# Modeling Interstellar Dust: Observational Constraints and a Dust Model Based on Compact Grains

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**Why we Study dust…**

"Sure it's beautiful, but I can't help thinking about all that interstellar dust out there."

# Modeling Interstellar Dust

- Observational Constraints on Dust Models
- One Tentative Model
  - compact amorphous silicate grains
  - compact carbonaceous grains
  - Polycyclic Aromatic Hydrocarbons = PAHs
- Modeling extinction, polarization of starlight, IR emission
- Observational tests: IR emission from galaxies
- Predicted polarization of FIR/submm emission
- Spinning dust: microwave emission
- Summary of model and future tests

# Some references

- Draine, B.T. 2003, "Interstellar Dust Grains", Ann. Rev. Astron. Astrophys., **41**, 241
- Whittet, D.C.B. 2003, "Dust in the Galactic Environment", (Bristol, Institute of Physics)
- Tielens, A.G.G.M. 2005, "The Physics and Chemistry of the Interstellar Medium", (Cambridge Univ. Press)

# “Direct” Observations of Interstellar Dust

**Scattering, absorption, emission** of light:

- extinction of starlight – $A_\lambda/N_{\rm H}$
  from IR to X-ray (continuous + spectroscopic features)
- variations of $A_\lambda/N_{\rm H}$ from one sightline to another
- polarization of starlight
- scattered light (reflection nebulae, DGL)
- small-angle scattering of X-rays by interstellar dust
- IR/submm emission from dust ($2\,\mu$m – 3mm), $I_\lambda/N_{\rm H}$
  - PAH emission features
  - FIR/submm continuum
- polarization of IR emission
- microwave emission from interstellar dust (3mm – 3cm)

Plus a few more direct approaches:

- dust grains entering the heliosphere today
- presolar grains trapped in meteorites 4.5Gyr ago

# Observational Constraints on Dust: *Observed Extinction*

- **10μm feature: amorphous silicate**

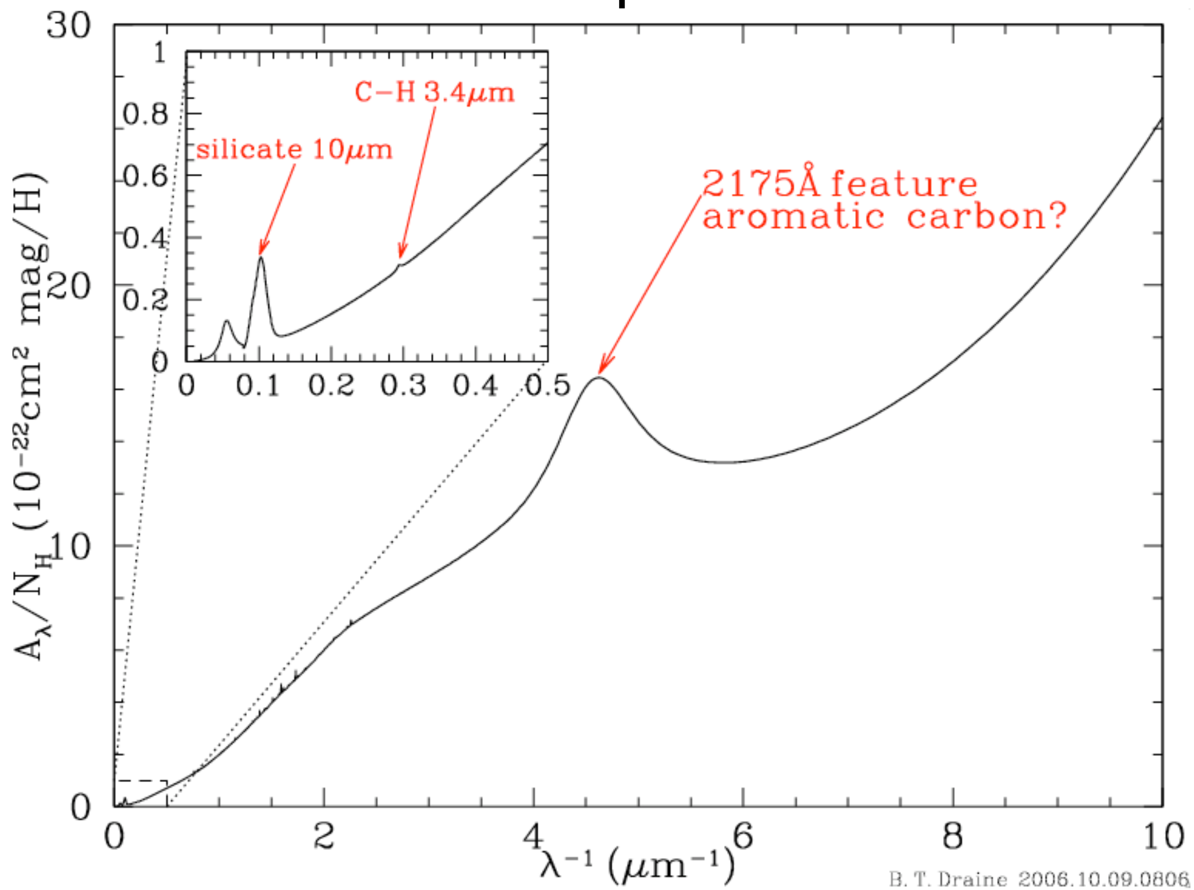
  ***< 2% of silicate material is crystalline***

- **2200A "bump":** probably aromatic **C** (prob. PAHs)

- 3.4μm feature: **C-H** stretch. Aromatic/aliphatic ratio is uncertain:
  ~85/15 (Pendleton & Allamandola 2002)
  <15/85 (Dartois et al 2004)

- λ dependence requires **size distribution from a<0.01μm to a>0.3μm**

Extinction per H nucleon




Draine, B.T. 2008, Space Science Reviews, in press (arXiv:0809.5233)

# *Indirect constraints on interstellar dust*

- Dust models are limited by abundances of elements X such as C, Mg, Si, Fe...:
  $X_{\rm dust} = X_{\rm total} - X_{\rm gas}$
- **IF** $X_{\rm total}/{\rm H} \approx (X/{\rm H})_\odot$, and $X_{\rm gas}/{\rm H}$ = observed values toward $\zeta$Oph, then $\mathbf{M_{dust}/M_H \approx 0.0075}$
- **Variable** depletions of heavy elements – atoms must be able to accrete onto dust, and to return from dust to gas
- Catalysis of $H_2$ on grains
- photoelectric heating of ISM
- Variable depletion of D from gas phase (!!)

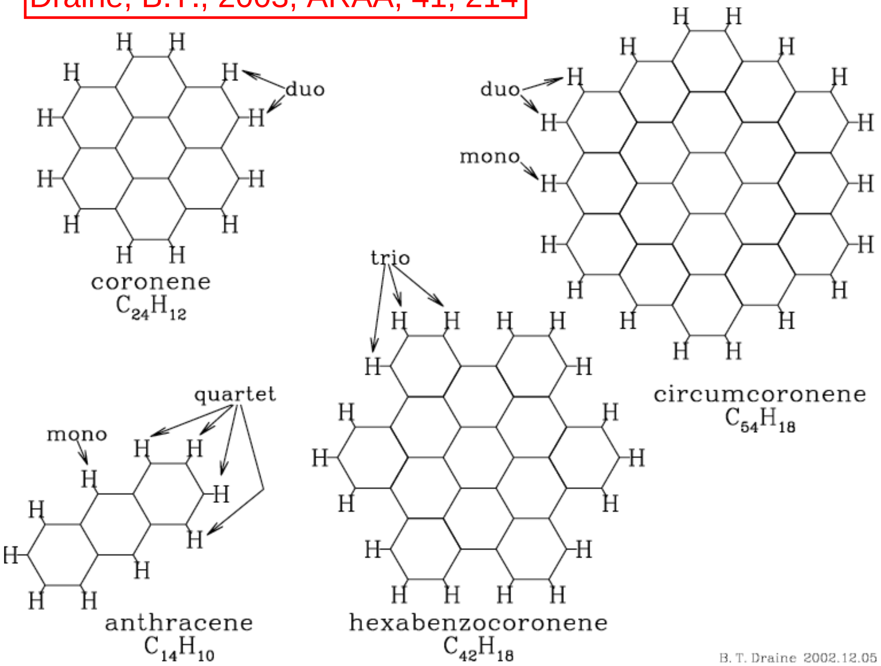
# One Tentative Model

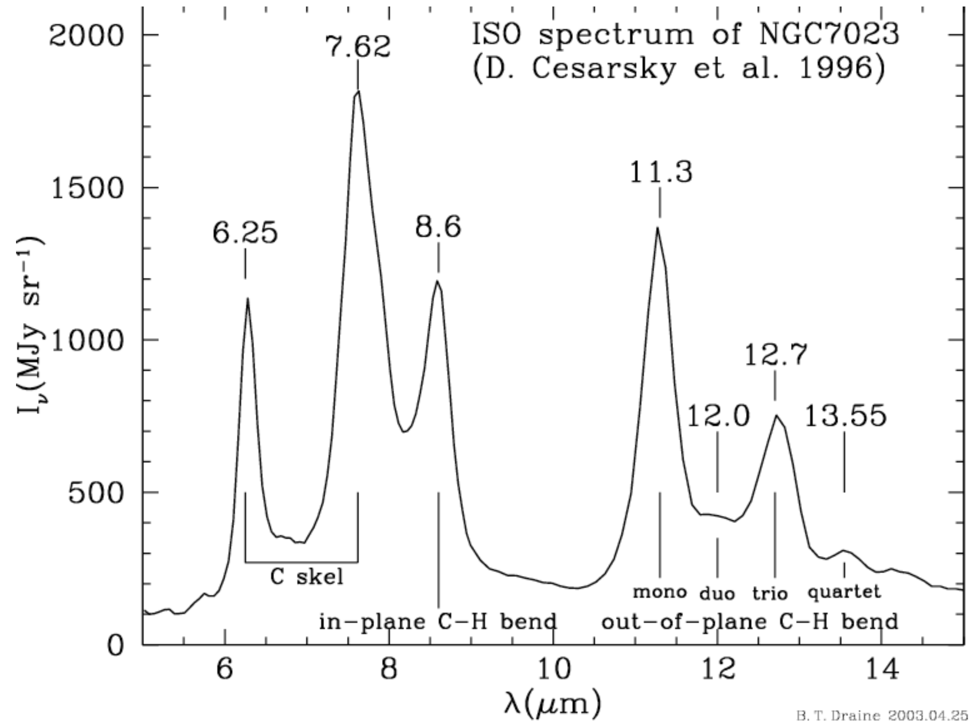
## (Draine & Li 2007; Draine & Fraisse 2009)

- Ingredients:
  - amorphous silicate grains (tentative dielectric function)
  - PAHs, with estimated absorption cross sections
  - larger carbonaceous grains. Try graphite.
- Shape:
  - for silicate and larger carbonaceous grains: oblate spheroids.
  - experiment with different axial ratios.
  - (if not studying polarization, OK to assume spheres)
- Size distribution $dn/da$:
  - vary $dn/da$ to try to reproduce observed $A_\lambda$
- Alignment with magnetic field [alignment fraction $f(a)$]:
  - adjust $f(a)$ to reproduce observed starlight polarization

