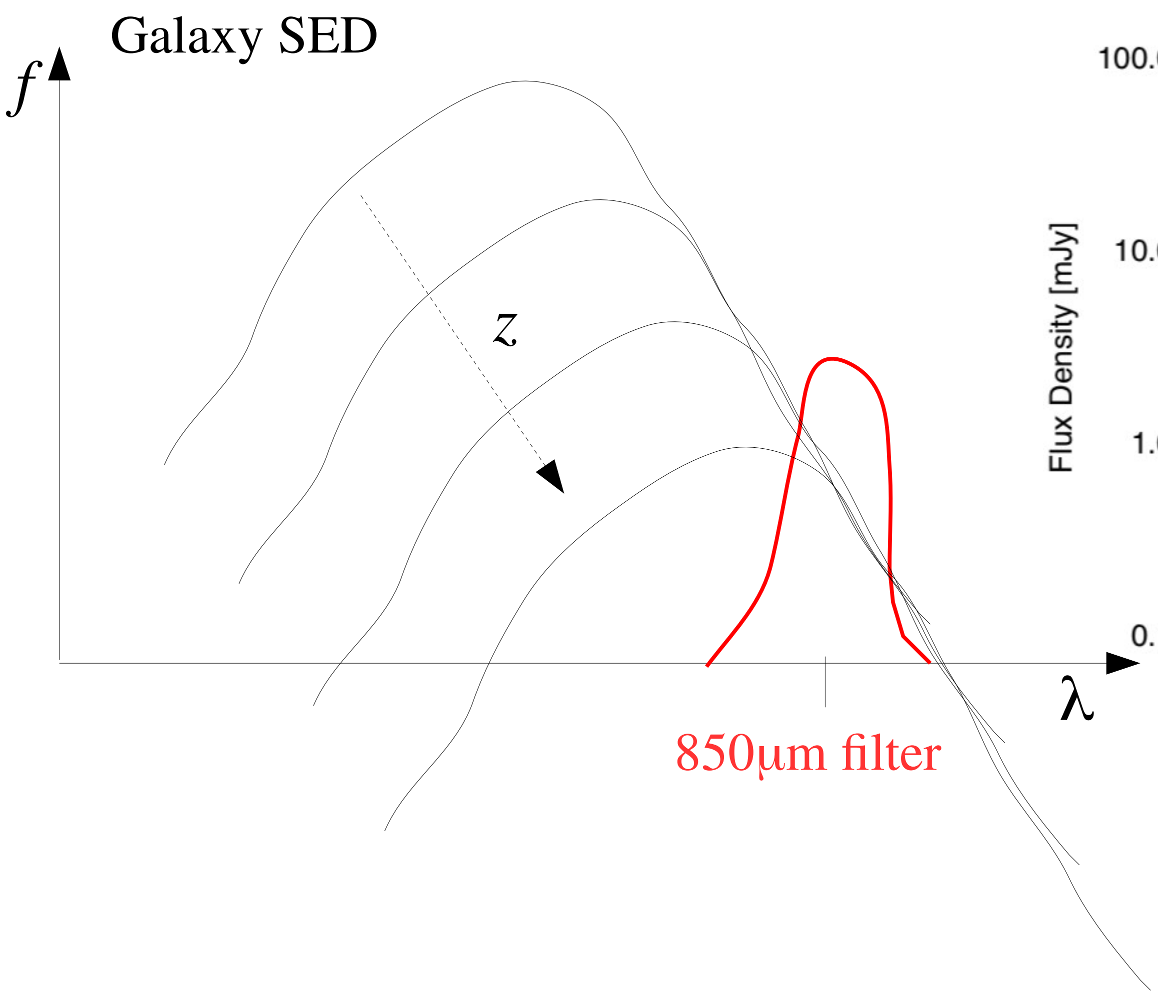
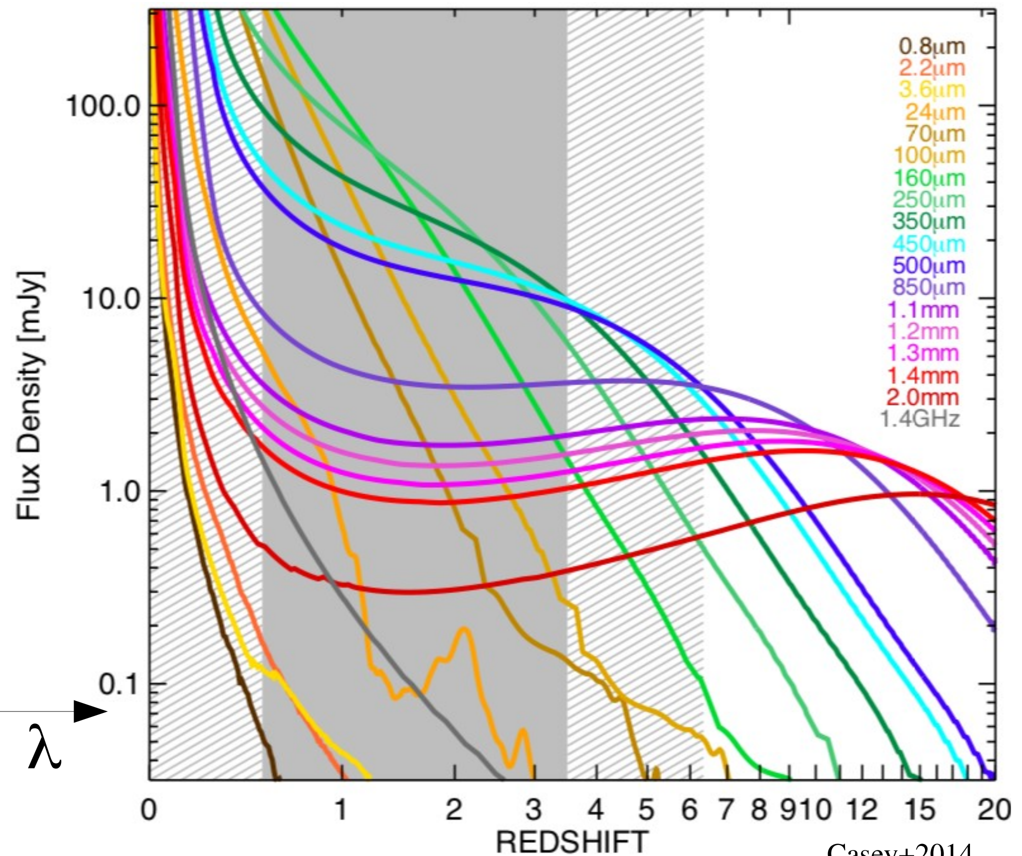


Fig. 7. Example probability distribution functions (PDF) from the consolidated sample. The first row shows two sources with high information content, $D_{KL} \sim 7$. The second shows broader and multimodal PDFs with $D_{KL} \sim 4$, while the last row shows the PDFs with the least information content $D_{KL} < 2$.

