Dust in Normal Galaxies

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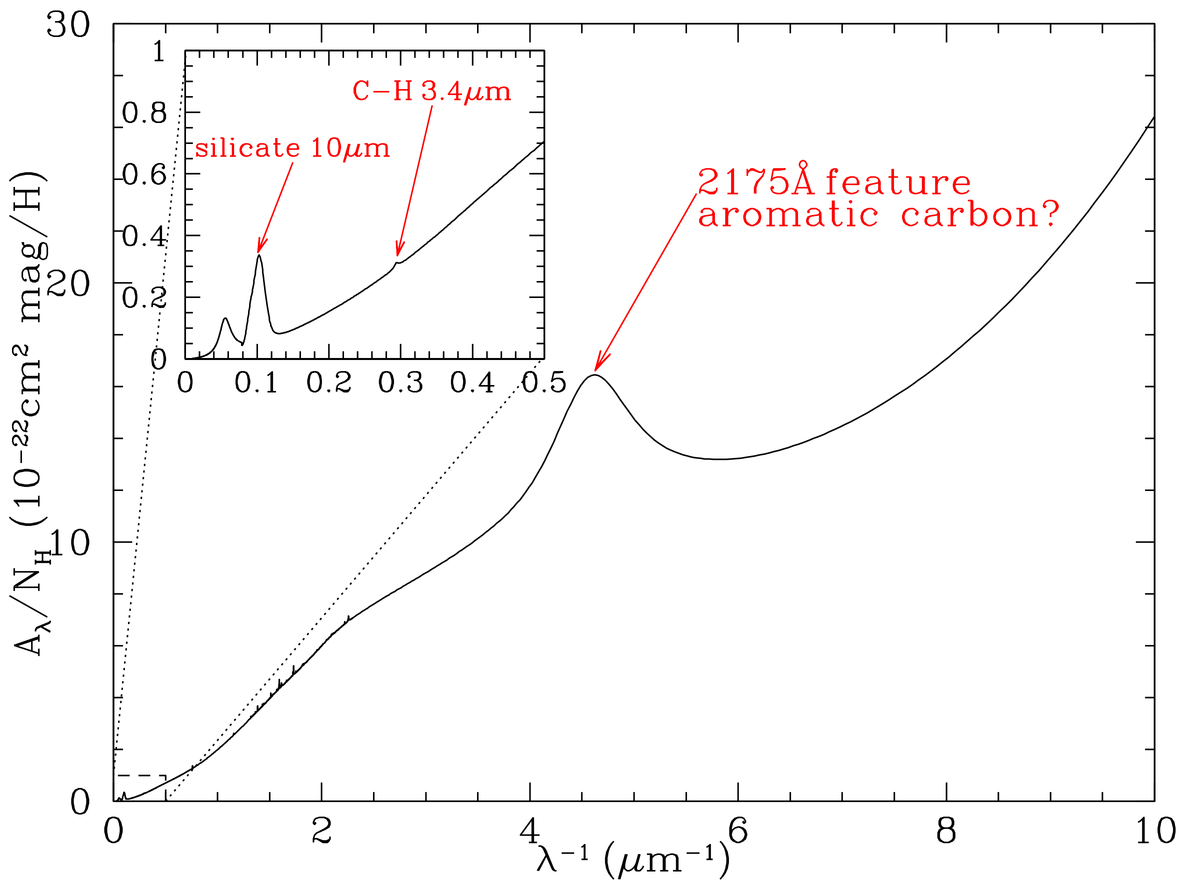
1. **Some Dust Basics**
2. **Physical Models for Dust including PAHs**
3. **Far-Infrared/Submm Opacities**
4. **Anomalies...**
5. **Applying the Dust Model to Normal Galaxies**
   - **Starlight Properties**
   - **Dust/Gas Ratios**
   - **Dust Mass Estimation with Different Camera Sets**

Acknowledgements: **Entire KINGFISH team, especially Gonzalo Aniano**

Observational Constraints on Dust Models

- **Wavelength-Dependent Extinction of Starlight**
- **Abundance Constraints**
- **Polarization of Starlight**
- **Scattering of Starlight**
- **Scattering of X-rays**
- **Infrared Emission**
- **Microwave Emission** *(Spinning Dust...)*
- **(photoelectric heating by dust)**
- **(H_2 formation rate on dust)**
- **(Dust in Meteorites)**

Average Diffuse ISM Extinction/H



A model for (MW) dust should be compatible with all of these observational constraints.

Physical Models for Dust in Normal Galaxies

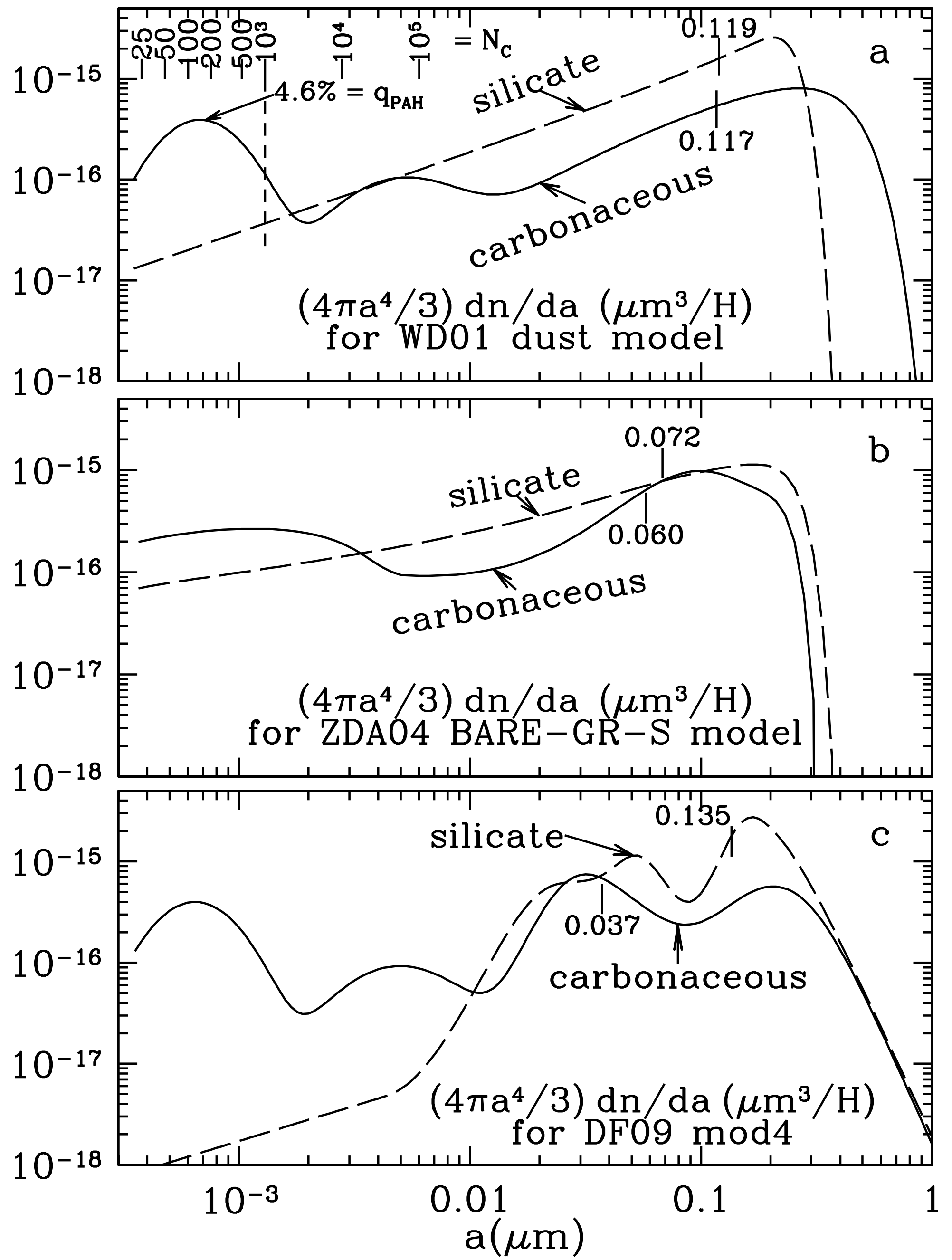
Contemporary models for dust in MW (and other galaxies) (e.g., Weingartner & Draine 2001; Li & Draine 2001; Zubko et al. 2004; Draine & Li 2007; Draine & Fraisse 2009, ...) are based on

- ◇ **amorphous silicate**
- ◇ **carbonaceous material**
  specific materials may vary – PAH, graphite, various forms of amorphous carbon...