# Polycyclic Aromatic Hydrocarbons (PAHs)

Draine, B.T., 2003, ARAA, 41, 214



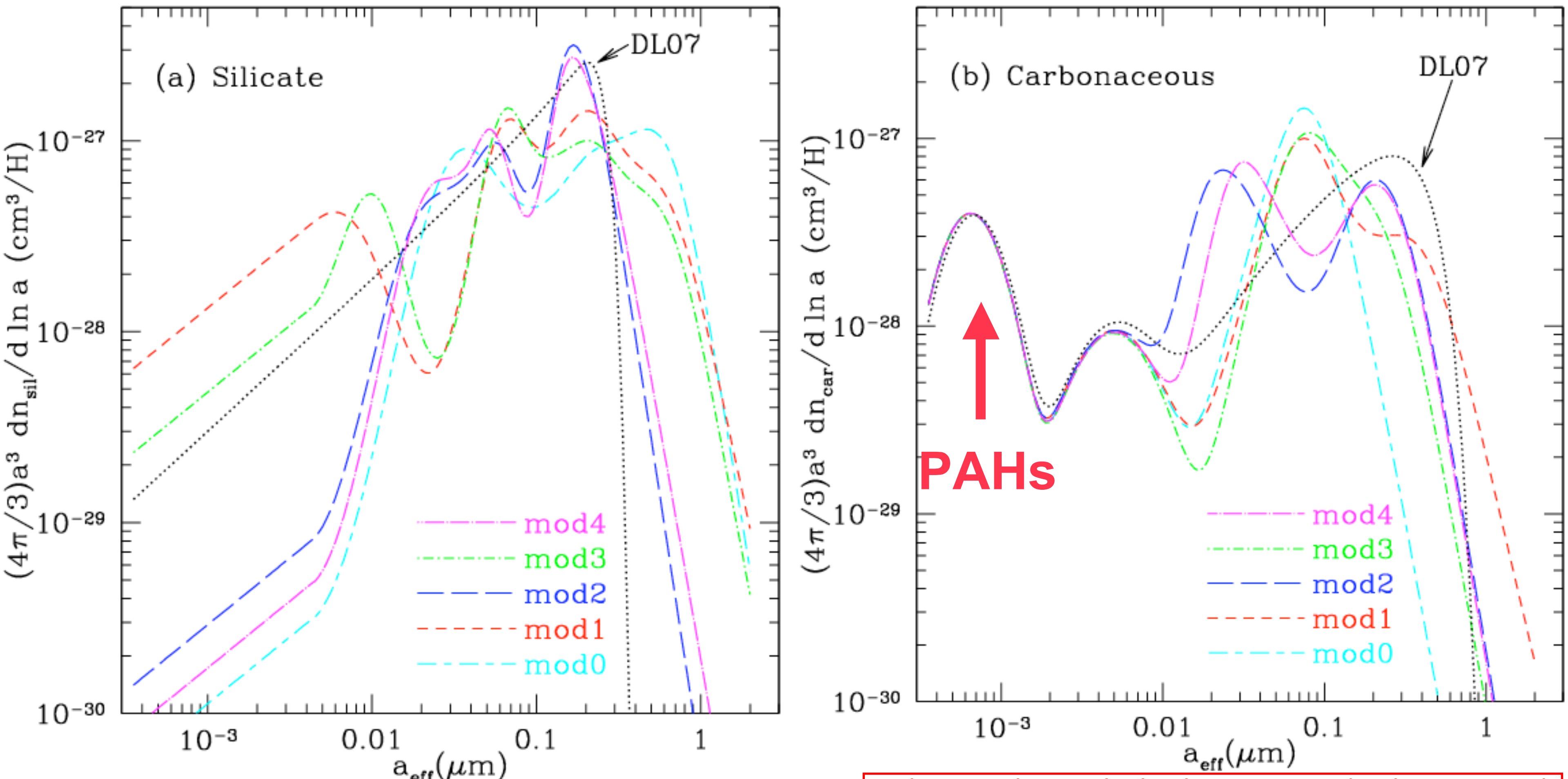

Cesarsky et al. 1996 A&A 315 L305

Emission features at

- **3.3** μm (C-H stretch)
- **6.2**, **7.6** μm(C-C stretch)
- **8.6** μm (C-H in-plane bend)
- **11.3**, **12.7** μm (C-H o-o-p bend)
- **16.4**, **17.0**, **17.4** μm (C-C-C… stretching/bending?)

# Size Distributions
## *(models are not unique…)*

dust mass per logarithmic interval in radius

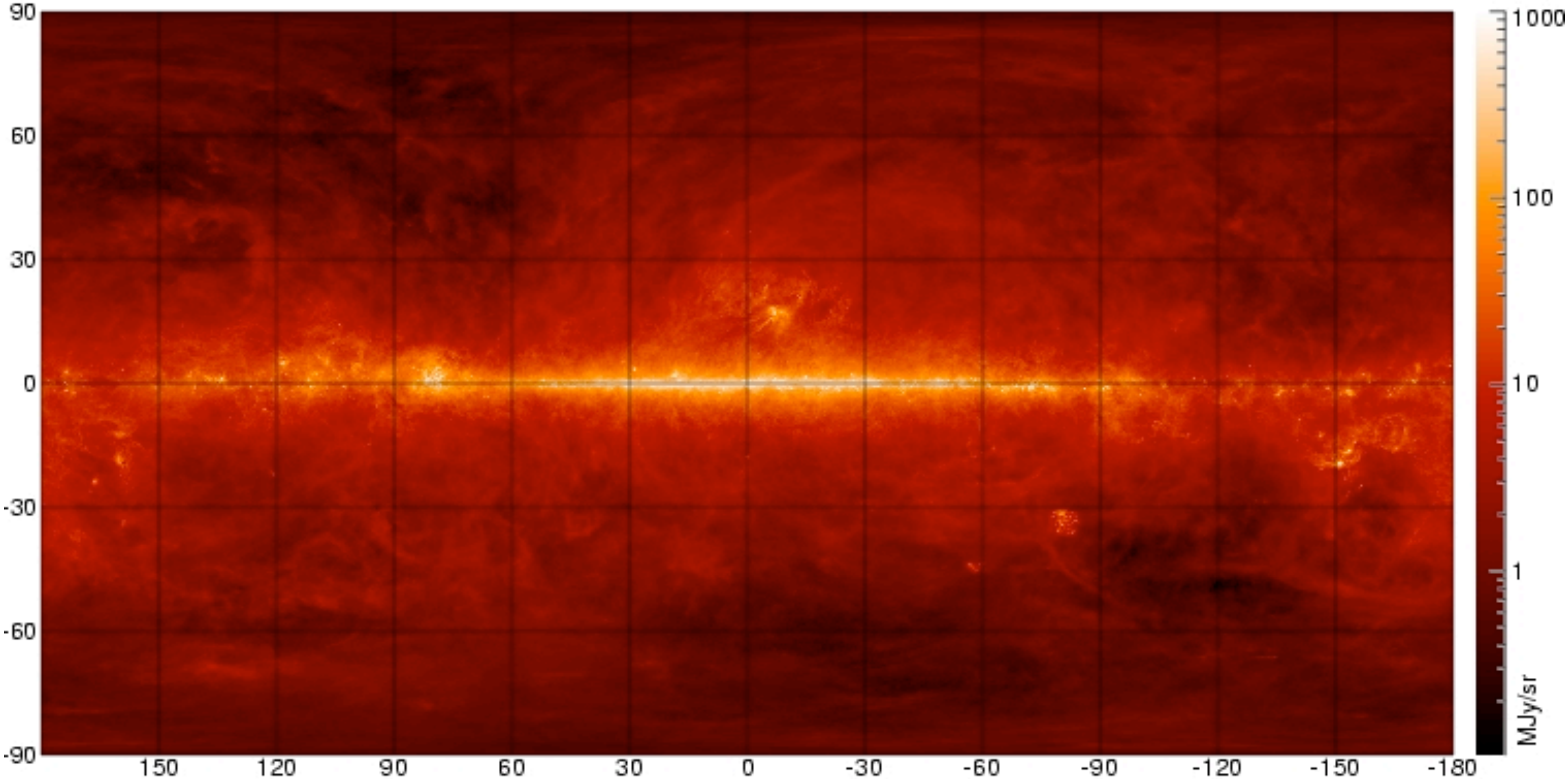



Draine & Fraisse, submitted to ApJ 2008 (arXiv:0809.2094)

(zodi-subtracted) **100μm sky seen by IRAS and COBE**

(processed by Schlegel, Finkbeiner & Davis 1998)

the Milky Way seen by ***DUSTGLOW***




Schlegel, Finkbeiner & Davis, 1998 ApJ 500, 525

# Modeling IR Emission

- Physical grain model: for each grain, calculate
  $C_{abs}(\nu)$ , heat capacity

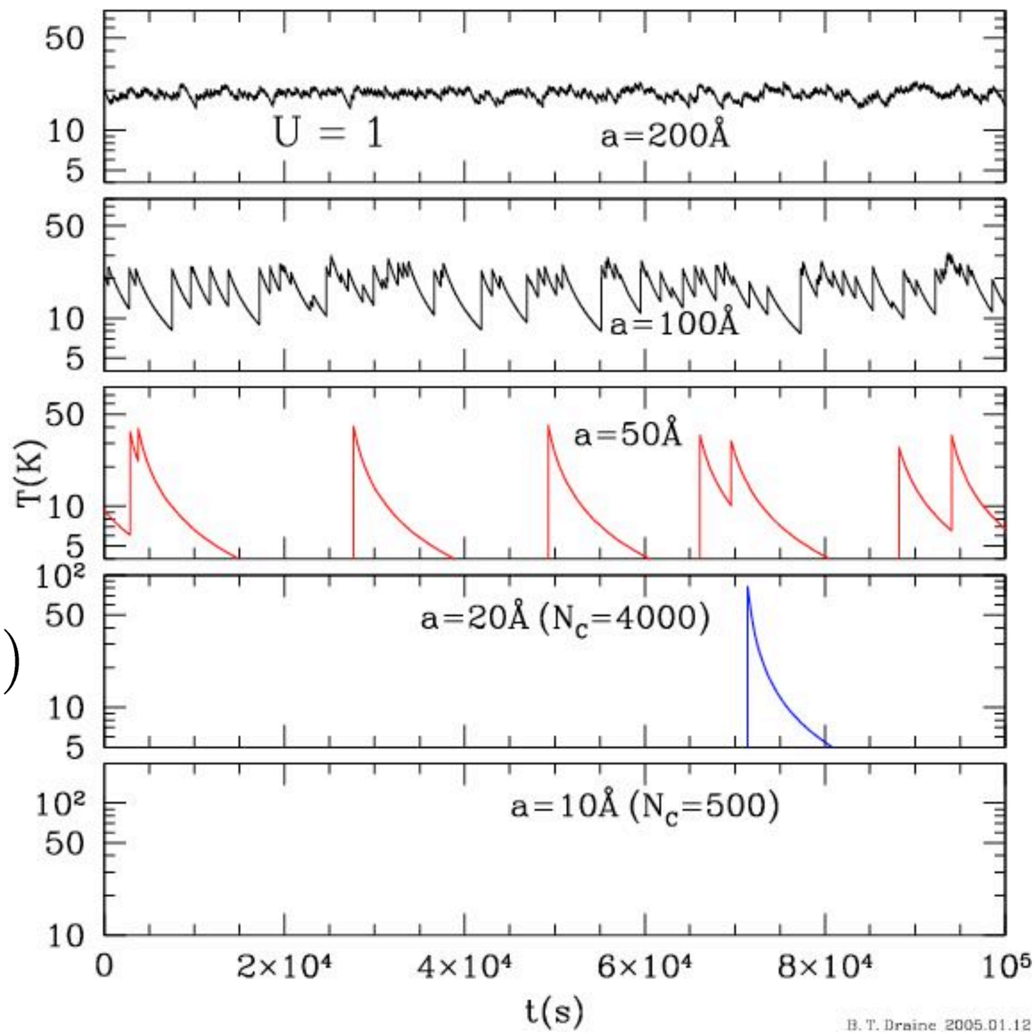
- **Stochastic heating:**
  **Find p(T; comp,size) for each composition, size**

- Time-averaged IR emission:

$$P_\nu = \int dT \frac{dP}{dT} C_{abs}(\nu) 4\pi B_\nu(T)$$

- Sum over compositions, size distribution

***A day in the life…***




Draine, B.T., 2003, ARAA, 41, 214

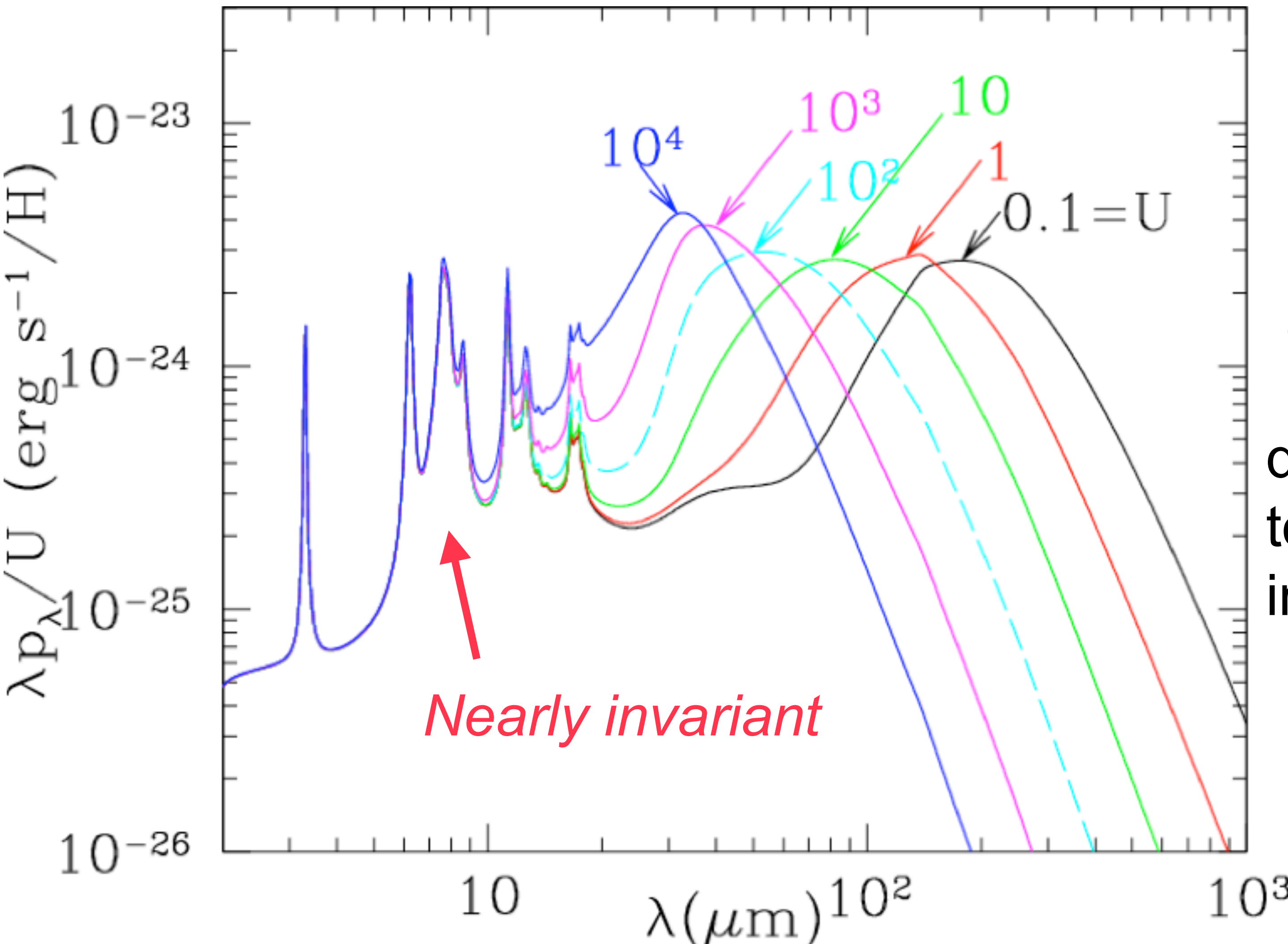
# Modeling IR Emission

$$U \equiv \frac{\text{absorbed starlight power/gram}}{\text{absorbed starlight power/gram in local ISRF}}$$

- For each $U$, find $T$ distribution function $dP/dT$
- Adopt suitable mix of $U$ values for dust in galaxy
- Calculate IR emission from model.
  - determine **dust mass** $M_{\rm dust}$
  - determine **intensity of starlight** heating dust

# IR Emission Calculated for Model

**Dust model heated by various starlight intensities**
**Galaxy spectrum: weighted sum of such spectra**

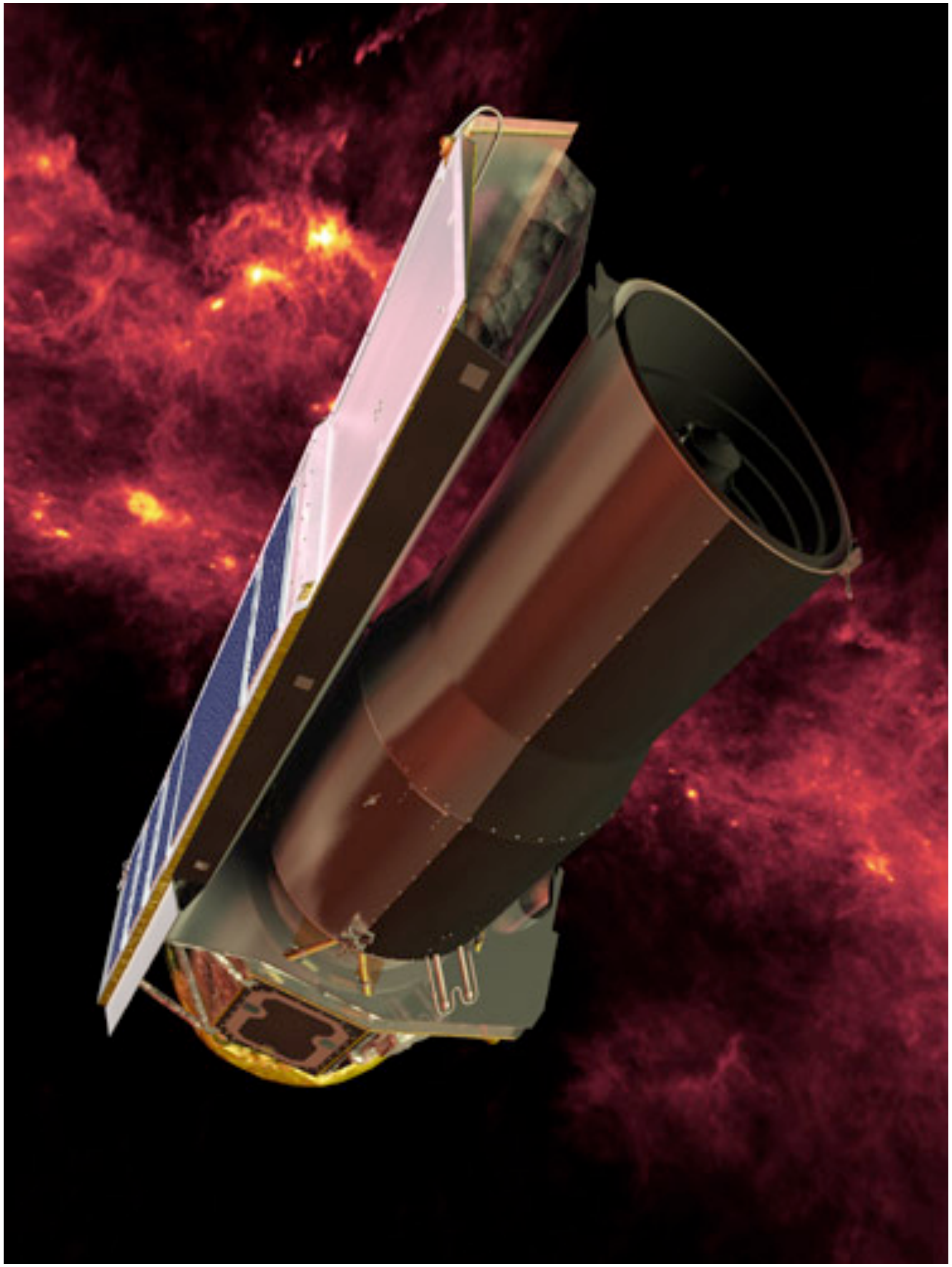



$q_{PAH}$=4.7%

$q_{PAH}$=fraction of total dust mass in PAHs

Draine & Li (2007)

Draine & Li 2007 ApJ, 657, 810-837



http://ipac.jpl.nasa.gov/media_images/screen_jpg/sirtf/SIRTF_ir_1small.jpg

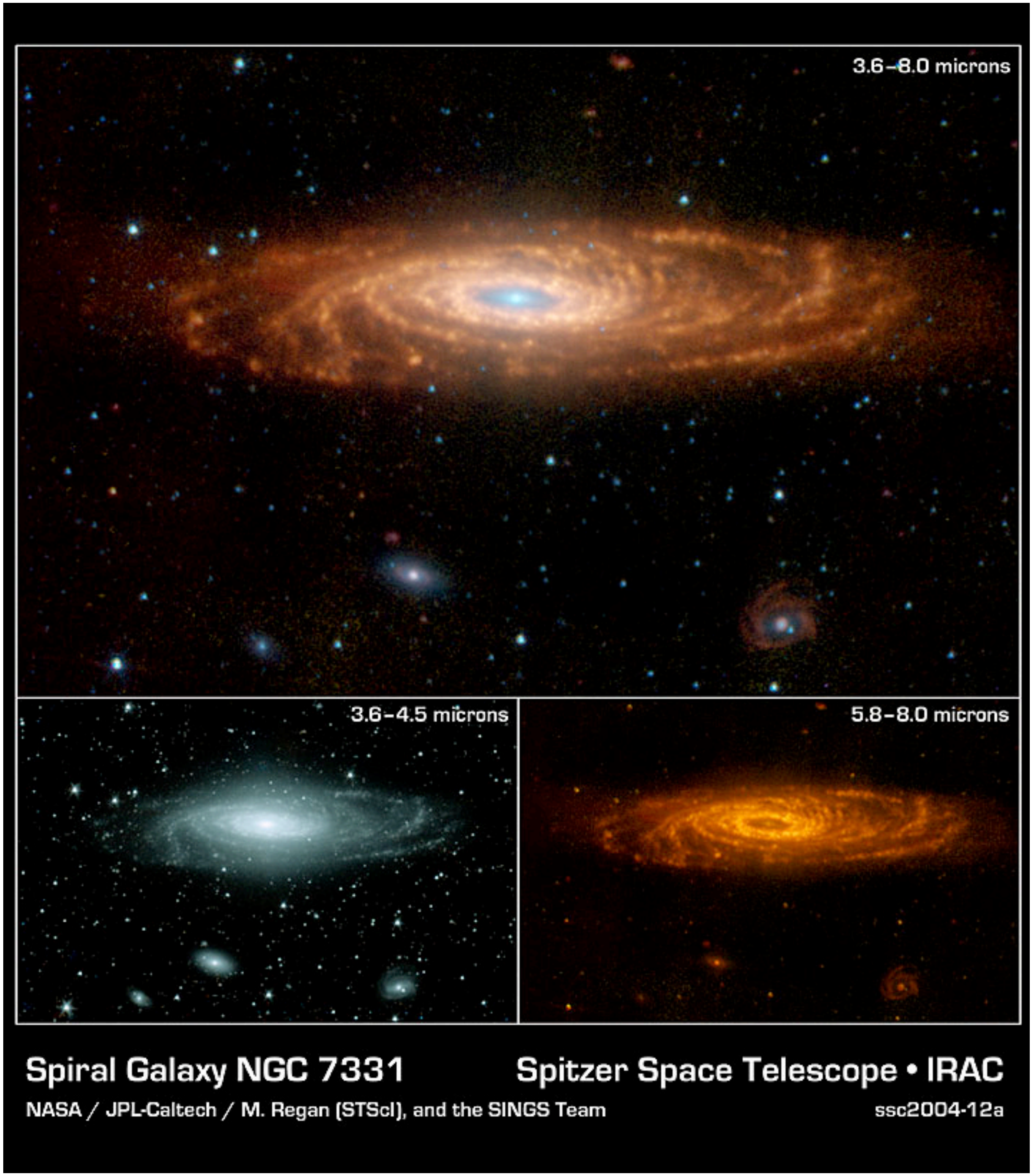
# Spitzer Space Telescope

85 cm, LHe-cooled optics
Launched: Aug. 2003
LHe exhaustion:
~April 2009

Imaging: 3.6 - 160μm
Spectra: 5 - 38μm

# IR View
# NGC 7331
# (SINGS)

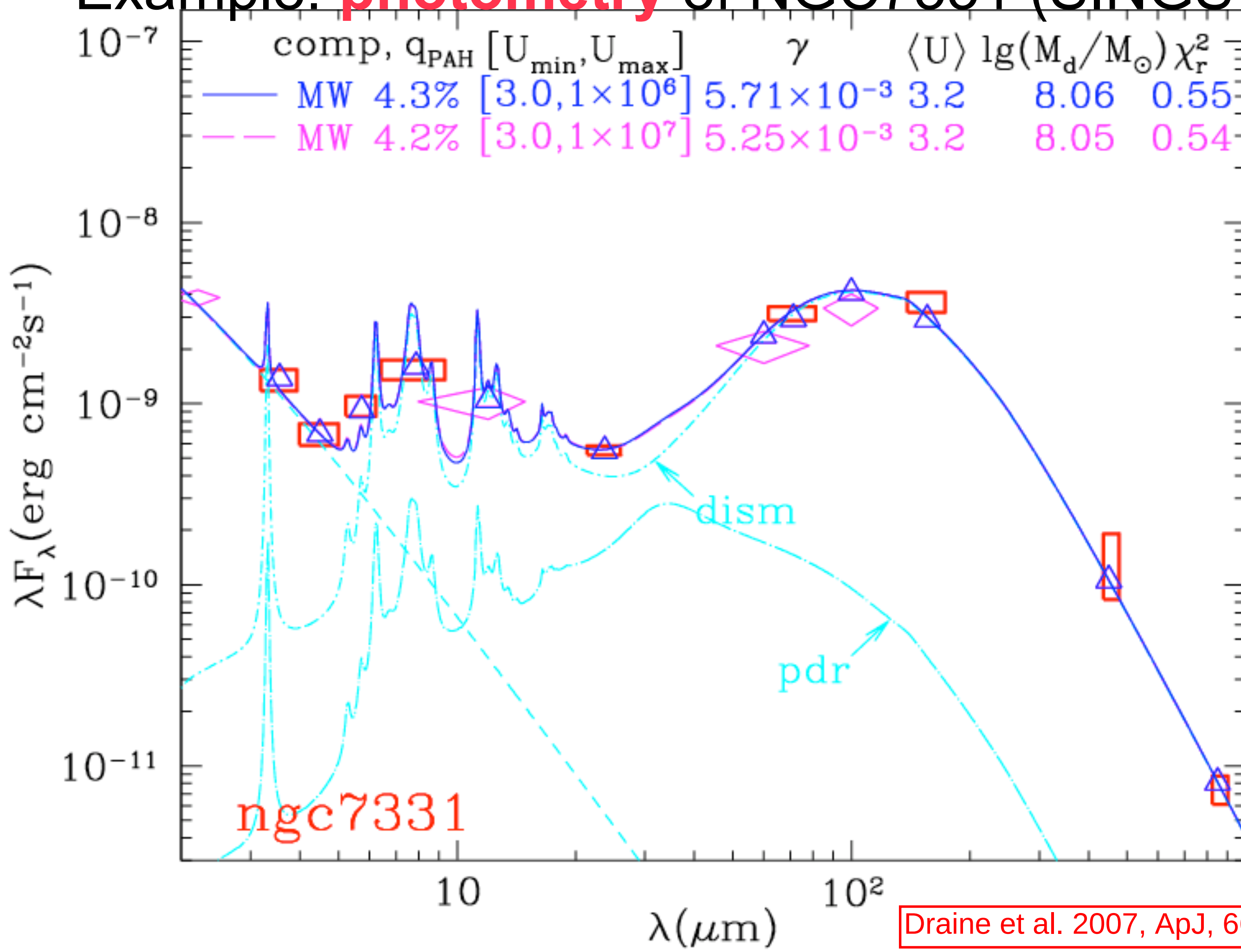
3.6μm: **starlight**
8.0μm: **dustglow**