A *k*-correction is the correction made to an observed flux or color to account for the redshifting of the SED with respect to the fixed filter(s) bandpass. In the submillimeter there is a unique twist, a 'negative' *k*-correction. The 850μm flux stays relatively fixed for all observable redshifts, making this wavelength particularly powerful for carrying out cosmological surveys of dusty galaxies.





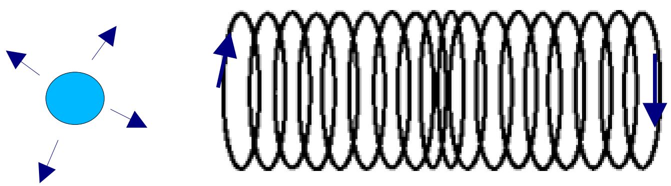
Casey+2014

The Infrared-to-Radio correlation is one of the tightest correlations known for galaxies.

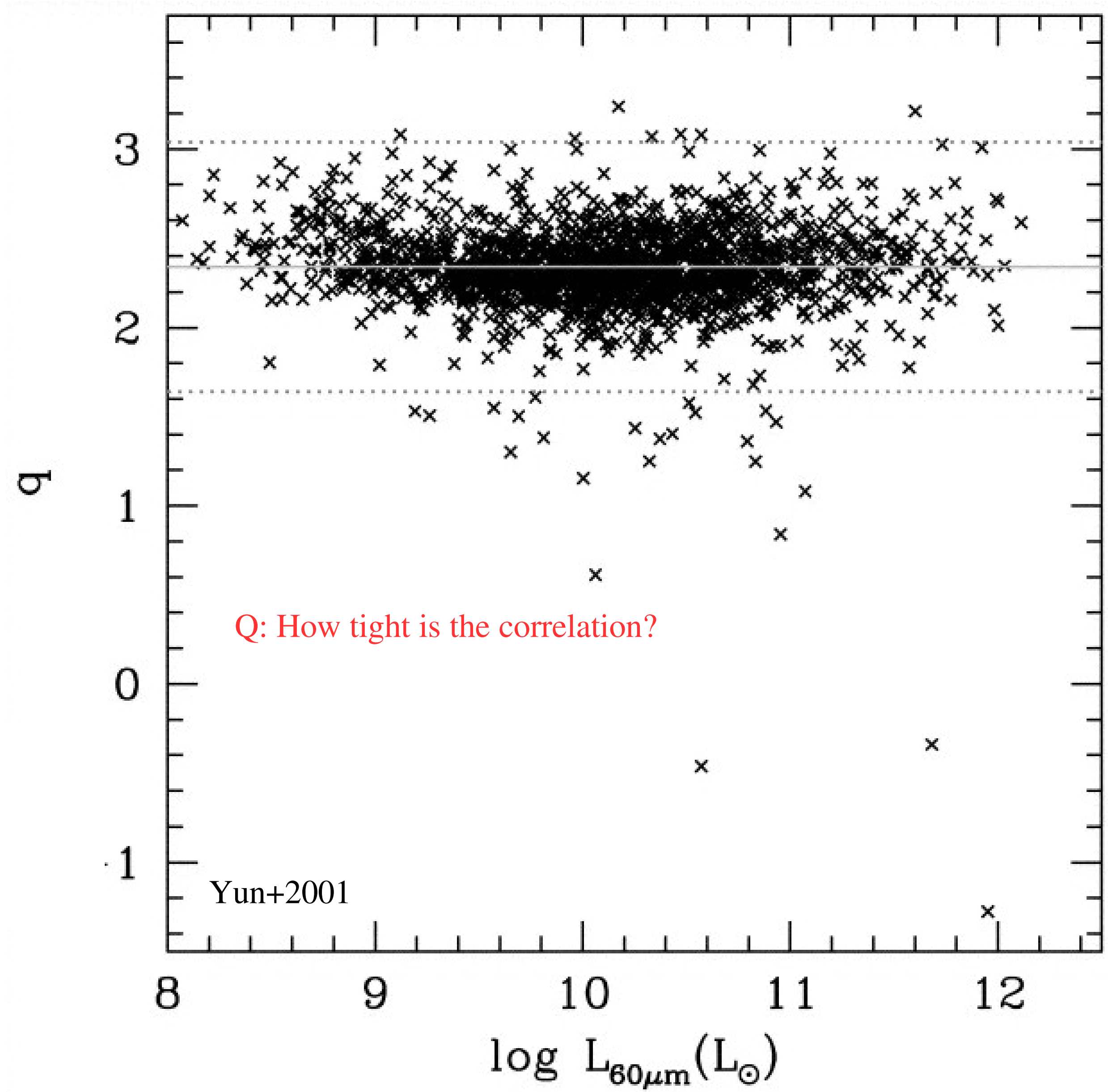
The correlation relies on the trapping of supernovae-ejected electrons within galaxy magnetic field lines, and is defined as

$$q = \log \mathrm{IR/Radio}$$

It is a *global* correlation, but we are exploring it on small scales with *Spitzer* and *Herschel*.



e-s spiraling around interstellar magnetic field lines→synchrotron radiation



The Infrared-to-Radio correlation

We understand the basic phenomena underlying this correlation. Massive stars are responsible for both i) heating dust grains which re-emit in the infrared and ii) kicking out energetic e^-s in supernovae. These e^-s spiral around B field lines producing synchrotron radiation.

However, though all stars can contribute to dust heating not all stars go supernovae. Moreover, the mean free path for UV photons is only ~100 pc whereas the diffusion length scale for cosmic ray e^-s is 1–2 kpc (after this distance the e^-s typically become entangled in B fields). Thus, there must be some sort of global averaging to get the global infrared-to-radio ratio to be so remarkably constant among galaxies.