Grain geometry (**compact** vs. **"fluffy"**) remains uncertain.
Whether individual grains are **single-composition** or **mixed-composition** remains uncertain.

- MW, LMC, SMC extinction curves can be reproduced by models consisting of PAHs + graphite + amorphous silicate, with only changes in the size distribution (and relative abundance of the 3 components) from sightline to sightline (Weingartner & Draine 2001).
- With spheroids instead of spheres for graphite and amorph. silicate grains, model can also reproduce polarization.
- In Milky Way (and LMC, SMC) dust models are constrained by extinction curve
- In galaxies where we do not know extinction curve:
  Use MW size distribution unless we are *forced* to change some property, such as relative abundance of PAHs.

Grain Size Distributions for Diffuse ISM in MW



Weingartner & Draine (2001)

Zubko et al. (2004)

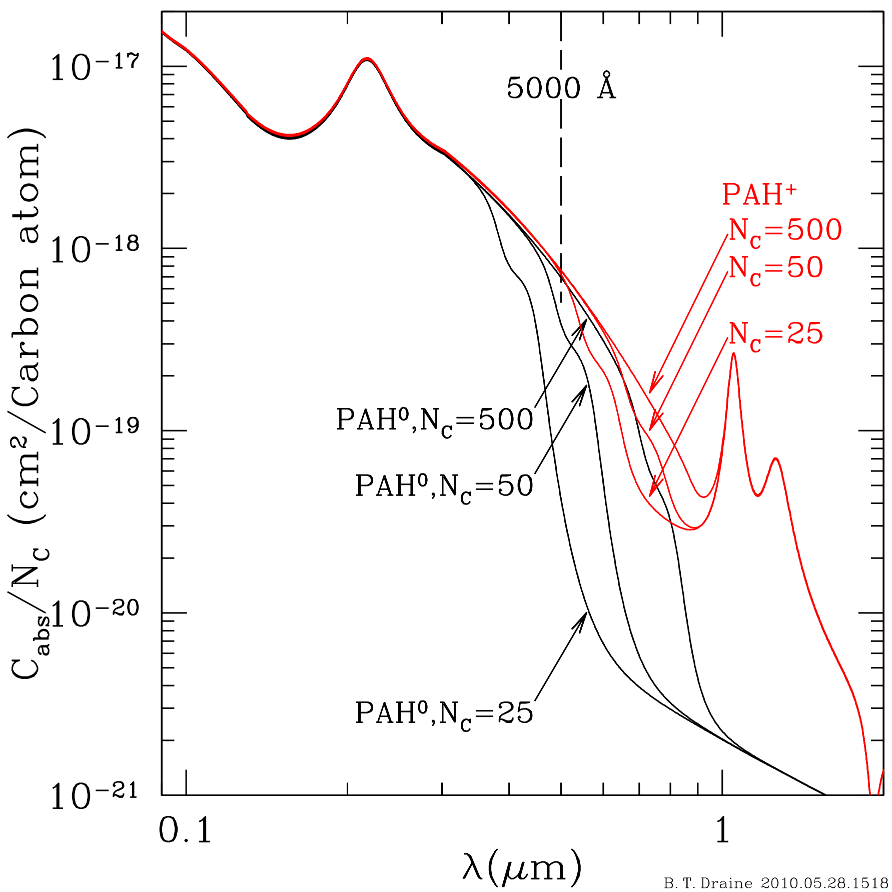
Draine & Fraisse (2009)

Size distributions are not unique, but strong similarities.

Physical Properties of the Dust

- Grains are heated by starlight: need absorption cross section $C_{\mathrm{abs}}(\lambda)$ in UV-optical

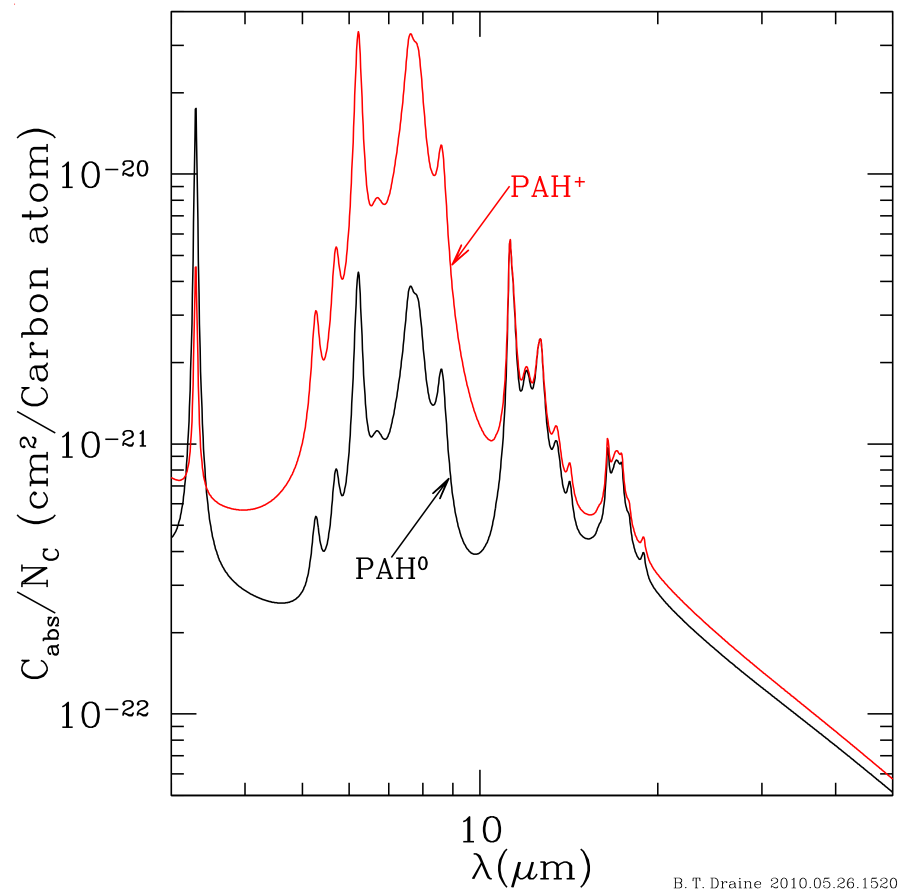
  PAH Absorption Cross-section/C



Cross section from Draine & Li (2007).

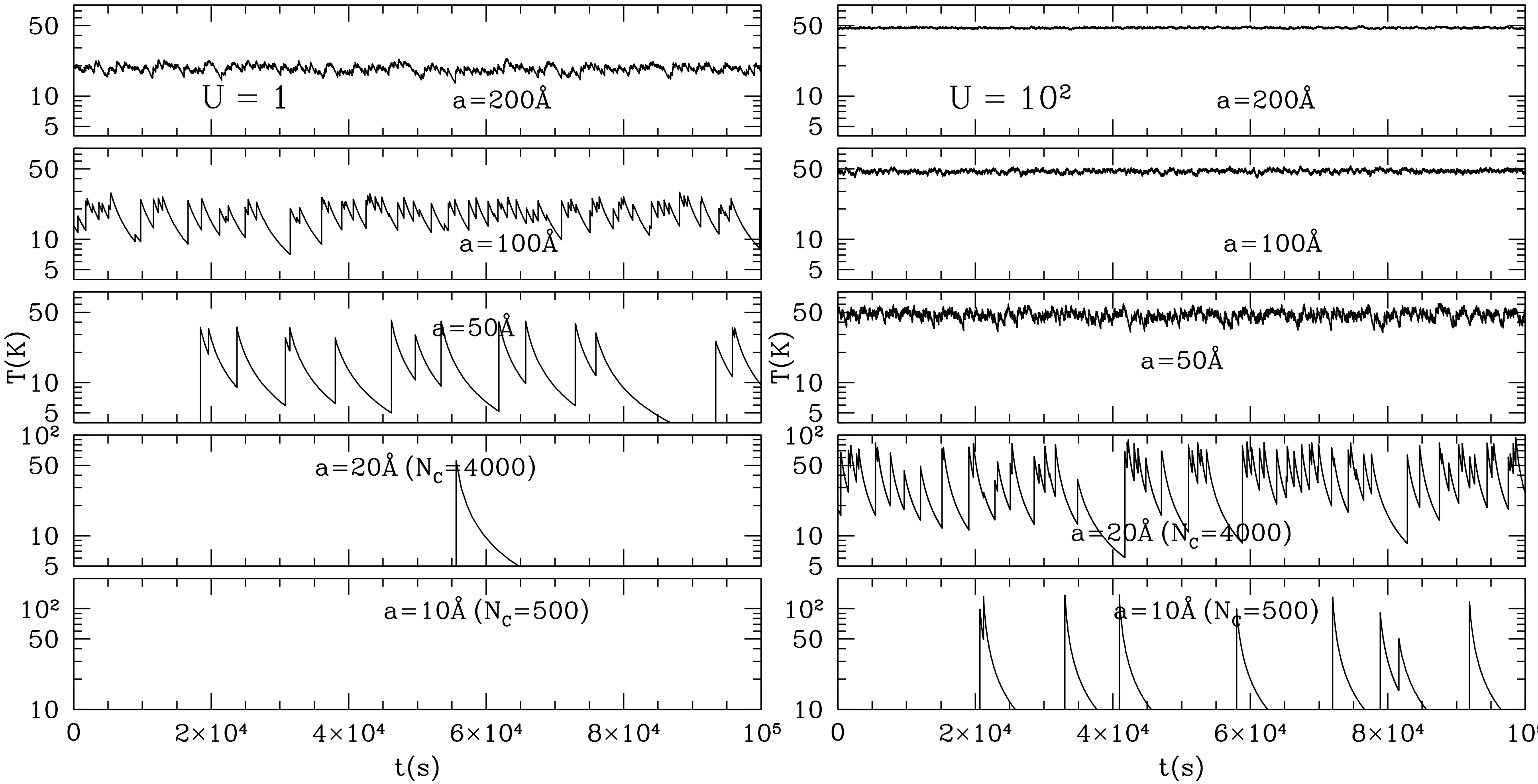
- Grains cool by emitting photons: need $C_{\mathrm{abs}}(\lambda)$ in IR