http://gallery.spitzer.caltech.edu/Imagegallery/image.php?image_name=ssc2004-12a

# *How well does the dust model do?*

Example: **photometry** of NGC7331 (SINGS data)

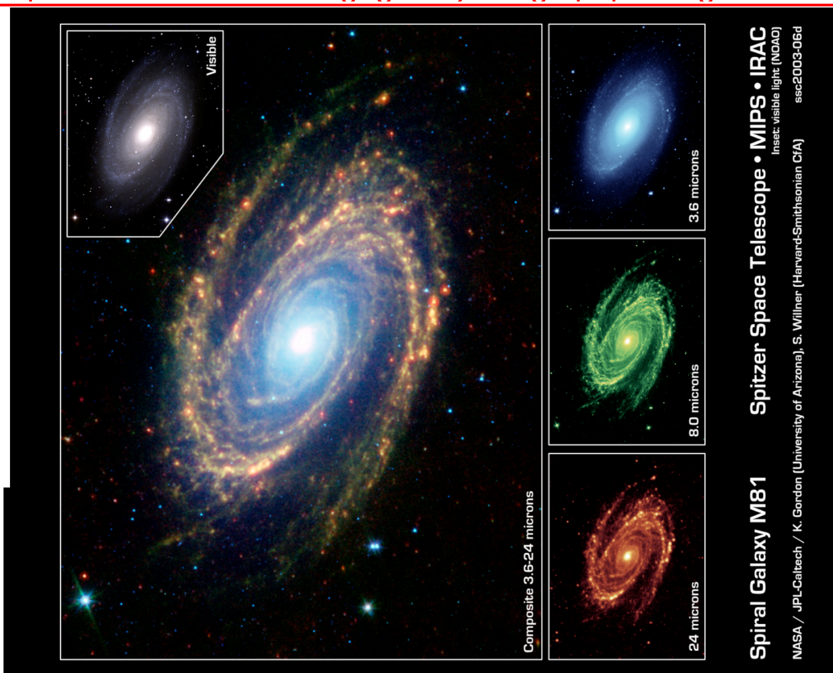



Draine et al. 2007, ApJ, 663, 866-894

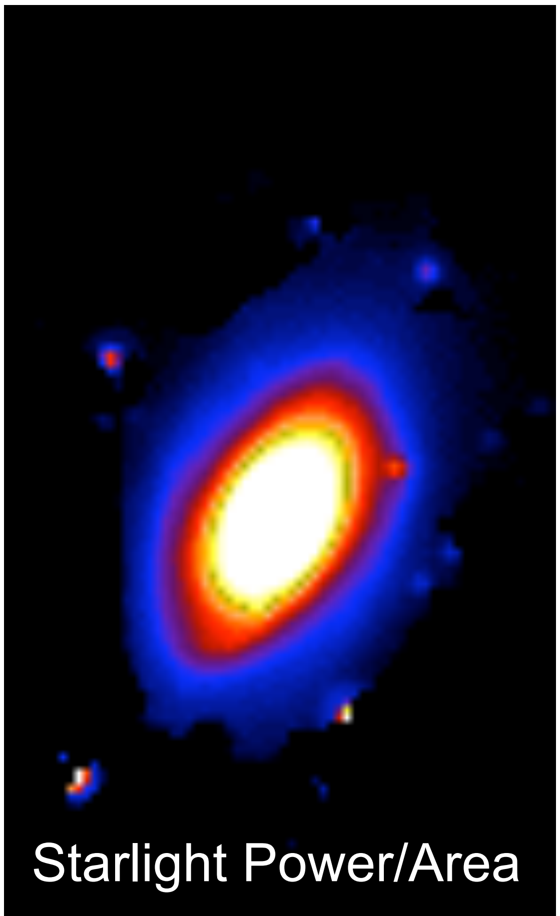
$$M_{\rm dust} = 1.1\times10^8 M_\odot$$
$$M({\rm HI}) = 1.0\times10^{10} M_\odot \quad\longrightarrow\quad \frac{M_{\rm dust}}{M_{\rm H}} = 0.0043$$
$$M({\rm H_2}) \approx 1.6\times10^{10} M_\odot$$

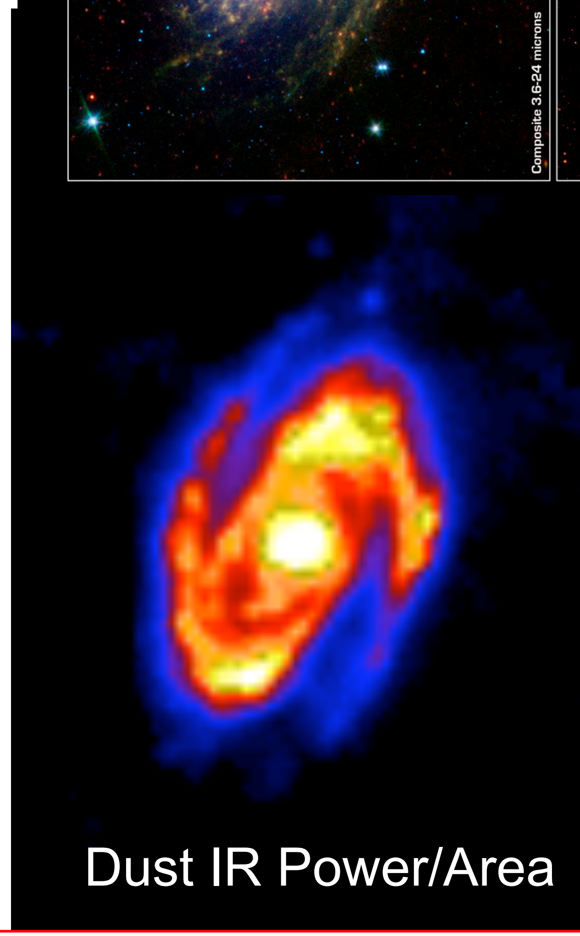
http://gallery.spitzer.caltech.edu/Imagegallery/image.php?image_name=ssc2003-06d