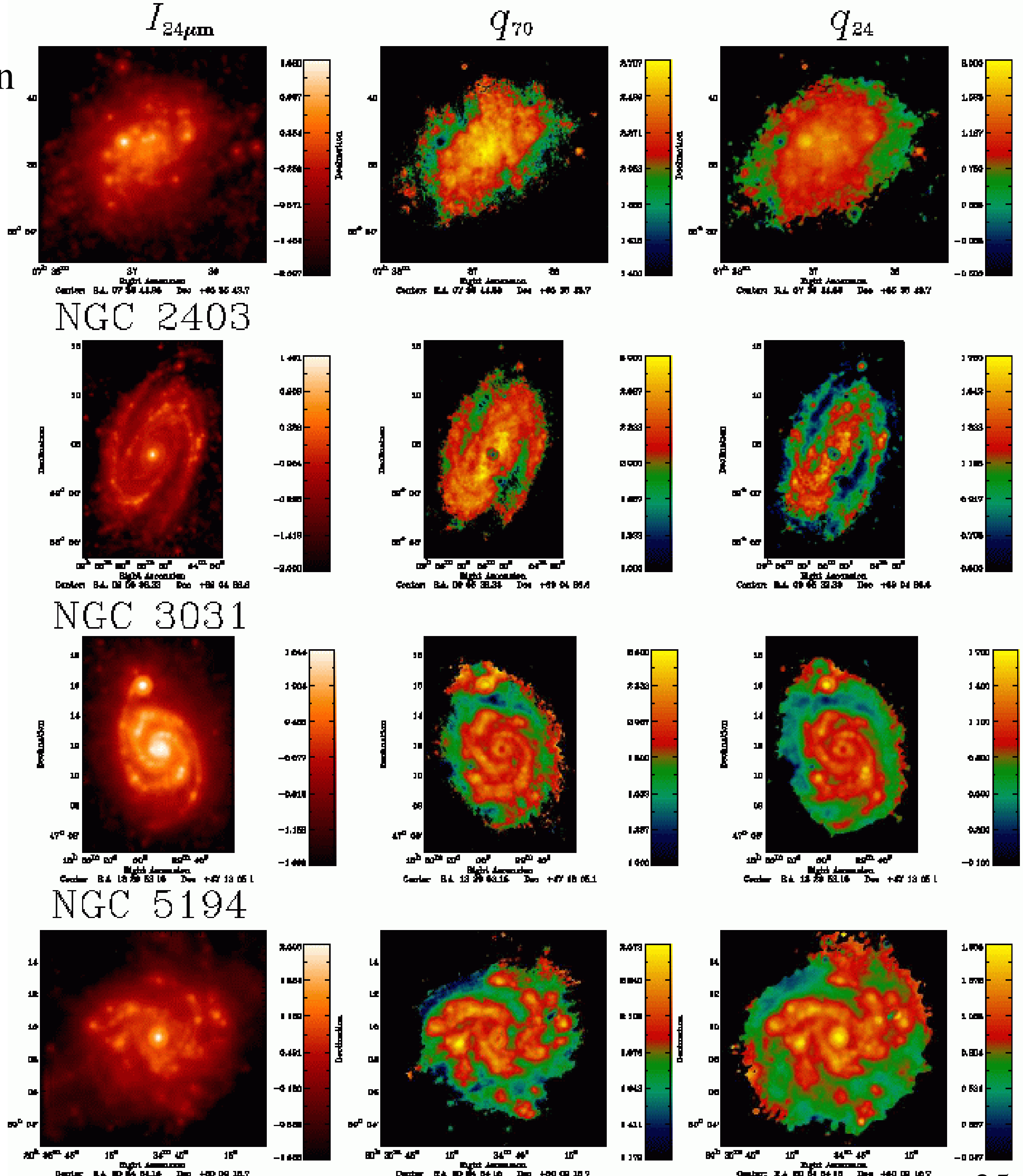
Also surprising is that this constancy holds for a wide range of galaxies. It holds for galaxy samples exhibiting a variety of metallicities, B field strengths, masses, grain populations, and star formation rates.

What occurs on smaller scales within galaxies, scales for which an even larger diversity in metallicities, B fields, dust grains, and star formation rates might be explored?

The Infrared-to-Radio correlation

Locally, the infrared-to-radio relation is higher in spiral arms and other sites of star formation; HII regions have an excess of infrared emission relative to the radio continuum emission.

Left to right:
1. 24μm map
2. q_{70}=70μm/22cm (FIR vs synchrotron)
3. q_{24}=24μm/22cm (MIR vs synchrotron)