  Cross-section/C for IR Emission by PAH



Cross section from Draine & Li (2007).

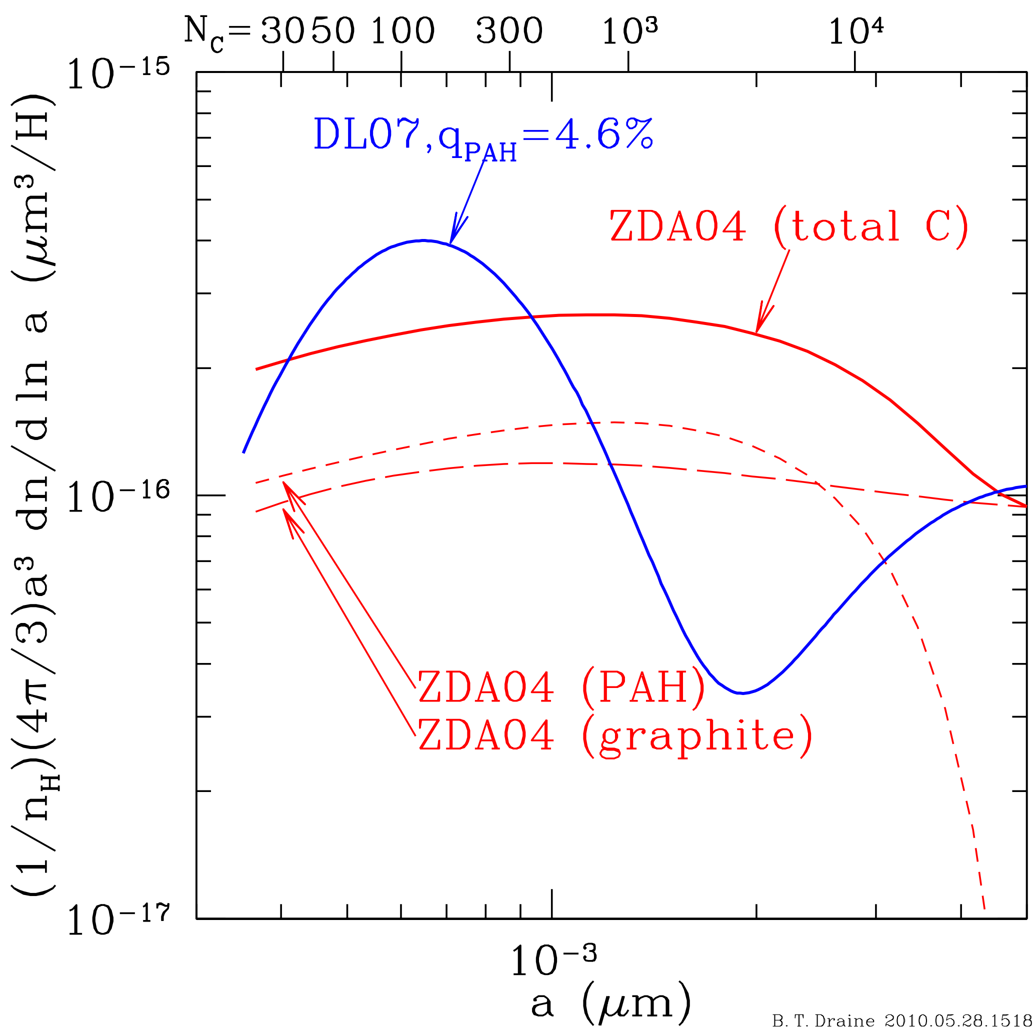
Interstellar Grain Temperatures



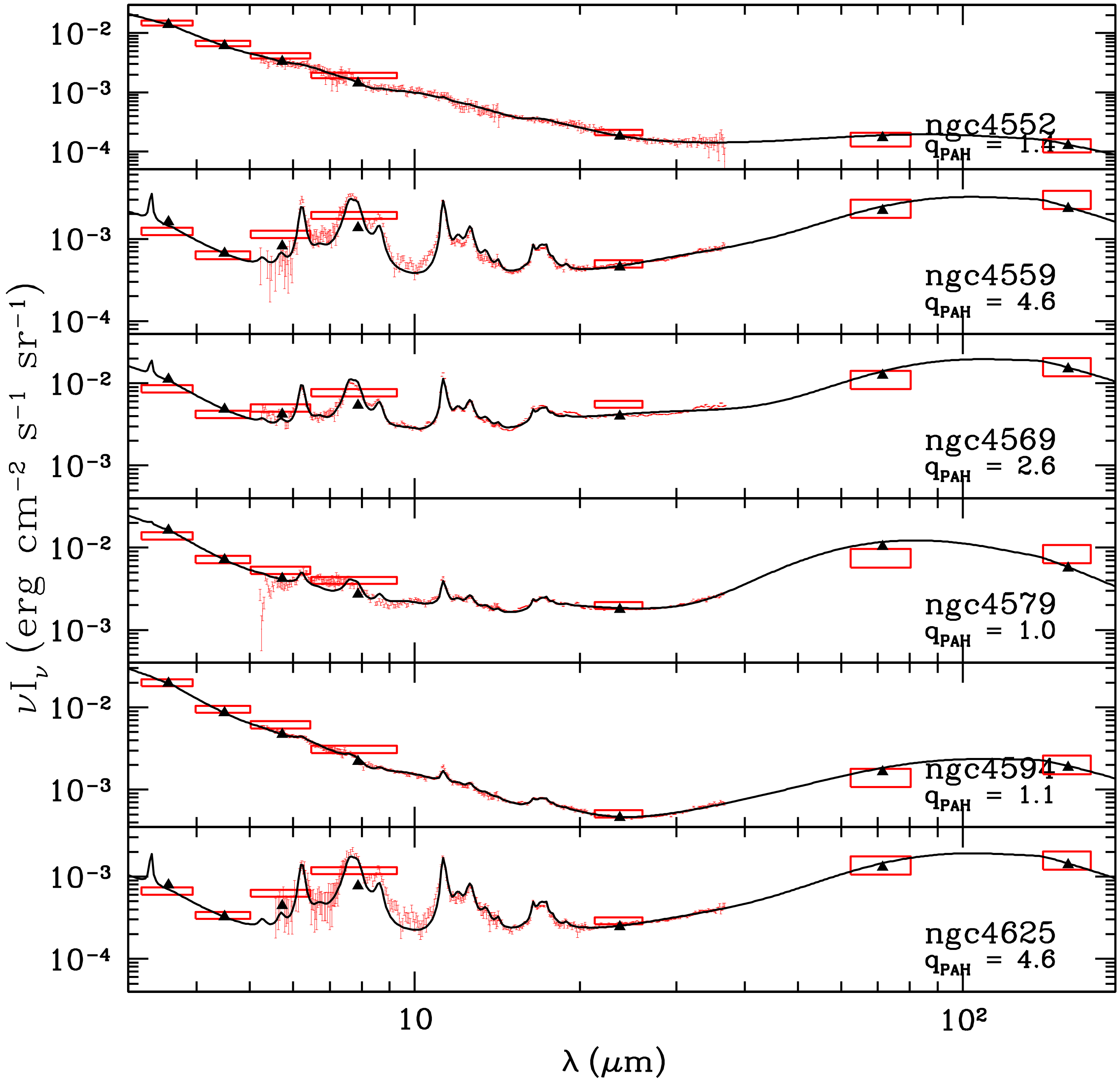
- For grain of given size and composition, need to find temperature distribution function dP/dT.
- dP/dT will depend on **spectrum** and **intensity** and of starlight.
  Use **local starlight spectrum**, $U \equiv$ **intensity/(local ISRF)**

PAH Size Distribution

- Mass in small PAHs must be sufficient to absorb energy from starlight to power observed IR emission
- Mass distribution (and ionization fraction for each size) must produce observed spectrum
- Size distribution of small carbonaceous particles remains somewhat uncertain – compare DL07 and ZDA04 size distributions.