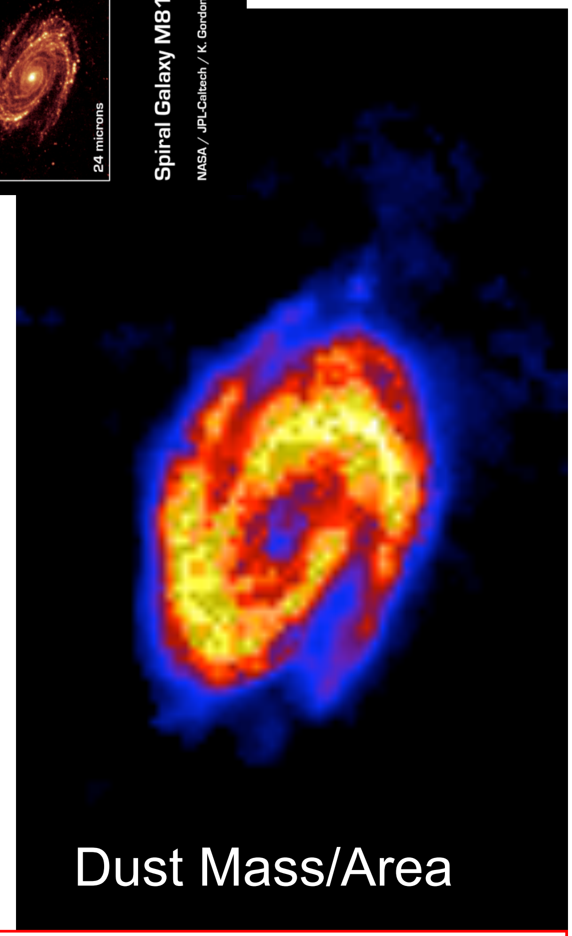
# *NGC 3031 (=M81)*




# DUST MAP



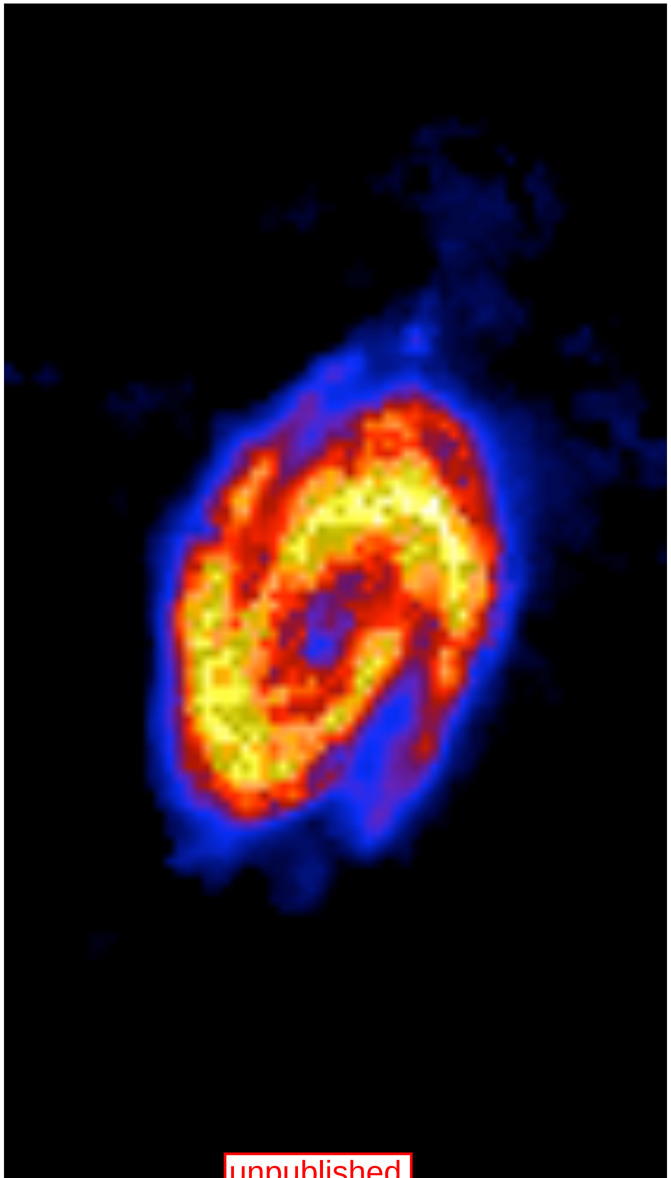




unpublished

# *NGC 3031 (=M81)*

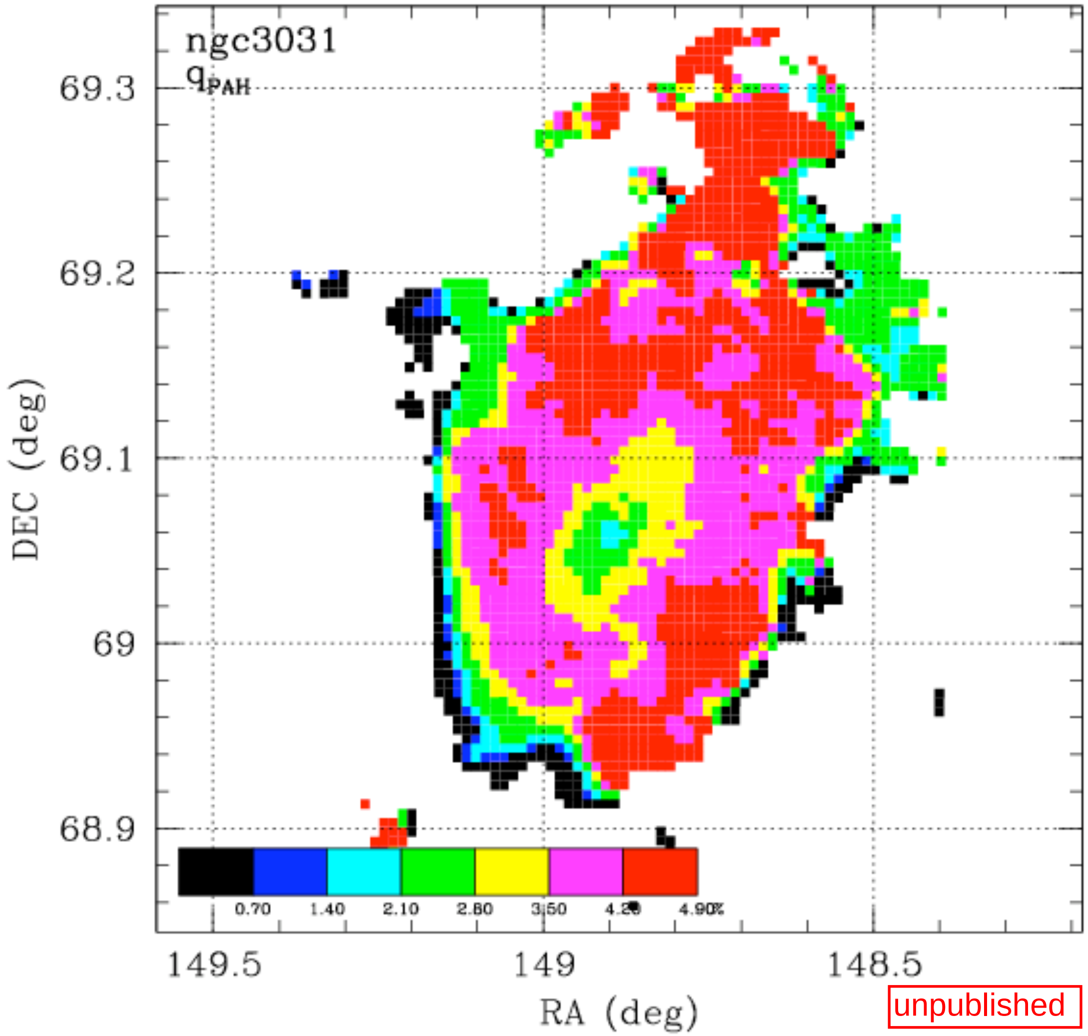
Dust Surface Density




**$q_{PAH}$≡(PAH mass)/(total dust mass)**

Global $q_{PAH}$ =4.0%

**$q_{PAH}$ Image**



# *IR Spectroscopy*

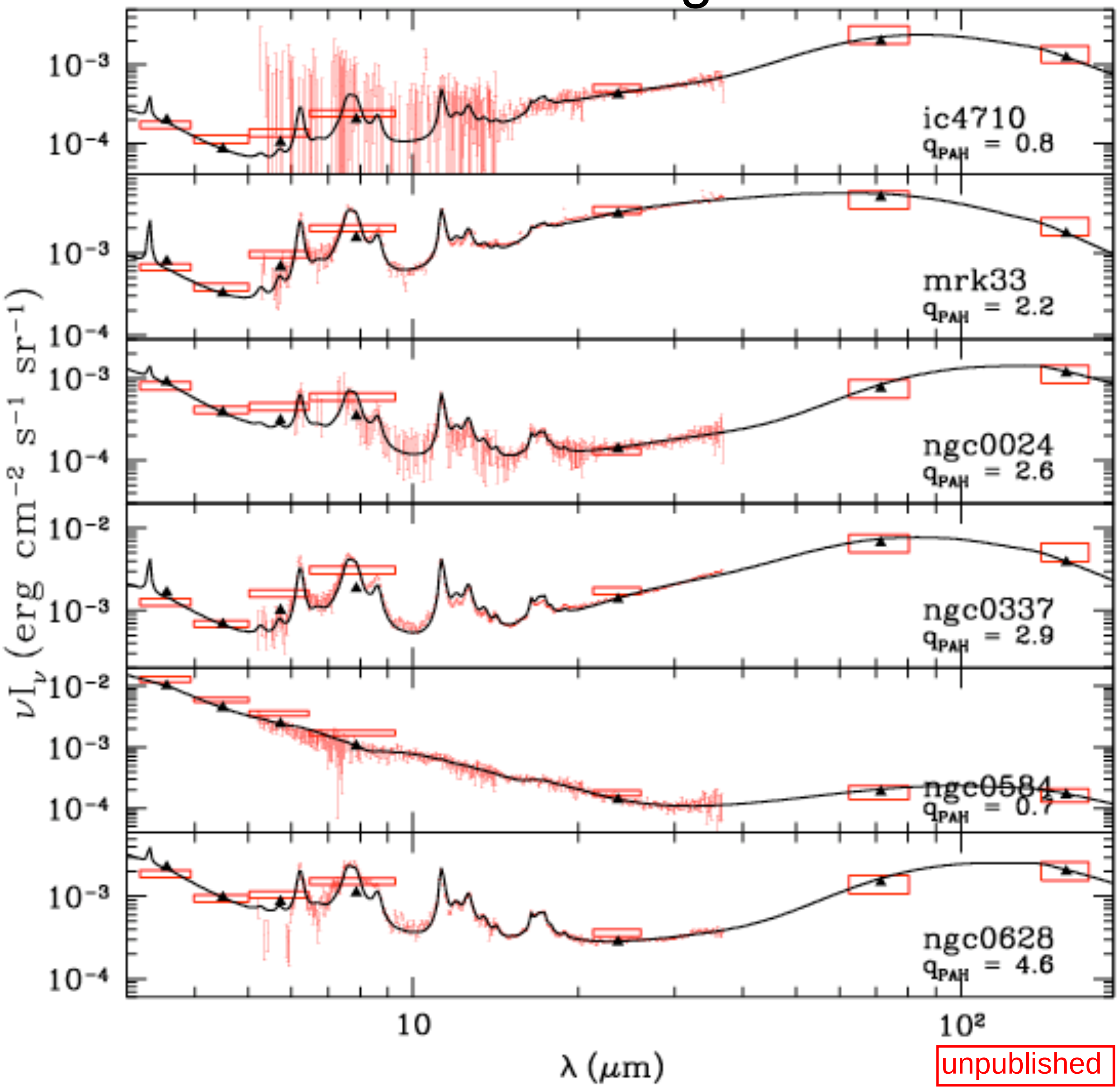
red: observations

black: model

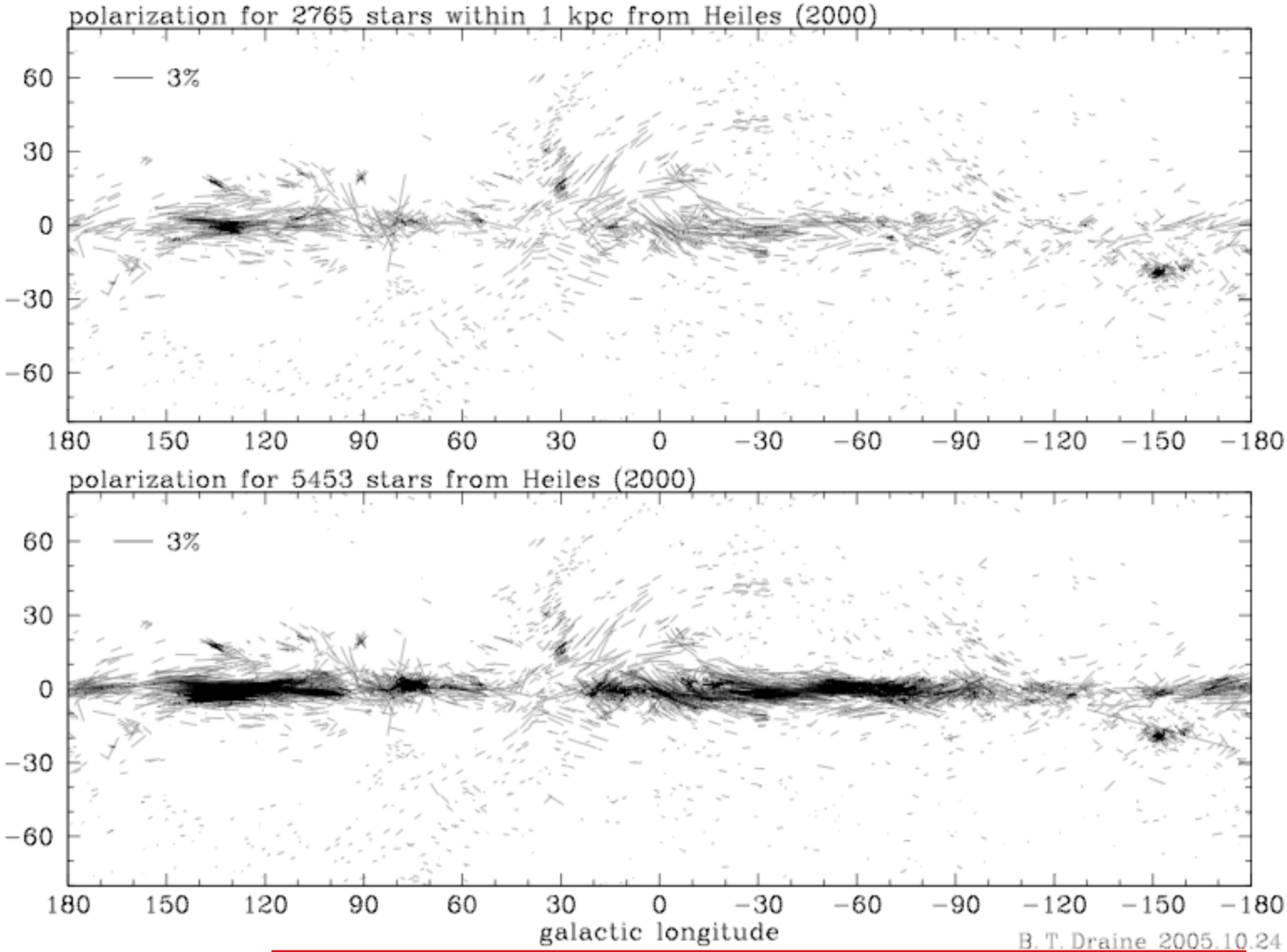
***model = dust mix heated by suitable mix of starlight intensities***

(BTD, R. Reyes, J.D. Smith, & SINGS team…)

Centers of galaxies:

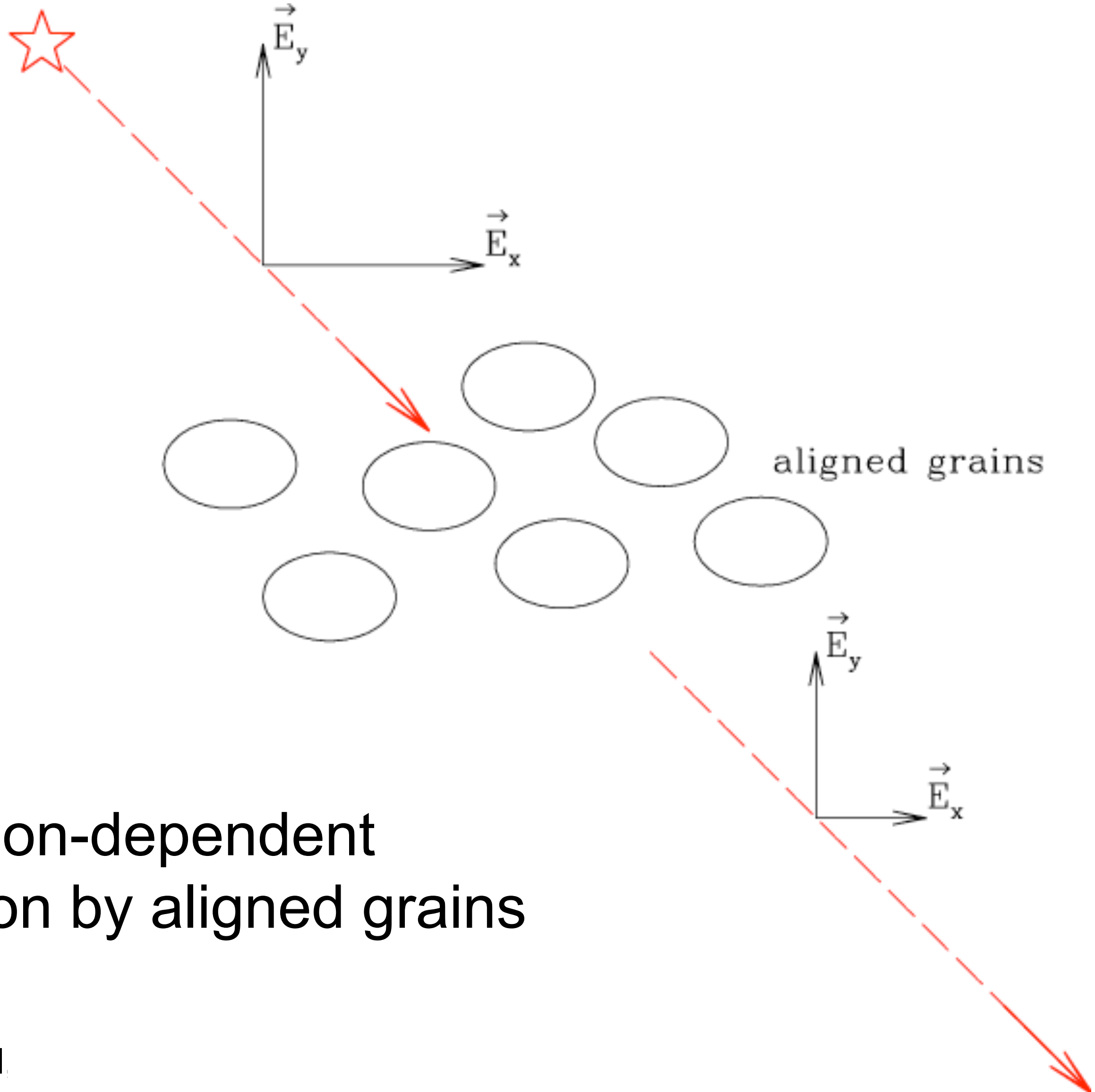


# Polarization of Starlight: Aligned Dust Grains




Whittet.D.C.B., 2003, "Dust in the Galactic Environment", (Bristol, Institute of Physics)

# Polarization of starlight




Polarization-dependent attenuation by aligned grains



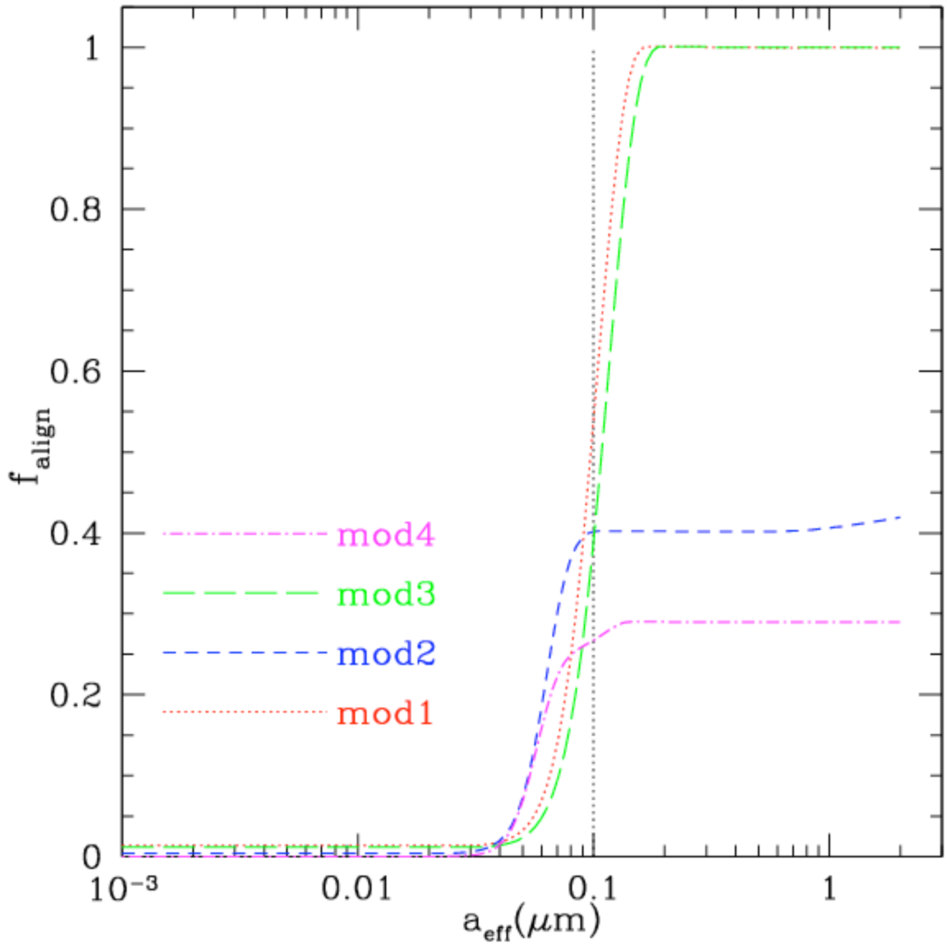
original schematics

# Polarization of Starlight in Milky Way

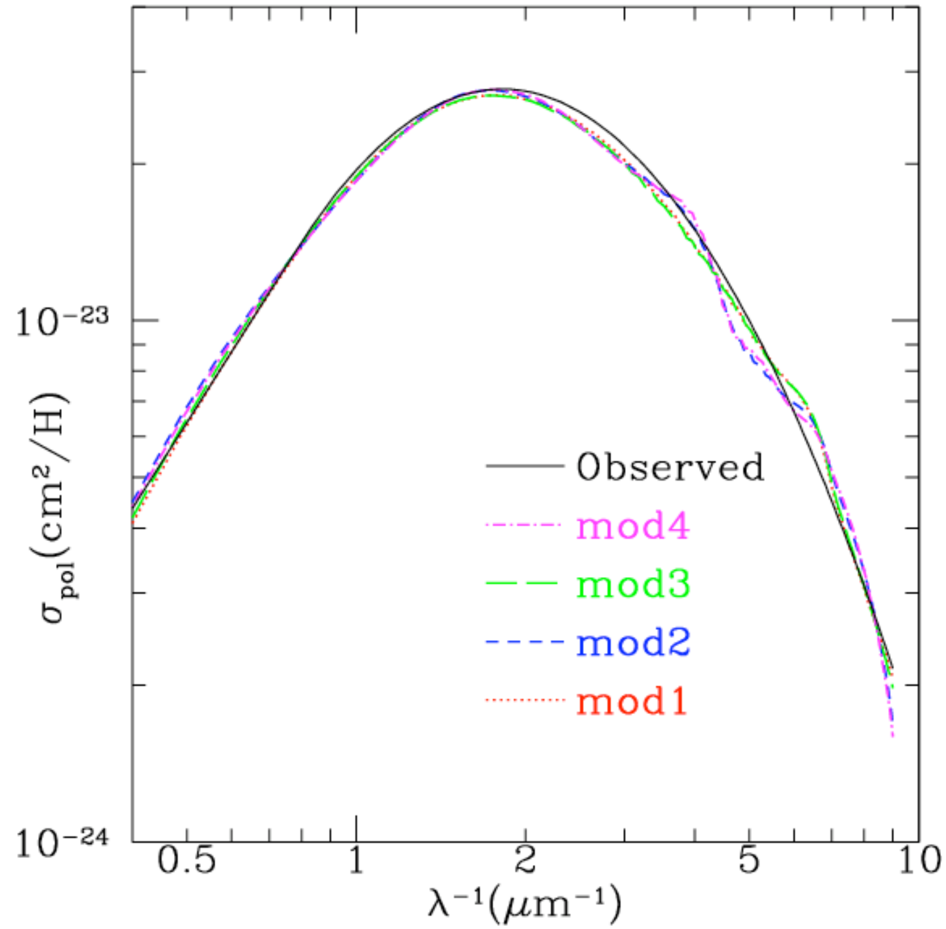
**(BTD & Fraisse 2009)**

***Different models: different axial ratios for oblate spheroids***

**Adopted alignment f(a)**




**Resulting polarization cross section**

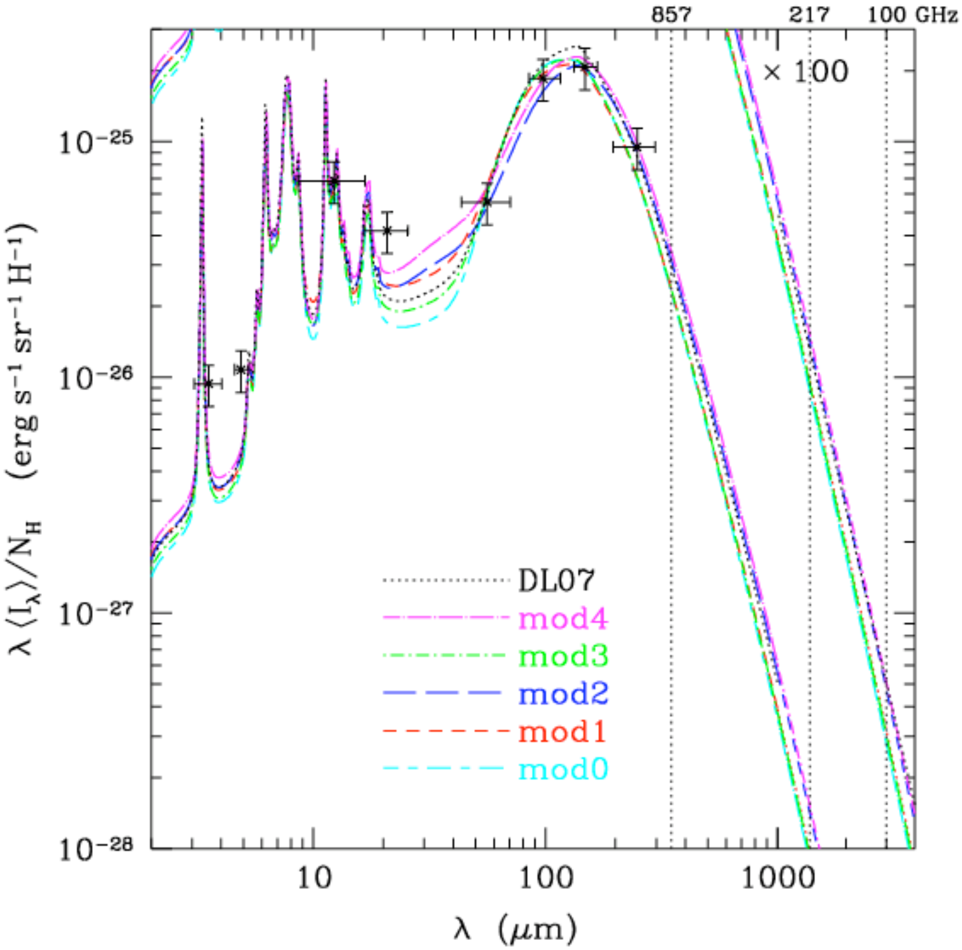



CPS School, Kobe
2009.01.08

Draine & Fraisse, submitted to ApJ 2009 (arXiv:0809.2094)

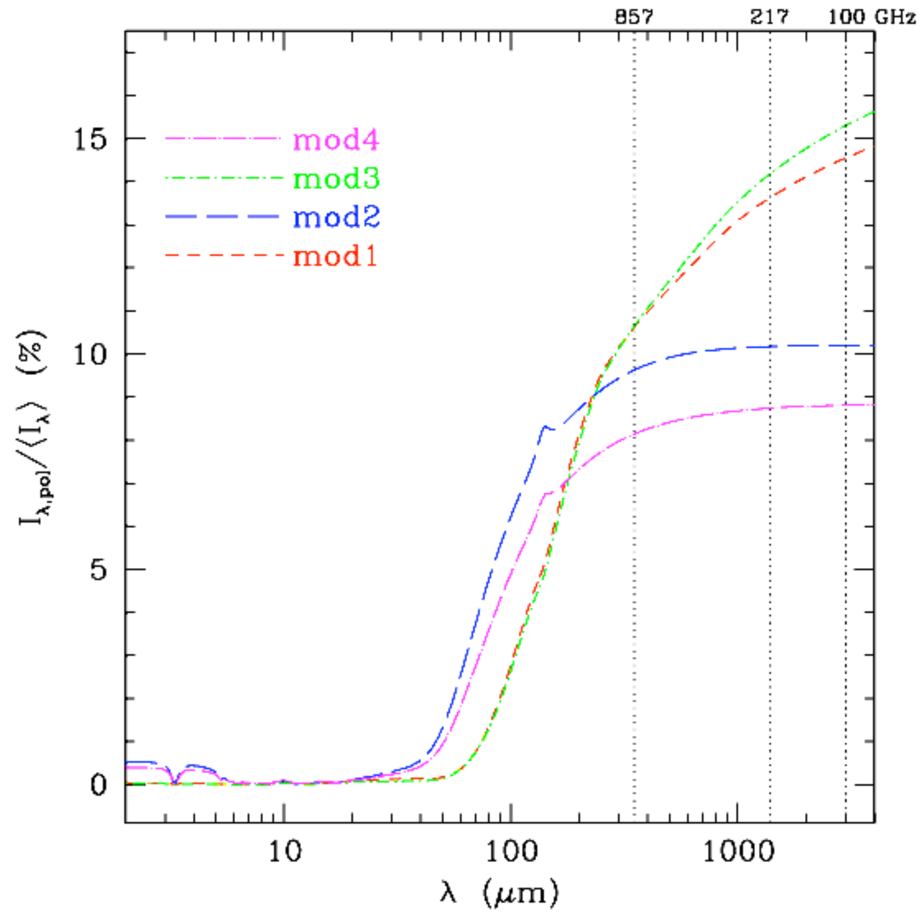
Draine & Fraisse, submitted to ApJ 2009 (arXiv:0809.2094)