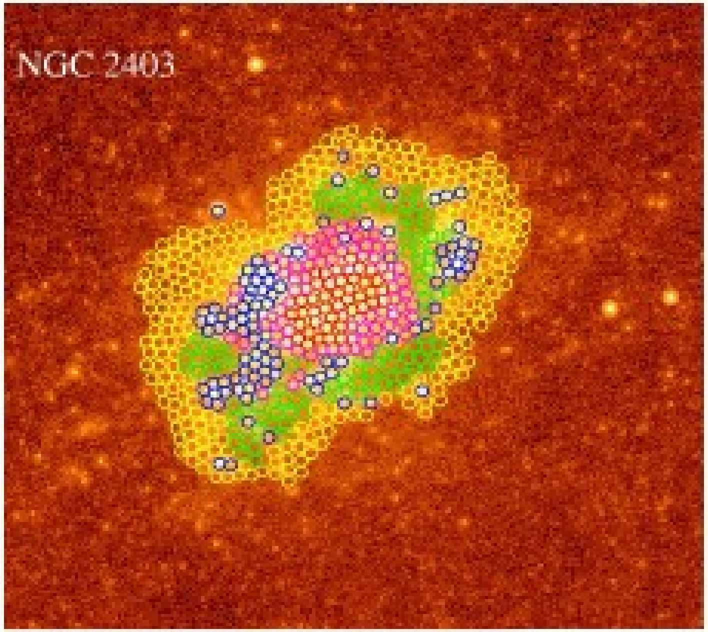


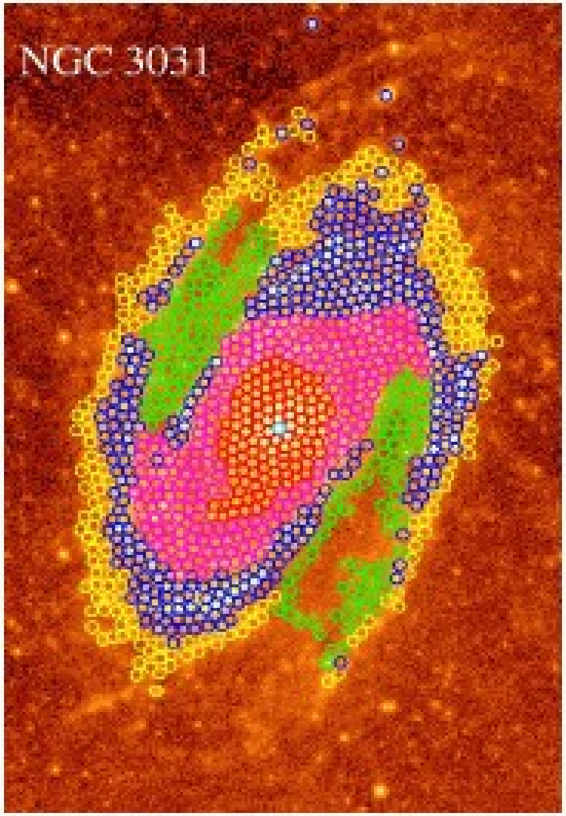
Murphy+2006

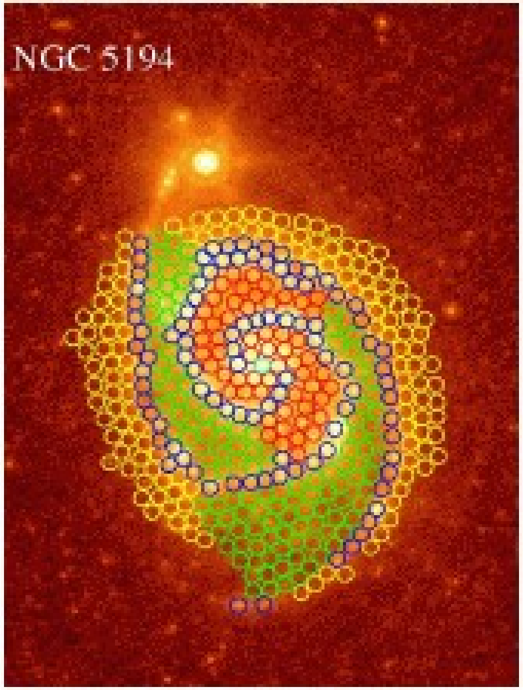
The Infrared-to-Radio correlation

Aperture masks overlaid
on 24μm images

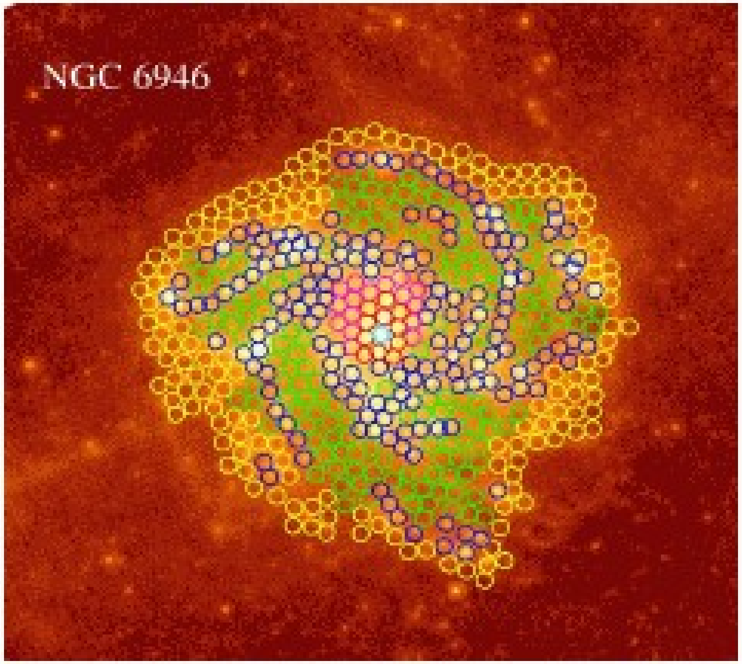
nucleus: cyan
inner-disk: red
outer-disk: yellow
arm: blue
inter-arm: green