Model vs. Spectroscopy+Photometry



G. Aniano, R. Reyes, BTD, J.D. Smith, SINGS team

amorphous sil. + graphite + PAH + distribution of starlight intensities.

vary $q_{\rm PAH}$

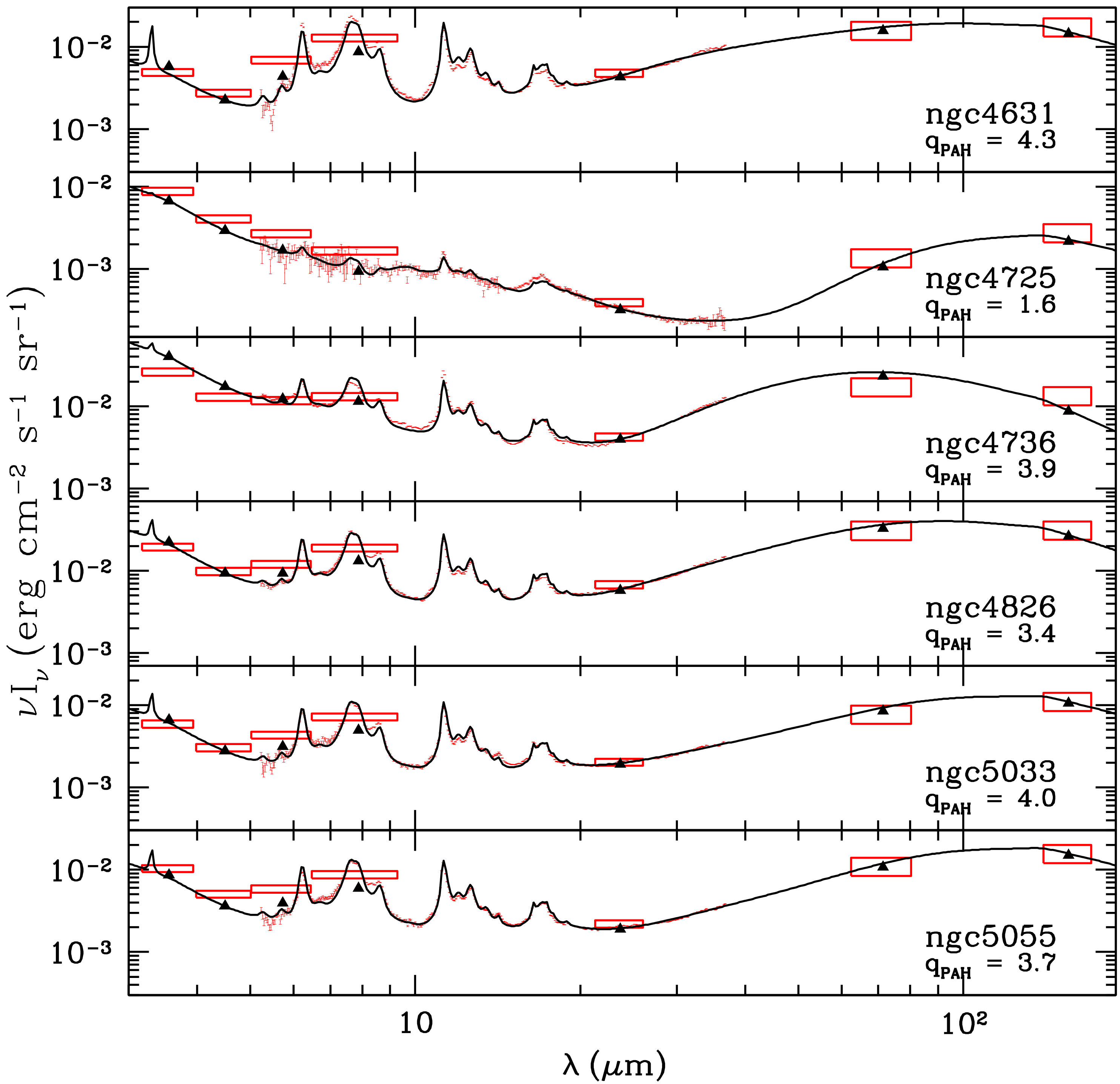
$q_{\rm PAH}$ ≡ fraction of total dust mass contributed by PAHs with $N_C < 10^3$ C atoms.

No adjustment of PAH size distribution.

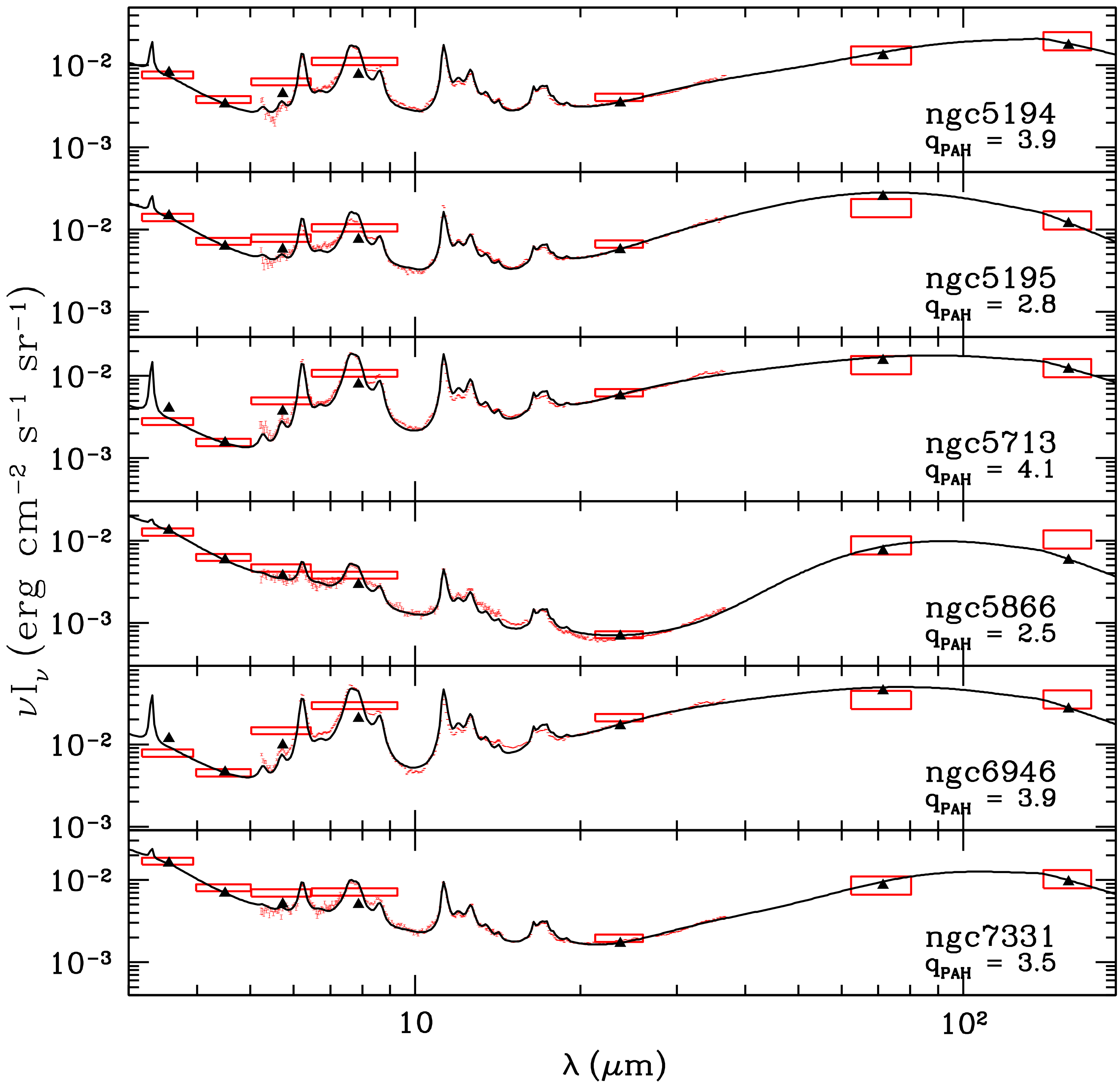
No adjustment of PAH ionization.