# Total Emission




# % Polarization

## (sightline ⊥ $B_0$ )




IR-submm polarization:

1. ***Model-dependent***
2. ***Frequency-dependent***

∴ ***TEST of models***

***Planck to be launched April 12***

CPS School, Kobe
2009.01.08

# Spinning Dust

- To reproduce strong PAH emission bands at 3.3, 6.2, 7.7, 8.6, 11.3 $\mu$m, need a very large population of small particles, with $\sim 4.5\%$ of total grain mass in carbonaceous particles with $N_{\rm C} < 10^3$ C atoms
- These particles MUST be rotating, and almost certainly have significant dipole moments, and will therefore produce rotational emission.
- Particles may be 2-d PAH molecules, or perhaps multilayer stacks of PAHs.
- If spherical, $N_{\rm C} = 58(a_{\rm eff}/5\,\text{Å})^3$

$$\left(\frac{\omega_{\rm rms}}{2\pi}\right)_{LTE} = \frac{1}{2\pi}\left(\frac{3kT}{I}\right)^{1/2}$$

$$= 30\,{\rm GHz}\left(\frac{T}{100\,{\rm K}}\right)^{1/2}\left(\frac{58}{N_{\rm C}}\right)^{5/6}$$

$$\frac{I\omega_{\rm rms}}{\hbar} = 210\left(\frac{T}{100K}\right)^{1/2}\left(\frac{N_{\rm C}}{58}\right)^{5/6} \quad \text{[Classical treatment OK]}$$

# Spinning Dust

Rotation is NOT in LTE – Rotational excitation discussed by Draine & Lazarian (1998). Processes exciting/damping rotation include:

- Collisions with neutral gas atoms
- Collisions with ions
- Torques due to ions passing near grain ("plasma drag")
- Absorption of photons
- Emission of infrared photons
- Electric dipole radiation from rotation

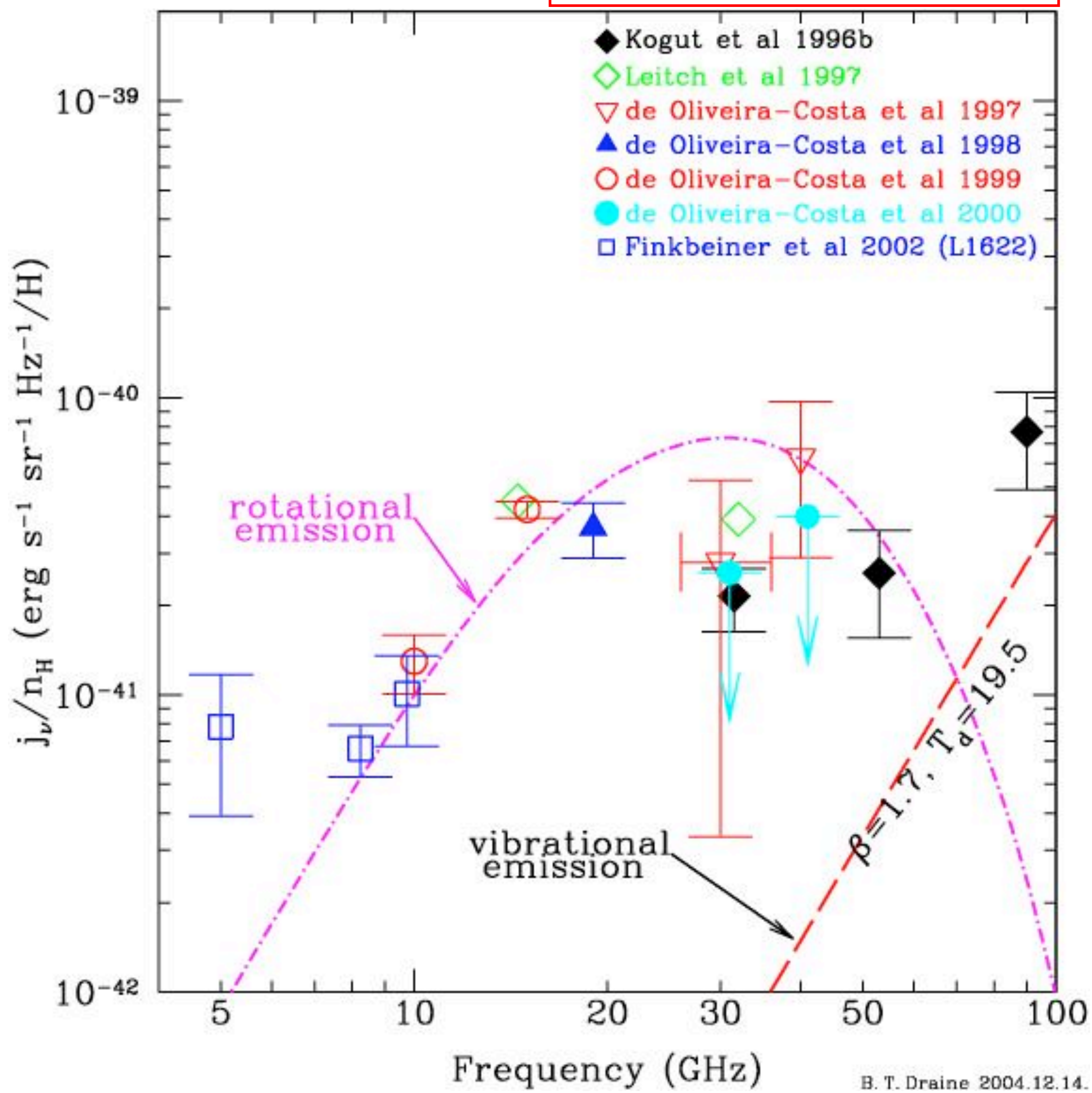
For assumed electric dipole moment and using PAH size distribution required to reproduce IR emission, DL98 estimated microwave emission from PAHs.

**"Spinning dust" emission appears to explain dust-correlated "anomalous" microwave emission detected in CMB studies.**

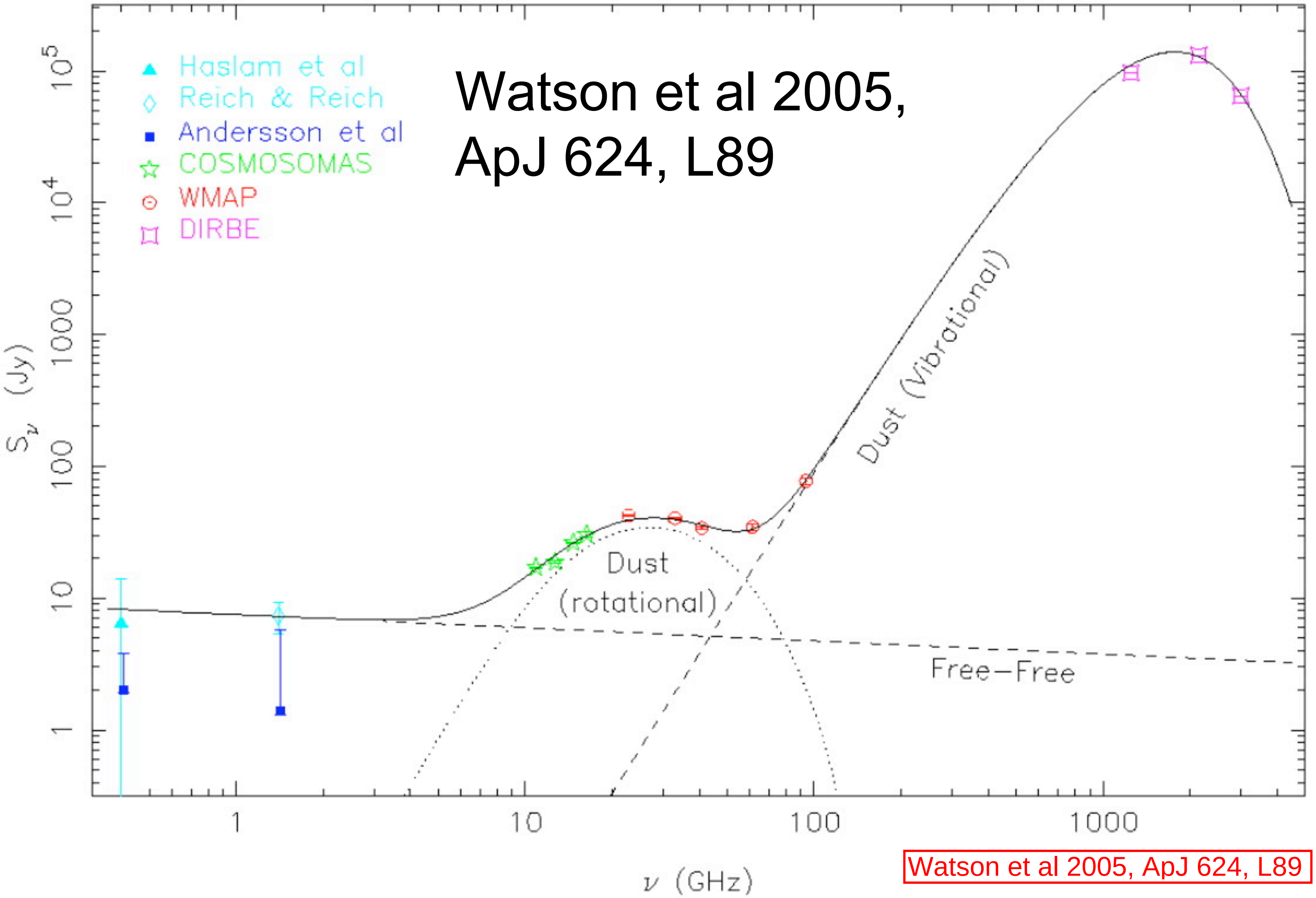
# Microwave Emission

- Dust-correlated microwave emission discovered by CMB studies.
- Likely due to **spinning dust** (Draine & Lazarian 1998) -- same ultrasmall dust grains needed to explain 3-15um “PAH” emission.