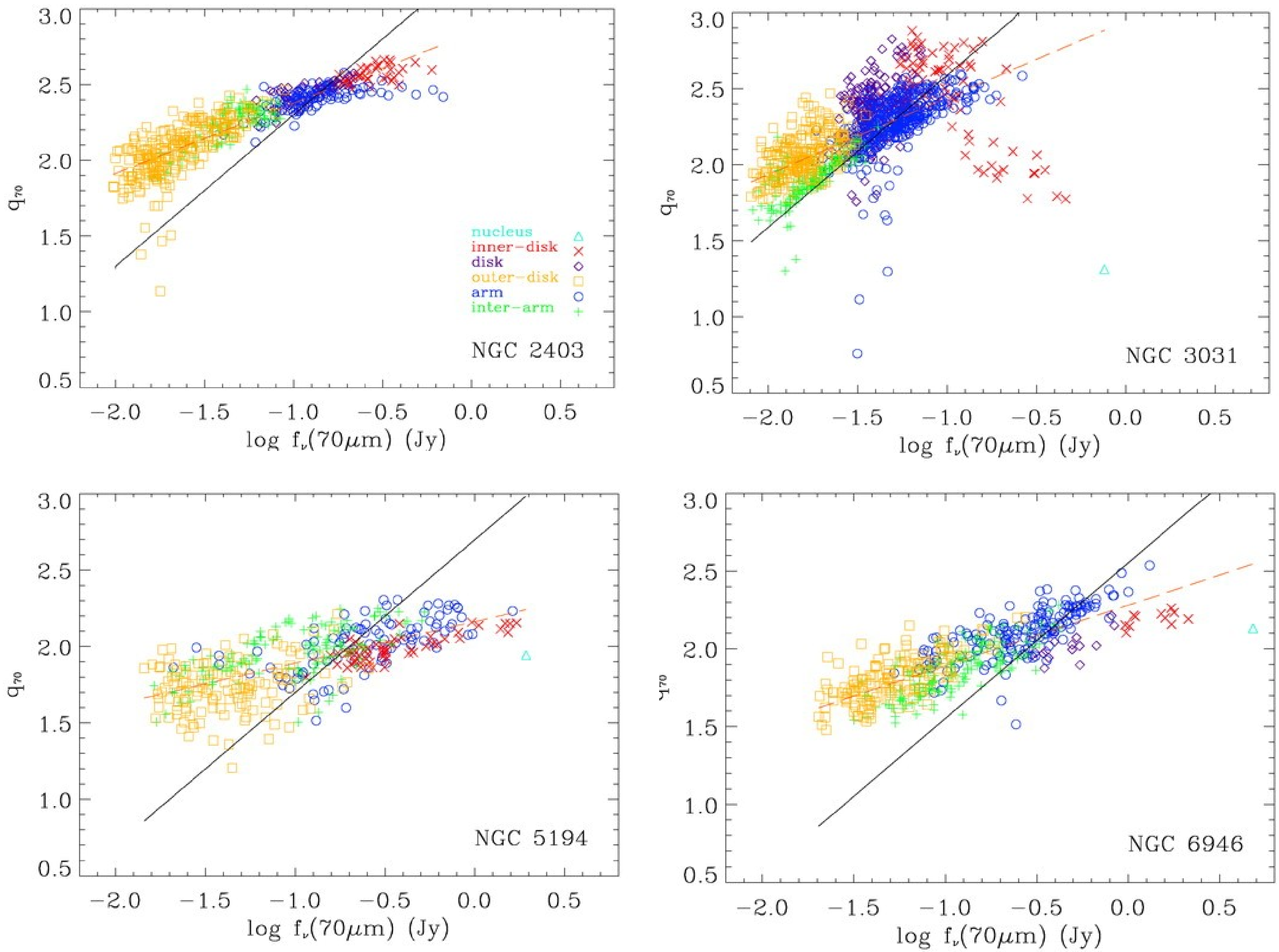


Murphy+2005



The Infrared-to-Radio correlation

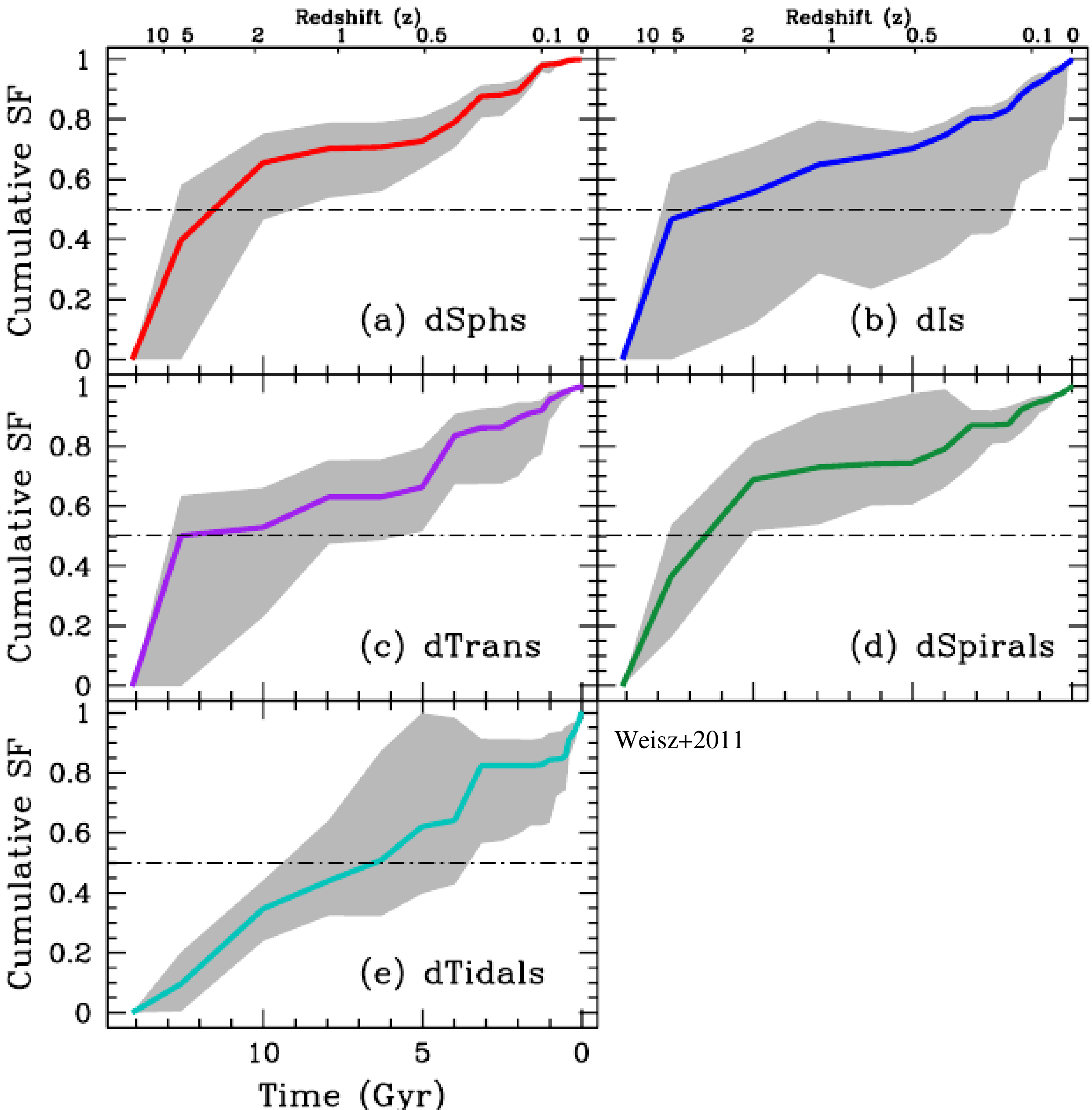
q_{70} grouped by different environments within each galaxy. Solid lines indicate the expected trend if the galaxy disk was characterized by a constant radio surface brightness.