No adjustment of starlight spectrum heating the PAHs.

Vary $U_{\rm min}$ and γ

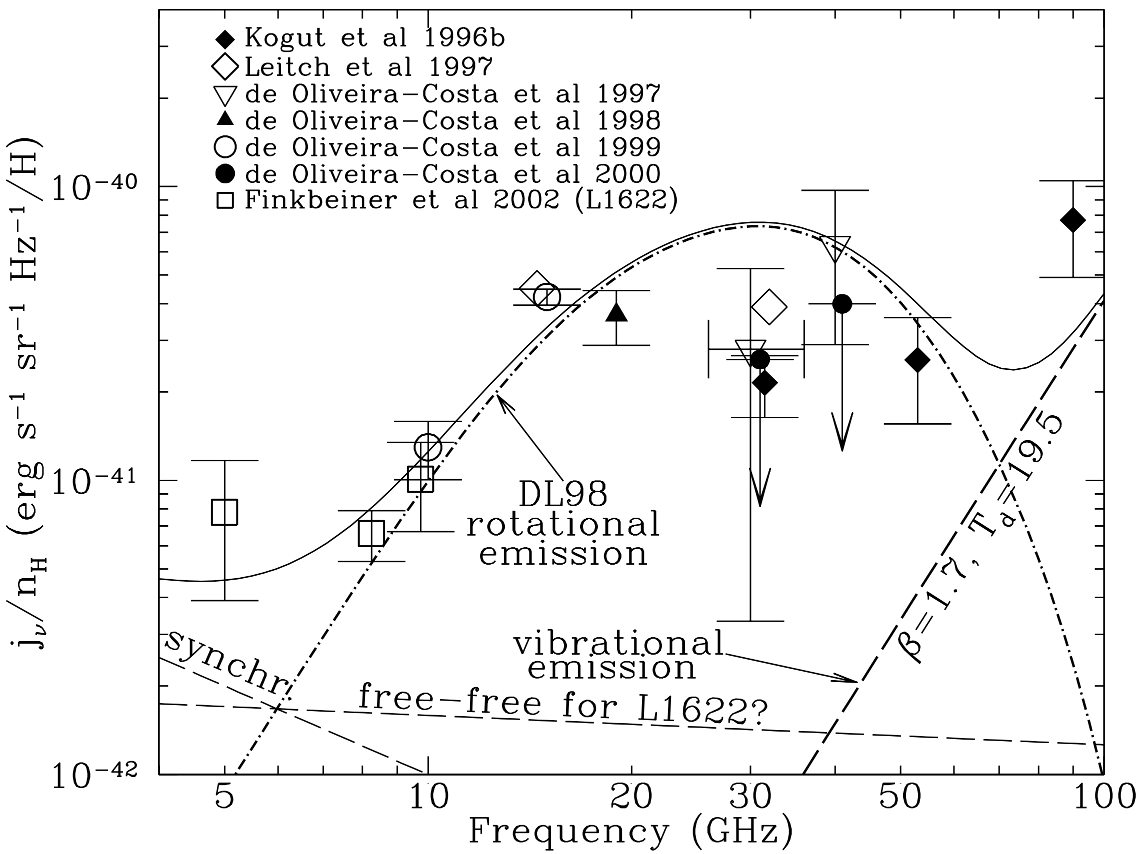


ngc4631
q_{PAH} = 4.3
ngc4725
q_{PAH} = 1.6
ngc4736
q_{PAH} = 3.9
ngc4826
q_{PAH} = 3.4
ngc5033
q_{PAH} = 4.0
ngc5055
q_{PAH} = 3.7
νI_ν (erg cm^{-2} s^{-1} sr^{-1})
λ (μm)

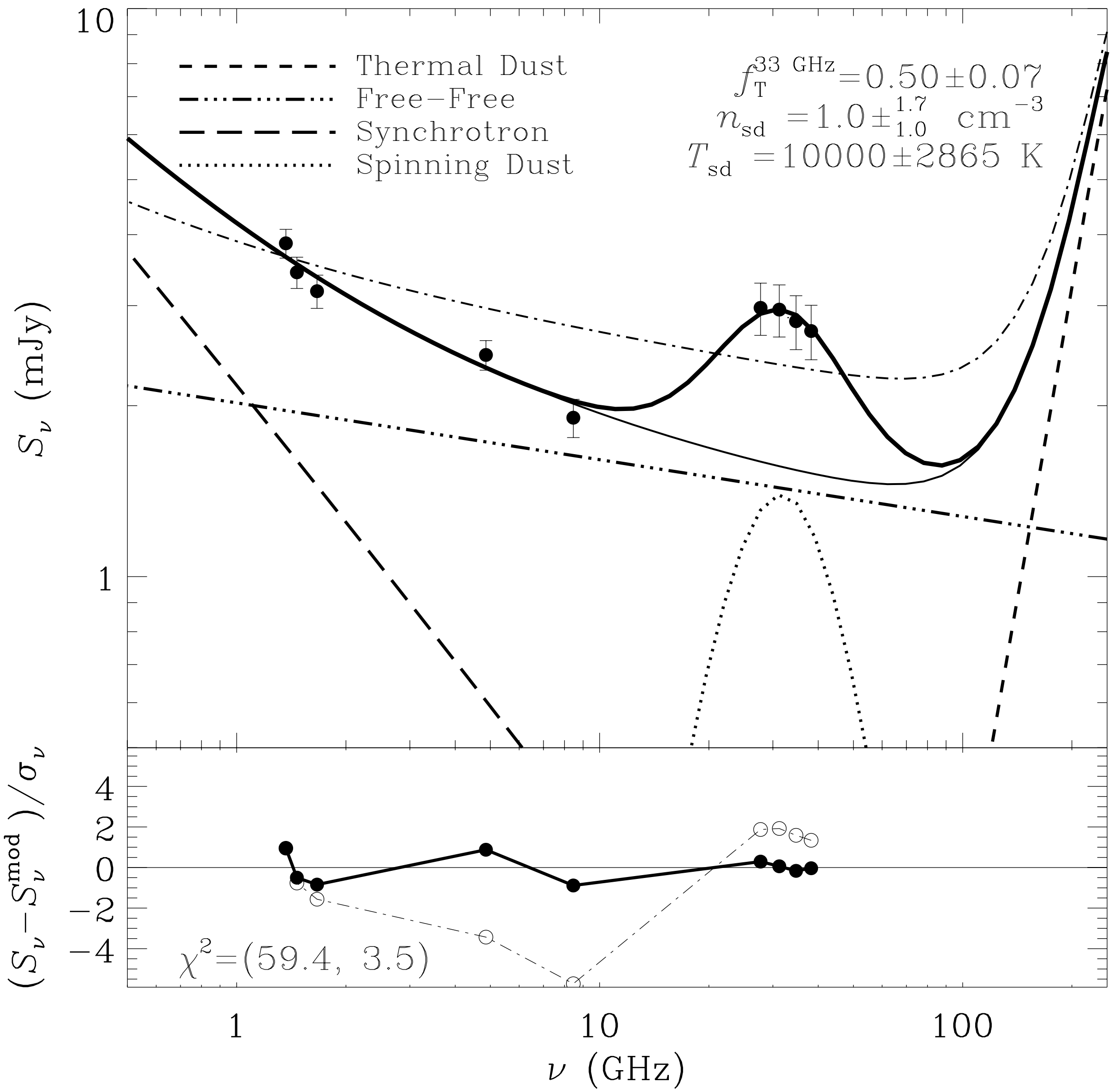

ngc5194
q_{PAH} = 3.9
ngc5195
q_{PAH} = 2.8
ngc5713
q_{PAH} = 4.1
ngc5866
q_{PAH} = 2.5
ngc6946
q_{PAH} = 3.9
ngc7331
q_{PAH} = 3.5
10^{-2}
10^{-3}
νI_ν (erg cm^{-2} s^{-1} sr^{-1})
10
10^2
λ (μm)

PAHs and Spinning Dust

- CMB studies discovered "anomalous microwave emission"
- spatially correlated with 100 μm emission from cirrus
- interpreted as "spinning dust" (Draine & Lazarian 1998): **Rotational emission** from the *same* PAH population required to explain IR emission.