Draine, B.T., 2003, ARAA, 41, 214



# Microwave Emission from Perseus Molecular Cloud



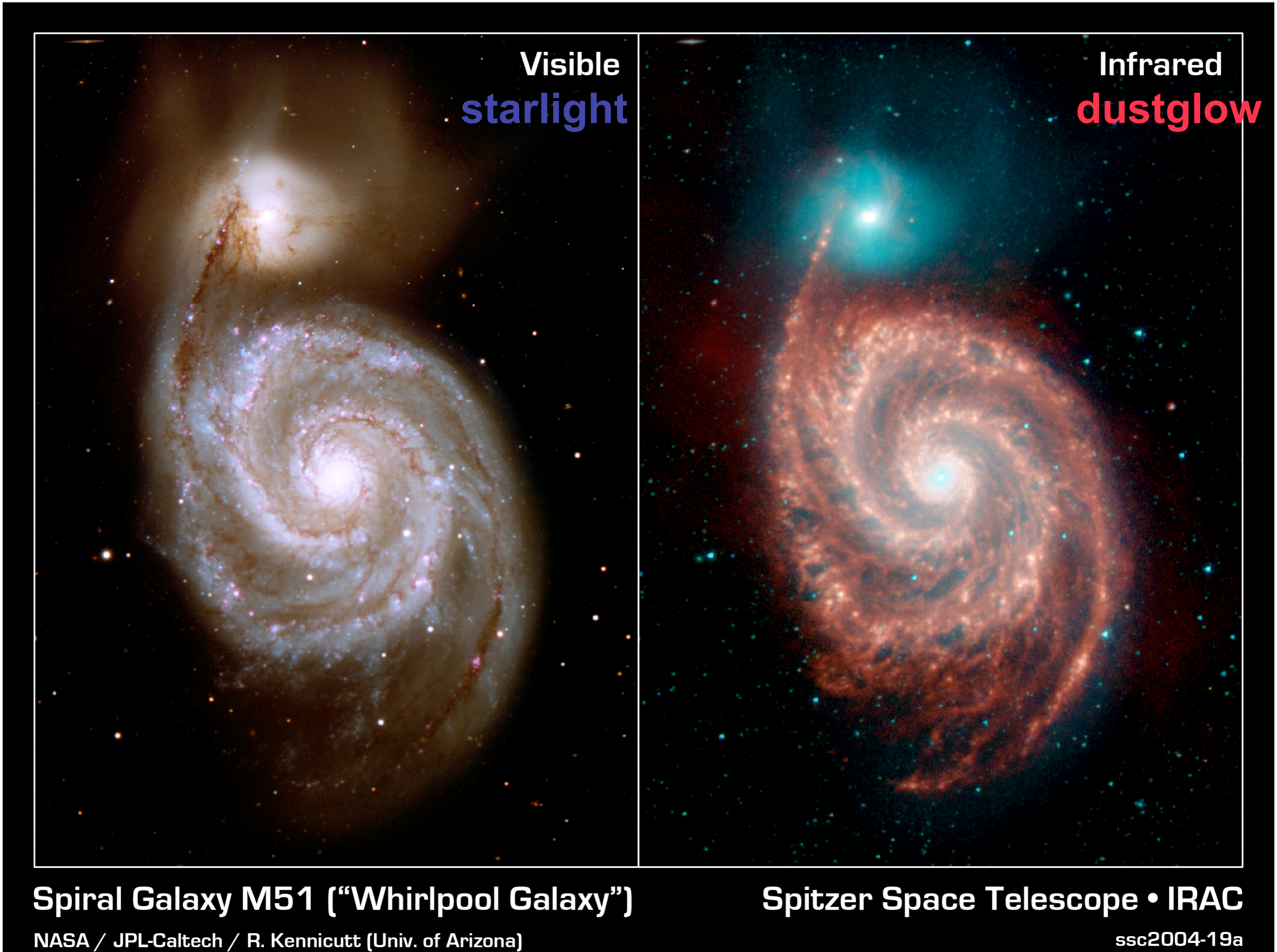

Watson et al 2005, ApJ 624, L89

# Summary of interstellar dust model requirements

- **To reproduce extinction, models require $\sim$100% of total Mg, Si, Fe (in amorphous silicates) + $\sim$70% of C in carbonaceous grains:**
  - **75% of grain mass in amorphous silicates ($< 2\%$ crystalline)**
  - **5% of grain mass in PAHs containing $\lesssim 10^3$C atoms (to reproduce observed 3–15 $\mu$m PAH emission features)**
  - **20% of grain mass in other carbonaceous material**
- **broad size distribution from $0.0004\,\mu$m – $\gtrsim 0.3\,\mu$m required to reproduce extinction and polarization**
- **$\sim$50% of grain mass above/below $a \approx 0.1\,\mu$m**
- **Starlight polarization requires that**
  - **$a \gtrsim 0.1\,\mu$m grains must be substantially nonspherical**
  - **$a \gtrsim 0.1\,\mu$m grains must be aligned by galactic B field (how?)**
  - **smaller ($a \lesssim 0.05\,\mu$m) grains are not aligned (why not?)**

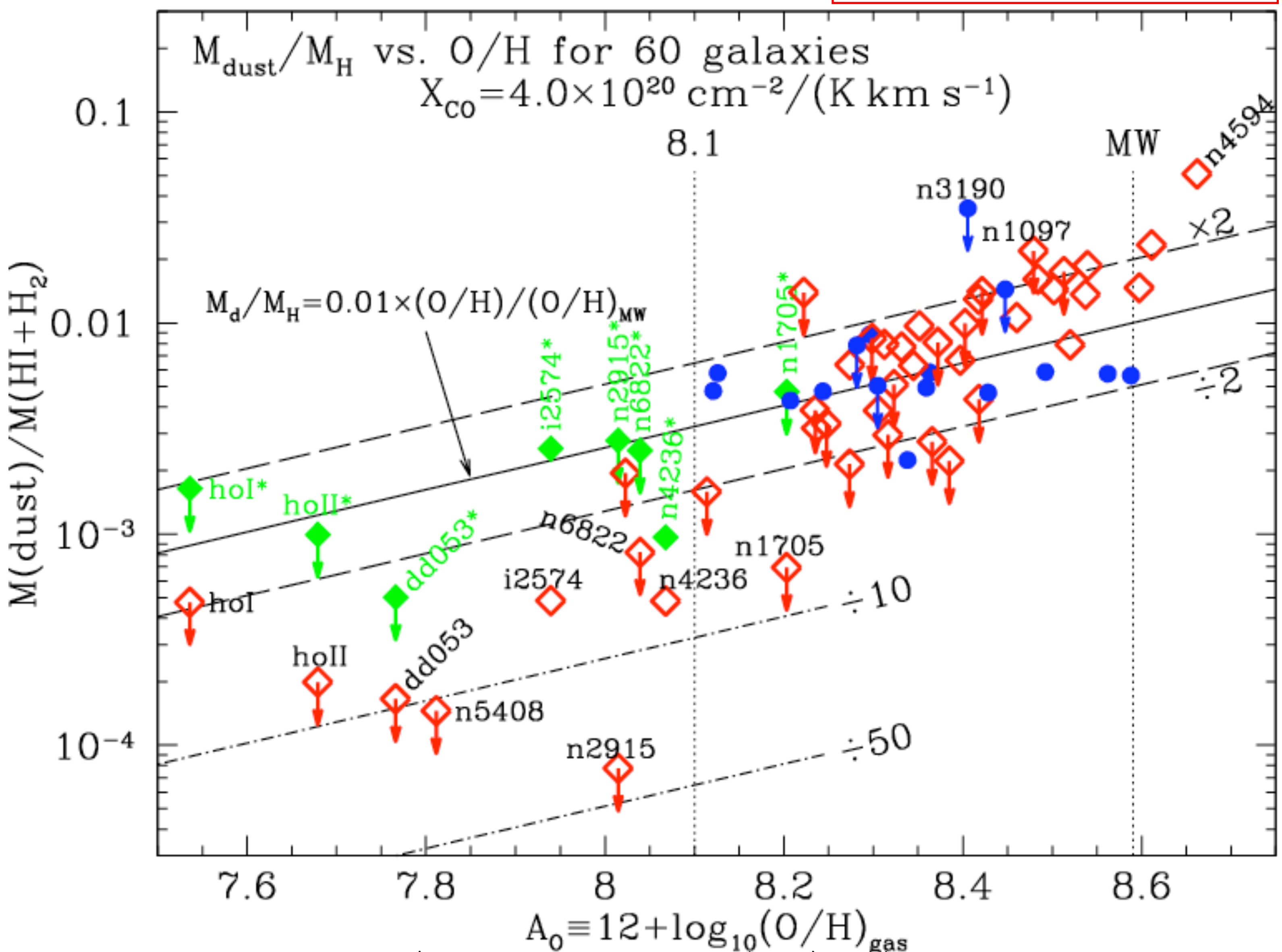
# Model for interstellar dust: tests and predictions

- **By adjusting size distribution, model successfully reproduces $\lambda$-dependent extinction in MW, LMC, and SMC.**
- **Dust model illuminated by starlight gives IR emission spectrum consistent with observations in MW and other galaxies.**
- **Albedo and $\langle \cos\theta \rangle$ inferred for scattering by interstellar dust are consistent with grain model.**
- **X-ray scattering properties of the dust model are broadly consistent with observations of X-ray scattering halos – but additional tests are possible (e.g., test for substructure in large grains: Heng & Draine 2009)**
- **PAH population explains observed microwave emission**
- **Prediction: if extinction lacks 2175Å feature, PAH features should not be present in IR emission (soon to be tested in SMC)**
- **Prediction: aligned grains → noncircular X-ray halos (Draine & Allaf-Akbari 2006)**
- **Prediction: [model-dependent] polarization $p(\lambda)$ in FIR/submm emission (Draine & Fraisse 2009)**




http://gallery.spitzer.caltech.edu/Imagegallery/image.php?image_name=ssc2004-19a

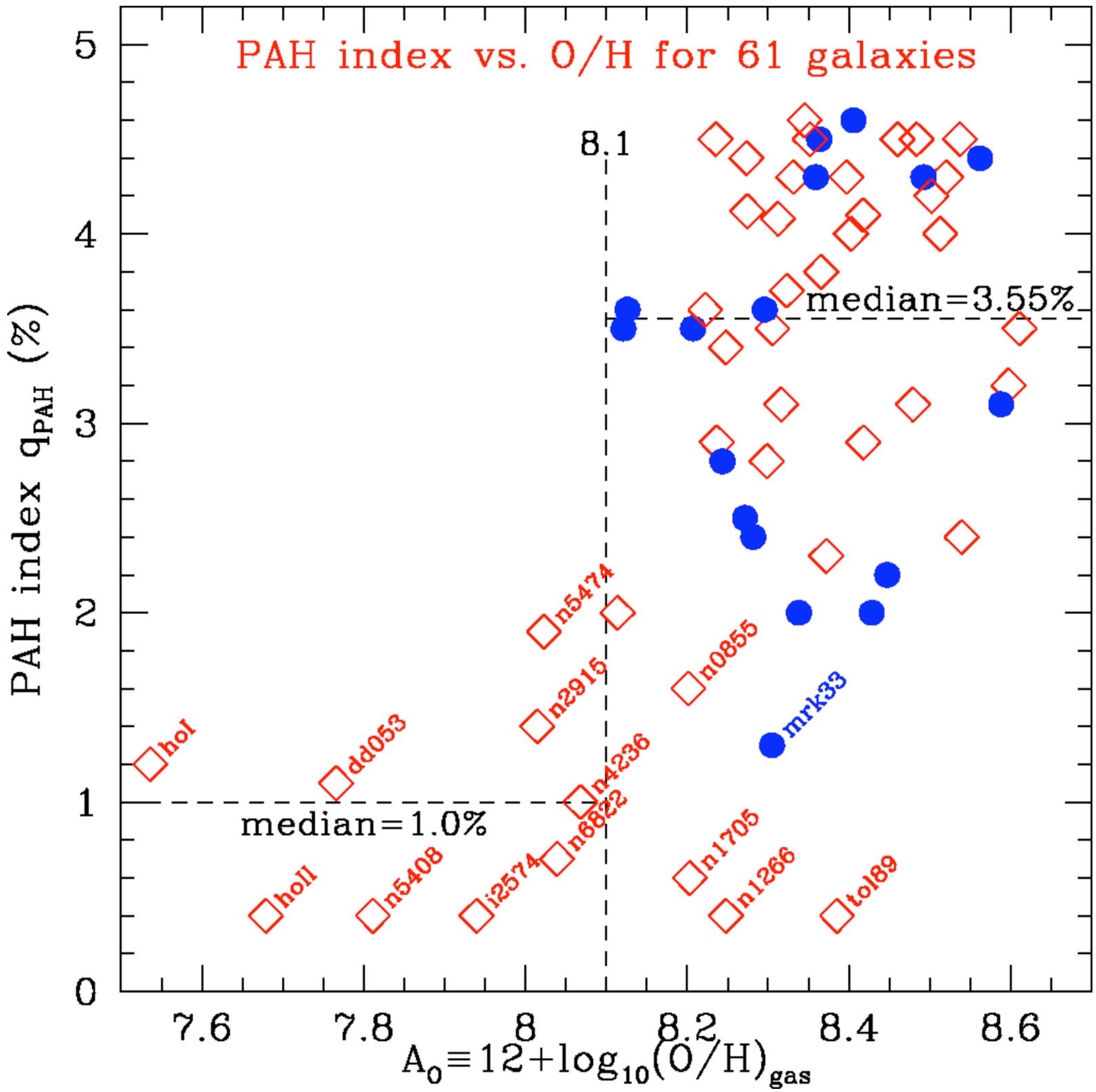
Draine et al. 2007, ApJ, 663, 866-894




$$M_{\rm dust}/M_{\rm H} \approx 0.01\times(Z/Z_\odot)$$

green: $M_{dust}/M_H$ in regions where IR emission is detected.

Draine et al. 2007, ApJ, 663, 866-894




**PAH index $q_{PAH}$= fraction of total dust mass in PAHs with $N_C$<$10^3$**

**PAH fraction correlates with metallicity:**

**galaxies with $A_O$<8.0 have $q_{PAH}$ < 1.2%**

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- Draine & Li, ApJ 657, 810-837 (2007)
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  URL: http://ipac.jpl.nasa.gov/media_images/screen_jpg/sirtf/SIRTF_ir_1small.jpg

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- Spitzer M51
  URL: http://gallery.spitzer.caltech.edu/Imagegallery/image.php?image_name=ssc2004-19a
- Draine et al., ApJ 663, 866-894 (2007)