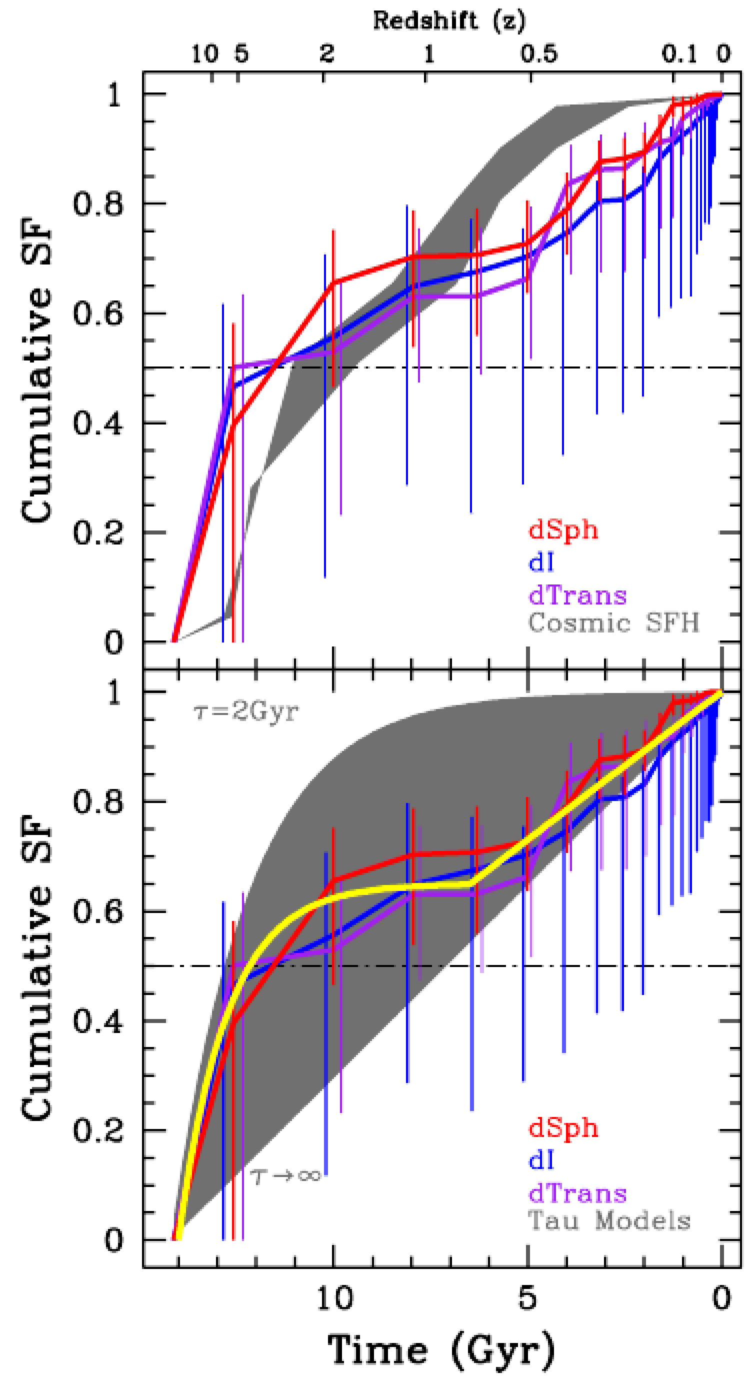
Murphy+2006

A quick primer on dwarf galaxy star formation histories

$SFR(t) = SFR(t_0)e^{-t/\tau}$



Weisz+2011



The Infrared-to-Radio correlation

A low metallicity dwarf galaxy has recently undergone a strong burst of star formation. Describe how each property below could affect the global infrared-to-radio ratio.

1. low metallicity

2. small

3. young stellar population

4. hard radiation field

Follow-up examples on emission and absorption with respect to cooling and heating

a) *Why isn't the absorption of a photon by an atom or molecule in an interstellar cloud necessarily a heating event? It deposits energy into the cloud, but what else must happen for it to heat the cloud?*
b) *Why isn't the emission of a photon by an atom or molecule in an interstellar cloud necessarily a cooling event?*

a)
Consider a 3 eV photon (Jose) that leaves his star (Sally) and heads out for his morning work of exciting hydrogen.

Consider a 13.7 eV photon (Jim) that heads out into a 10^4 K HII region (Sue).

Consider Jim exploring a 50 K HI region (Marta).

b)
Consider Jose, the 3 eV photon again.

Consider an 8 eV photon (Jerry) that leaves a Hydrogen atom within Marta, and runs into a neutral iron atom (Janet).

Interstellar Grains

Slide 1
Based on the 2020 Decadal Survey, there's currently a competition between a ~1B$-class far-IR and X-ray probe.

Slide 2
SOFIA flew at 41km altitude, and you can see from the absorption vs wavelength figure on Slide 3 that this raises it above most of the IR absorption problem

Slide 3
Why (stratosphere and) space-based? The atmosphere both absorbs and emits in the infrared.

Slide 4
DU built a "10 & 20 Cam" for WIRO, which operated at 10 & 20 microns. Point to the atmospheric holes in the figure.
http://mysite.du.edu/~rstencel/MtEvans/TNTCAM.html

The air above Mt. Jelm has a water vapor column density comparable to that at Mauna Kea, and on the coldest nights essentially no ground-based site could compete with WIRO in the mid-infrared. The antarctic is not as high, and not really used for IR astronomy (but definitely used for mm/submm/microwave!). For data, see Figure 6 of Grasdalen+1985.

Slide 5
The geometry that yields f(IR) $\propto h\csc(b)$ derives from the figure: $\sin(b) \propto h$/hypotenuse

Interstellar space is 10^6 times dirtier than Earth's atmosphere. Which means if you compressed to Earth pressure (by factor of 10^{21}), objects would be lost in the haze by a distance of 1 m (couldn't see your hand at arm's length). p. 131 B&M. Most of this dirtiness is due to the fact that stellar atmospheres are the site of soot condensation, like the flue gases of furnaces.

50% IR on cosmic scales – see Slide 17

Slide 6

$\tau_\lambda \propto \lambda^{-4}$ (Rayleigh) –> derive!

$\tau_\lambda \propto \lambda^{0}$ (geometrical) what does this mean?

This means that photons scatter if their trajectories are in the path of a dust grain – the wavelength doesn't matter.