Spinning Dust Emission Seen from Other Galaxies



NGC 6946: Murphy et al. (2010)

DL07 Dust Model: Basis for Adopted Opacities

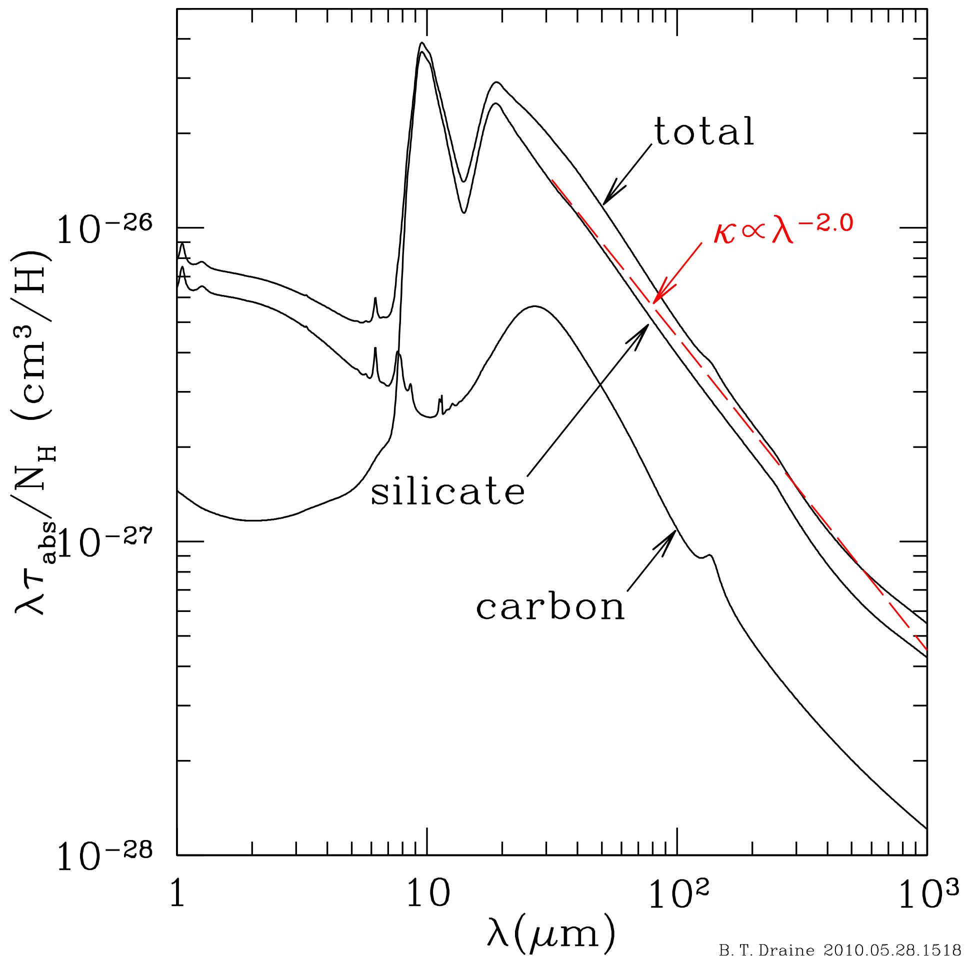
Draine & Li (2007) (=DL07) grain model: amorphous silicate
+ carbonaceous (incl. PAHs)

◇ Spherical grains for simplicity (except for PAHs)

◇ Carbonaceous grains calculated using model dielectric tensor for graphite: $C_{\rm abs} \propto \nu^2$ for $\lambda > 200\,\mu$m.

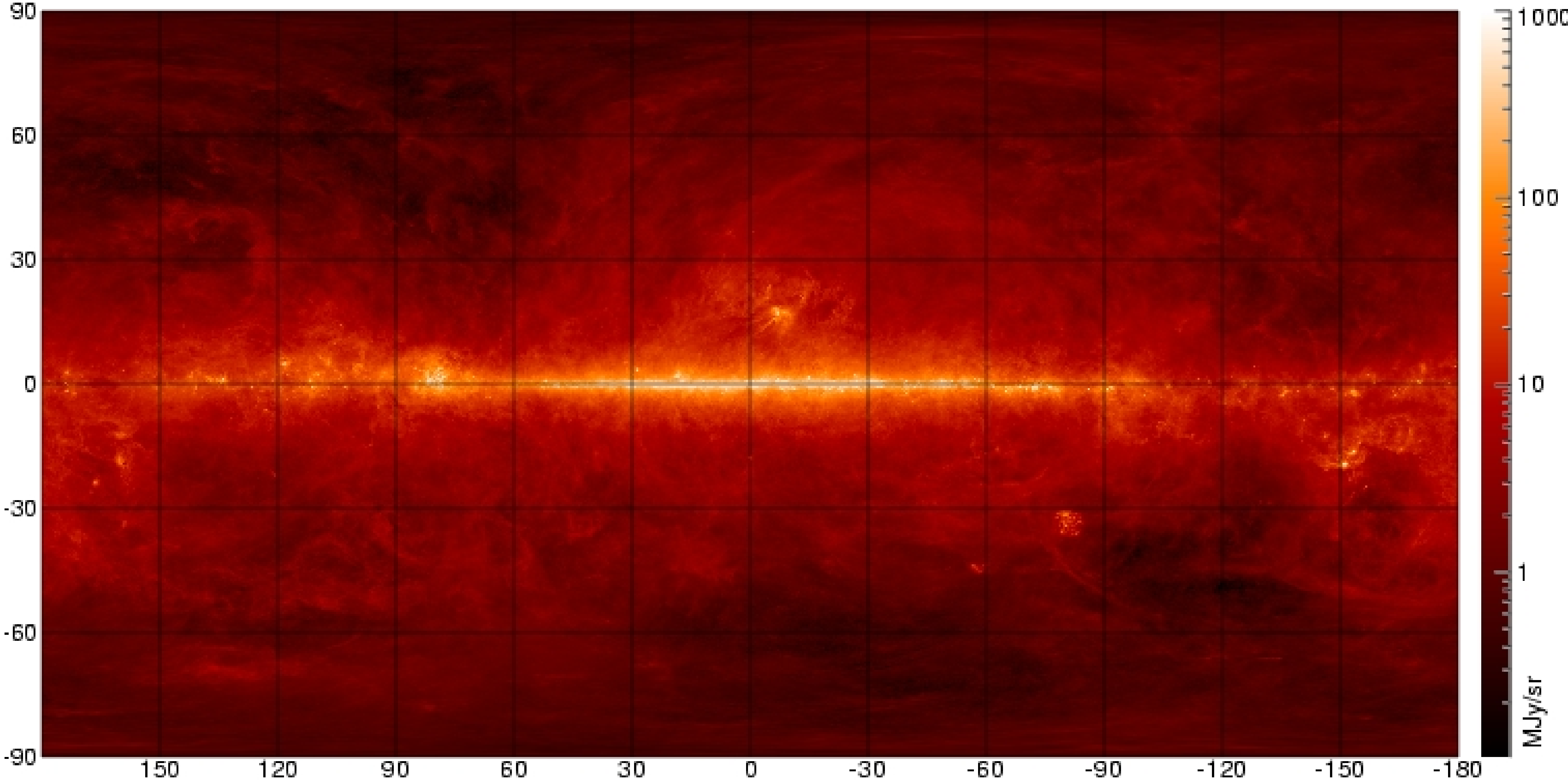
◇ PAH opacity from Li & Draine (2001) adjusted slightly to improve agreement with Spitzer mid-IR spectra

◇ Amorphous silicate opacity: dielectric function of Draine & Lee (1984) **with small adjustments (Li & Draine 2001) to improve agreement with COBE-FIRAS observations of FIR-submm emission from Milky Way cirrus**



- **Together, opacity is close to λ^{-2} for $50 - 1000\,\mu$m but is *not* a power-law**