Follow-up: if a~λ, $\tau_\lambda \sim \lambda^{-1}$ (p. 440 Carrol & Ostlie Mie Theory)

λ^{-4} very blue if you observe scattered light off of a dust cloud

λ^{-1} slightly blue

λ^{0} colorless, or at least the intrinsic color is unaffected, since all wavelengths equally scatter.

Extinction is higher towards the blue ⇒ stars appear redder

What about the 'blueing' of reflection nebulae?! More dust means more dust scattering, meaning reflection nebulae are bluer.

Explain "extinction" (absorption & scattering losses out of l.o.s.; for individual objects) vs "attenuation" (can also have scattering into l.o.s.; for galaxies in general). Figure 1 caption from Salim & Narayanan 2020: Schematic summarizing the difference between (a) extinction and (b) attenuation. The former encapsulates absorption and scattering out of the line of sight, whereas the latter folds in the complexities of star-dust geometry in galaxies, and may include scattering back into the line of sight, varying column densities/optical depths, and the contribution by unobscured stars.

$A_V/N_{\mathrm{Htot}} \sim 3\ 10^{-22}$ updated value from 5.33e-22, based on Rachford work on Slide 1. Actually this is for A_I! So change the slide.

FYI: light is not 'extincted' but 'extinguished' or 'attenuated'

Slide 7

2175 A bump in extinction curve comes from large PAH molecules. Binney&Merrifield p. 136; Draine review Section 3.1

Classical grains of size ~0.1-0.2 μm. These beasts are interplanetary (zodiacal) dust, which can be far larger than interstellar dust.

Slide 8

$\log_a(x)=\ln(x)/\ln(a)$, so if $10^{-A_V/2.5}=e^{-\tau}$ then $\log_e 10^{-A_V/2.5}=\log_e e^{-\tau}$ -> $-A_V/2.5*\ln(10)/\ln(e)=-\tau$

Get the next equation by plugging and chugging using previous relations on this slide:

$\rho_{\mathrm{gas}}/\rho_{\mathrm{dust}} = \frac{3}{4}\, m_H/\pi a^3\rho_{\mathrm{grain}}\ n_H/n_d = \frac{3}{4}\, m_H/\pi a^3\rho_{\mathrm{grain}}\ Q\pi a^2 N_H/\tau_V = 1.086\ \frac{3}{4}\, m_H/a\ Q/\rho_{\mathrm{grain}}\ N_H/A_V$

Slide 9

10^0 reminds me of Salpeter saying tau ~ 1± 6 in log space…

Plug and chug in cgs units gives you 128.3 for gas/dust ratio.

Adding up number density times atomic weights from Ch2&3 table yields $(0.0224)^{-1}$, or 45. And it makes sense that this # is < 130, since not all the heavy element are locked up in dust grains; some are in the gas phase, else we wouldn't see their emission lines!

130 is from the actual calculation; Mayya & Rengarajan indicate 160 for local MW, and 300 for galaxies in general.

What does the curve of Q vs $x=2\pi a/\lambda$ mean?
1. As you go to shorter wavelengths or larger grains, the extinction cross section is large.
2. It flattens out since bigger and bigger grains don't change the extinction much – they all do a good job! (Eventually, we know the curve will turn back over since X-rays are able to pass easily.) Mie Theory: $\tau_\lambda \sim \lambda^{-1}$
3. At longer wavelengths or smaller grain sizes, the extinction grows smaller, the whole Rayleigh Scattering argument: steep $\tau_\lambda \sim \lambda^{-4}$
4. It levels off at 2 (and not 1) b/c of the effects of diffraction! (read that from Draine somewhere; also in Tielens' text). See Figure 5.1 and the text on that and the preceding page; it explains the envelope is Q_total vs just one of the Q components.

Slide 11

A_V scales with N_H column density. It doesn't scale with n(H) b/c it additionally depends on how large (long) the cloud (path length) is. Clouds don't obey 1 mag/kpc of extinction since this is a number averaged over the entire ISM, not a single cloud (which undoubtedly would be higher). Show that $A_V/(2R)$ is ~1e4 mag/kpc and $A_V/(n(H)*2R)$ is ~3e-20 mag/cm^2; these individual environments have ~constant values that are >> larger than the ISM's average.

I added Thomas Lai's beautiful spectral suite. Point to students how the 10um peak in extinction corresponds to 10um emission valley. Might also show Hao+2005 for why there are extinction/absorption features at both 10 and 18um.

Slide 12

R_V goes to infinity for large grains since A doesn't vary with lambda
Does the trend make sense: Yes – larger grains (larger R_V and thus smaller $1/R_V$) have higher extinction x-sections (high A_V/N_H)
Rachford calculated this by measuring NH via UV absorption spectroscopy toward stars with known l.o.s. extinctions.

See https://ned.ipac.caltech.edu/level5/Sept07/Li2/Li2.html
In the Small Magellanic Cloud (SMC), the extinction curves of most sightlines display a nearly linear steep rise with lambda^-1 and an extremely weak or absent 2175 Å bump, suggesting that the dust in the SMC is smaller than that in the Galactic diffuse ISM as a result of either more efficient dust destruction in the SMC due to its harsh environment of the copious star formation associated with the SMC Bar or lack of growth due to the low-metallicity of the SMC, or both. The Large Magellanic Cloud (LMC) extinction curve is characterized by a weaker 2175 Å bump and a stronger far-UV rise than the Galactic curve, intermediate between that of the SMC and that of the Galaxy. Regional variations also exist in the SMC and LMC extinction curves.

Slide 13

The ratio makes absorption features seem like emission.

Q: These DIBs represent absorption lines, since:

λ(Ic)~800nm & 1/λ=1.25um^{-1} & extinction higher at shorter λ→ features should switch to absorption at 800nm. Campbell+2015 ID'd 2 DIBs using lab spectroscopy of C60 (Bucky Balls) at T=5.8K.

Slide 14

In case anyone asks why there is π multiplying Bν: see wiki page for blackbody emission/planck function: π accounts for integrating over the solid angle→ removes the "per steradian" in the units of Bν on Slide 24 of chapter 1 notes.

Slide 15

What is plotted on y-axis? Flux (not flux density).

Slide 16

λ_{peak} ~ 10μm

the effective radiating area is πa^2 rather than $4\pi a^2$

Slide 17

Half of the EBL is in the IR. A small portion of this is optical light from high-z sources redshifted into the IR. But the vast majority is from photons with IR rest wavelengths. The importance of this plot is that there was dust in galaxies far back in time, implying that galaxy formation is not a recent event.

Slide 18

Have them compute Tdust=16K * (Q_UV/Q_IR)^1/4 since 0.15 pc = 30940pc

But based on the peak wavelength for the Sellgren spectrum and Wien's Law we would infer Tdust=2900umK/3um~1000K.

Dust grains evaporate around a couple thousand degrees (so you should never hear of a 5000 K dust grain!).

Slide 19

heat capacity: the amount of heat required to change a body's temperature by a given amount, e.g., C=dE/dT = hν/ΔT

6N degrees of freedom for a grain could come from x,y,z translational plus spinning about each of these axes

$N = h\nu / 3kT_d$ ~ 24 since h*nu ~ 9.93e-19 J

Slide 23

Review Physics Today Nov 2018 article on PAHs.

Slide 24

Show the 6-second video clip I took of Brett McGuire's 2024 AAS prize talk. Shows PAHs in 4 different bending and flexing modes. Use VLC for bending.PAHs.MO

Slide 25
Show (COBE all-sky?) diffuse cirrus image
In the (StarTrek) Voyager episode "The Caretaker", the Ocampa homeworld's atmosphere didn't have any dust, so no precipitates could form -> desolate. See http://en.wikipedia.org/wiki/Ocampa –> wiki page no longer exists as of Sep 2021! :(

Slide 27
a) different T_d
b) $\lambda_{peak} T_d \sim 0.29$ cm K; $B_\nu(T_d)=2h\nu^3/c^2\ (e^{h\nu/kT}-1)^{-1}$
c) not T_d dependent -> bending & stretching modes don't change λ
d) if it were constant, it'd be fantastically helpful. As it stands, there are significant # of features, and that helps to constrain photo-z's

When you show the Dale & Helou SEDs, ask what is the difference between the mid-ir and far-ir emission. PAHs vs big grains. But how do you know? The FIR emission i) has more energy b/c the grains are bigger and thus intercept more photons, ii) is at wavelengths typical of 20-100 K dust, iii) has the shape of blackbodies (or sum thereof)

Slide 30
Animated gif for photo-z
http://zfourge.tamu.edu/

Slide 33
Visually show them how the relation works using my SEDs on Slide 25.
How tight is the correlation? Average is 2.34+/-0.01 with a sigma of 0.26dex.
But first ask them to estimate 2sigma as 68.3% of a Gaussian/normal scatter and here it's ~0.5dex.
Rules of thumb: 0.3dex = 2x; 0.5dex = 3x; 1dex = 10x
Show that 0.26dex/Sqrt(1809)=0.006 is how they come up with an uncertainty of +/-0.01dex.

Slide 37
http://www.geek.com/articles/gadgets/star-trek-dustbuster-phaser-replica-does-not-suck-20100622/

Enumerate far-IR peak λ_{peak} B_ν more energy
Ask why the positive slopes make sense: large fraction of light is from nucleus, and those photons do not diffuse far.

Slide 38

Explain why bottom right graph has a straight line for tau=infinity. On the next slide I specify “dwarf ” and “recent star formation” b/c the bulk of dwarf stellar mass was formed prior to z~1 (l.h. figure). However, it's still fair to conceptually think of dwarf irregulars as fairly young, since in their conclusion they say dwarfs have formed a larger fraction of their stars more recently than most galaxies (top panel of r.h. figure shows dwarfs have more recent SF than cosmologically average).

Slide 39

SF-ing dwarf irregular galaxies: i) small→hard to trap CRe-s with small B volume; ii) young→maybe hasn't had enough time to develop substantial population of e^{-}s since few SNe, and lots of OB stars heating dust; iii) low Z→little dust so low IR; iv) hard isrf→either strong IR or low IR due to grain destruction (but the latter only applies to PAHs, so not a big effect).

From: Eric J. Murphy <murphy@astro.yale.edu>
> 1. small - smaller volume of B fields makes it harder to capture e-s: they might escape
Definitely true. And the important thing here is that besides being harder for CRe-s to escape, having no B-field means no synchrotron radiation period and the only radio continuum would be thermal (and only detectable on actual SF regions).

> 3. young - maybe not enough time for SN to go off and produce a substantial amount of CR e-s
This is a good one since you can argue what to expect for different SF histories of the galaxy. 1) SF just turns on in the past few millions of years, 2) Constant past average SF, 3) SF immediately turns off, 4) a quiescent disk for > few million years, and 5) no star-formation for more than a few hundred million years (this is complicated since the synchrotron lifetime is inversely prop. to the B-field squared).

> I was thinking of introducing q and its physics, show some of your plots to talk about what happens inside
> galaxies, and then ask for properties of dwarfs and the likely impact on q. then i'll go through my SBS paper where i show q_TIR is high.
Sounds like a really interesting class discussion, and a fun one since you can try to work reasonable expectations for these scenarios in your head which involves a broad range of physics. The only other thing I can think of discussing, which may be fun as a wrap-up of the class or something, is specifically how a galaxy's IMF will affect 'q' (which is basically what you are doing). Then you can tie this in with why measuring 'q' is important for high-z galaxies since it is a way to answer the question of whether/when high-z galaxies might have had an IMF much different than galaxies today (which of course is useful for all these galaxy evolution theorists).

Slide 40

3eV is roughly Balmer delta, or lambda=410nm.

a1) Such a photon will not ionize, and hence no heating will occur

a2) Such a photon will ionize, but the e- will only have 13.7-13.6=0.1eV of KE. The HII gas particles have KE of $3/2kT=1.29\text{eV}(T/10^4\text{K})$. This wimpy e- will not heat the gas

a3) Such a photon will ionize, and the ejected e- will have KE greater than the ambient gas $3/2kT=1.29\text{eV}(T/10^4\text{K})=0.006\text{eV}$ -> it will heat!

b1) A 3eV photon could be absorbed and re-emitted all day long, with no effect on the gas *T* (*T* defined by typical KE of particles, not the bound e- energy states)

b2) Jerry would create an ejected e- with KE=8.0-7.9=0.1eV, which would heat up Marta.