FIR-Submm Dust Opacity: Look to the Cirrus

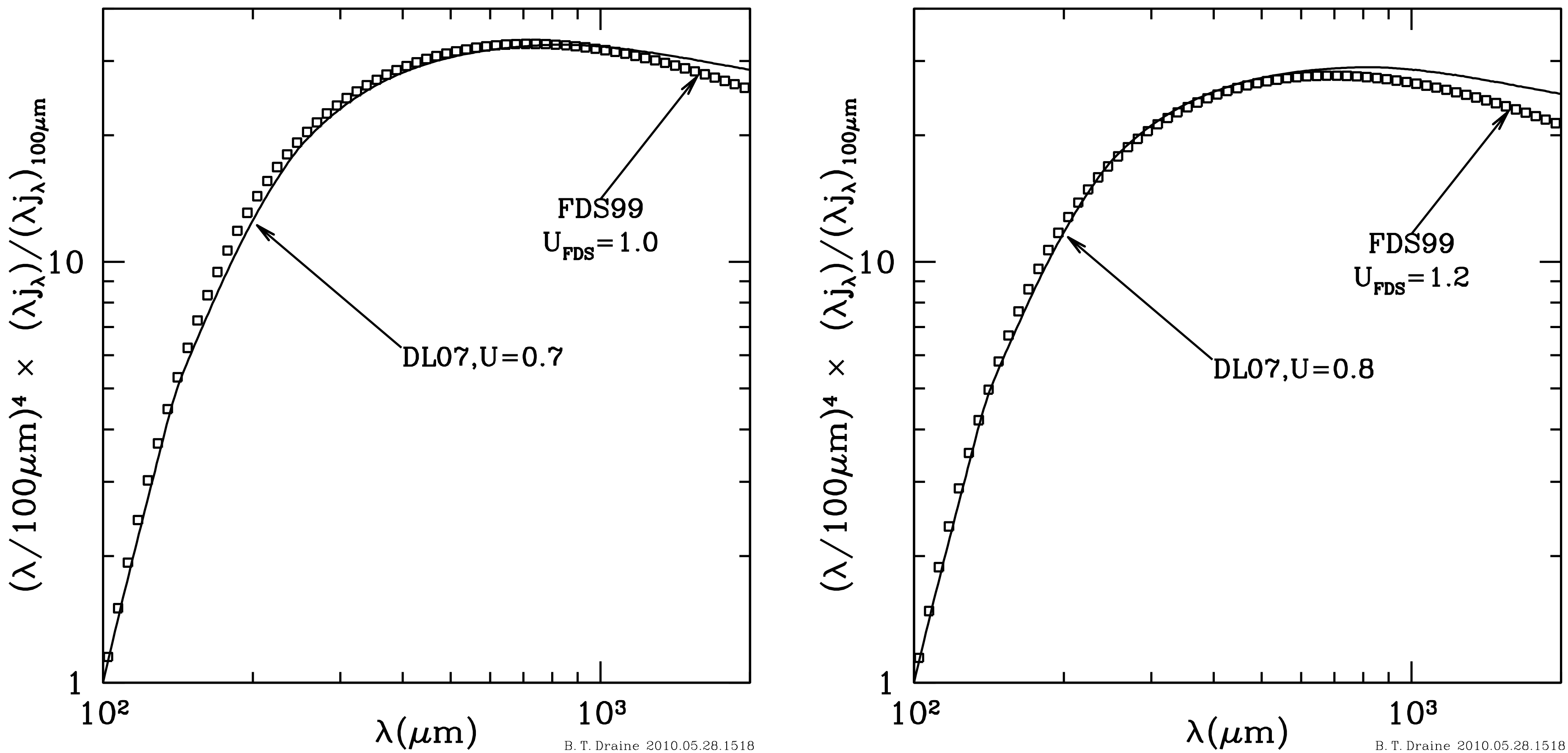


100 μm IRAS/COBE Map of Sky (after zodi subtraction). Image credit: D. Finkbeiner

Finkbeiner et al. (1999) studied correlation of COBE/FIRAS Submm Map with 100 μm to determine 100 – 2000 μm emission spectrum of cirrus

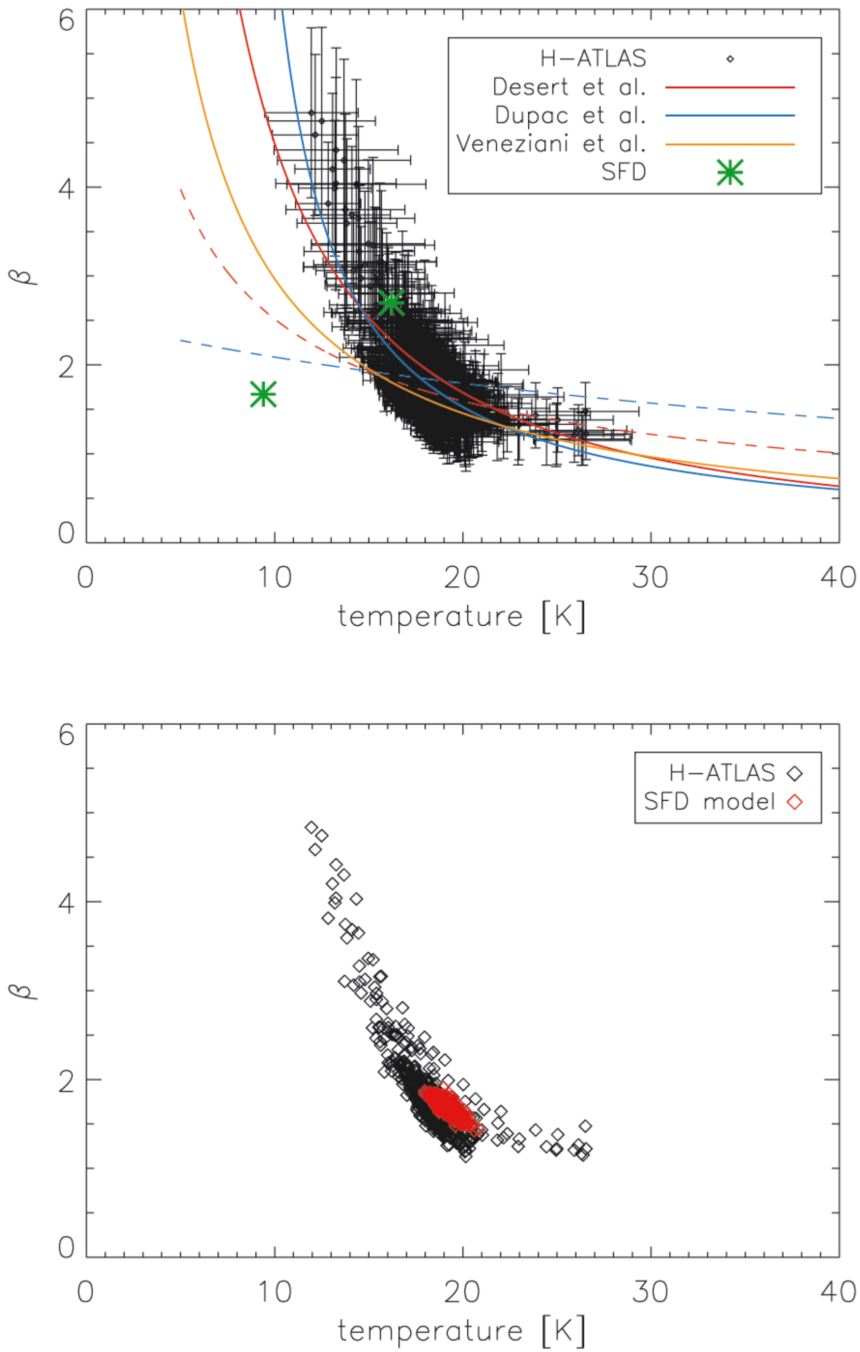
How does Model Compare with FIR-Submm Observations?

- Finkbeiner et al. (1999) (FDS99) studied Galactic contribution to COBE-FIRAS spectrum of high-latitude cirrus
- Li & Draine (2001) adjusted amorphous silicate opacity to reproduce COBE-FIRAS
  - ◇ modest *ad-hoc* **reduction** between 250 and 850 μm (maximum change -12%)
  - ◇ modest *ad-hoc* **increase** for $\lambda > 850\,\mu$m (+26% at 1.5mm = 200 GHz)



- **DL07 opacity reproduces cirrus emission for** $100\,\mu m \lesssim \lambda \lesssim 2000\,\mu m$**.**

ANOMALIES...



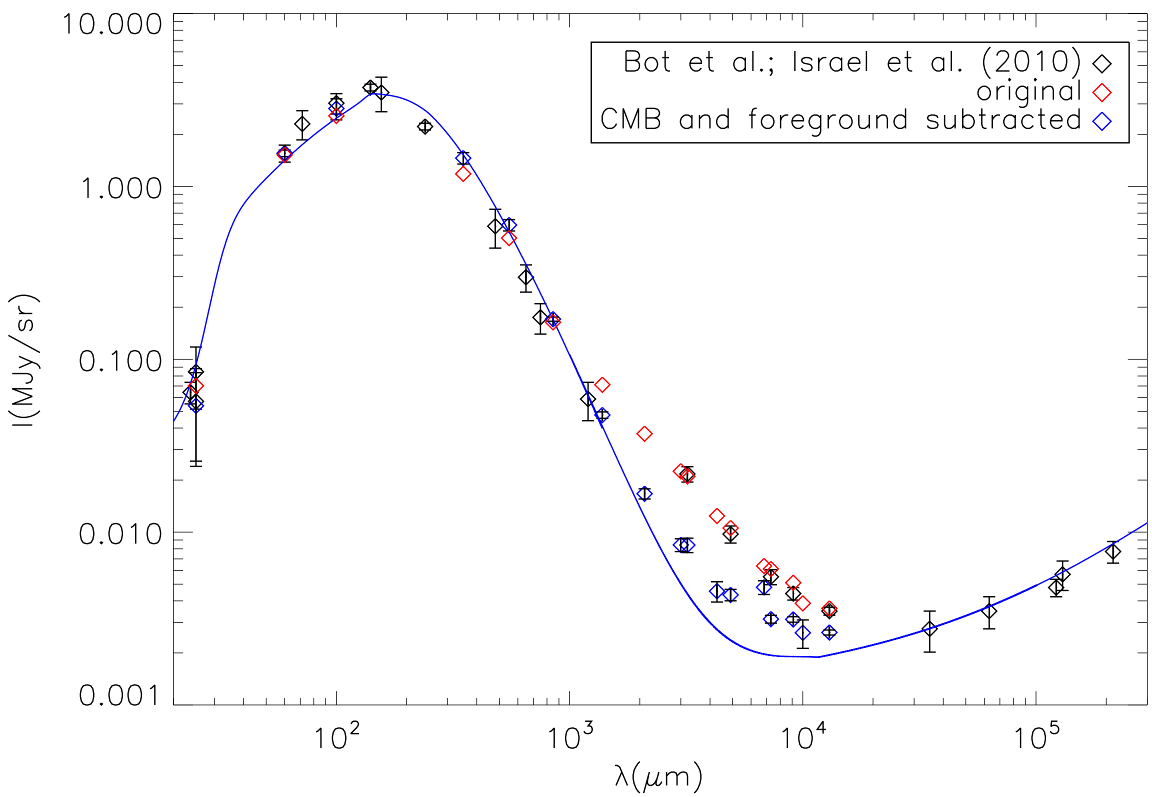
Galactic cirrus:

- Bracco et al. (2011) report anomalous 100–500 μm colors (IRAS100, SPIRE250,350,500) in 6 deg^2 field centered on $(\ell, b) = (232^\circ, 34^\circ)$
- Single-T fits ($\nu^\beta B_\nu(T)$) to diffuse emission in $6' \times 6'$ pixels.
- NB: **MOST** points have $\beta \approx 1.7$ and $T \approx 19\,\text{K}$, as expected.
- Deviant points interpreted by Bracco et al. (2011) as T-dependence of opacity index β as proposed by Dupac et al. (2003) and Désert et al. (2008).
- Follow-up observations with Herschel of deviant regions would be valuable to confirm deviant points. (Noise or contamination by extragalactic sources could be an issue).

ANOMALIES, contd: The SMC

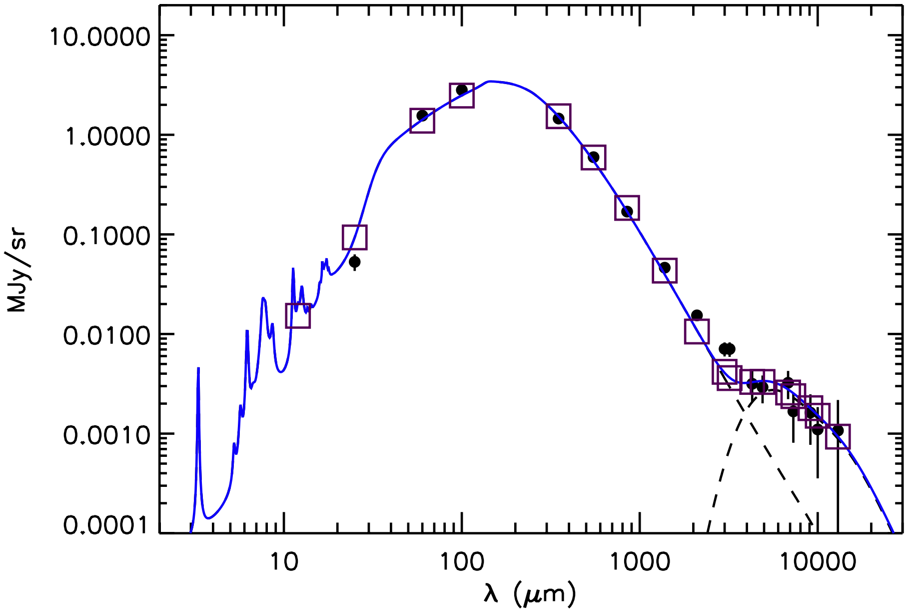
Low-metallicity dwarf galaxies often show excess submm emission.

- e.g., $850\,\mu\mathrm{m}$ excess emission from NGC 1569 (Galliano et al. 2003)
- LMC SED appears to be consistent with "normal" dust (Planck Collaboration et al. 2011).
- Integrated photometry of the SMC shows submm excess (Israel et al. 2010; Planck Collaboration et al. 2011):

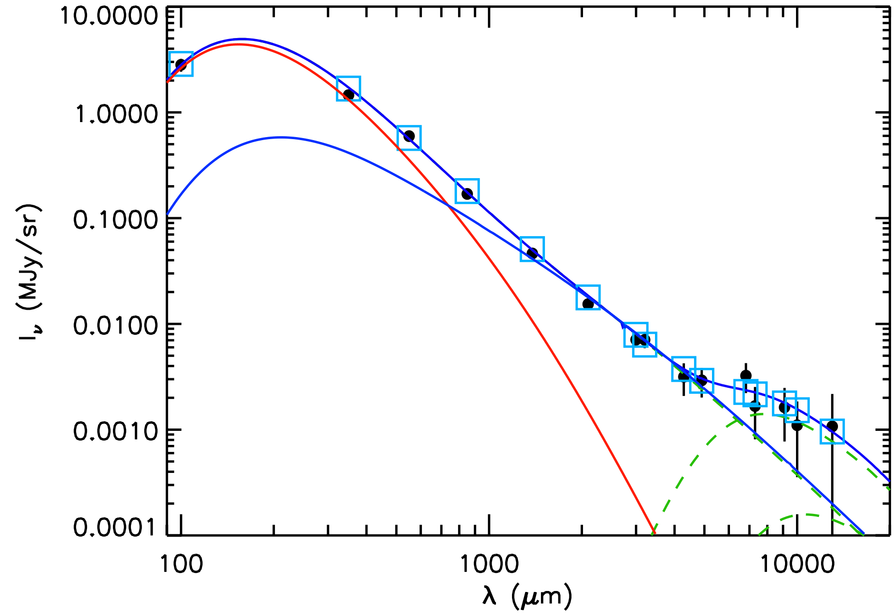


SED of the SMC (Planck Collaboration et al. 2011)

SMC: Nature of the Submm Excess



Standard dust + spinning dust (Planck Collaboration et al. 2011)



"TLS" dust + spinning dust (Planck Collaboration et al. 2011)

- Planck Collaboration et al. (2011): fit SED using DL07 dust model plus spinning dust.
- **model is low at 2 mm and 3 mm** (150, 100 GHz).

- Fit with "two-level-system" (TLS) dust model (Meny et al. 2007) with $\beta(T)$ plus spinning dust: good fit is obtained.
- TLS parameters adjusted to fit SMC – different from TLS parameters previously obtained for MW (Paradis 2007, PhD thesis).

Applying the Dust Model to Normal Galaxies

Observe region ("pixel") in a galaxy.

Seek to reproduce observed SED with model.

Adjustable parameters:

1. $M_{\rm dust}$ in pixel
2. $q_{\rm PAH}$ = fraction of dust mass in PAHs with $< 10^3$ C atoms.
3. Characteristics of starlight heating the dust.

In real galaxy, both intensity and spectrum of starlight vary with position.

Ideally:

- specify 3-D locations of stars and dust
- obtain radiation field at each point by solving radiative transfer problem.

In practice: not feasible.

Simple approach:

- Use universal spectrum (adopt ISRF in solar neighborhood).
  $U =$ starlight intensity scale factor
  ($U = 1$ for solar neighborhood).
- Assume simple parametric form for distribution of starlight intensities:
  - fraction $(1-\gamma)$ of $M_{\rm dust}$ is heated by single starlight intensity $U = U_{\rm min}$ (general diffuse ISM)
  - fraction $\gamma \ll 1$ of $M_{\rm dust}$ is heated by distribution of higher starlight intensities

$$dM_{\rm dust} \propto U^{-\alpha} dU \quad , \quad U_{\rm min} < U < U_{\rm max}$$

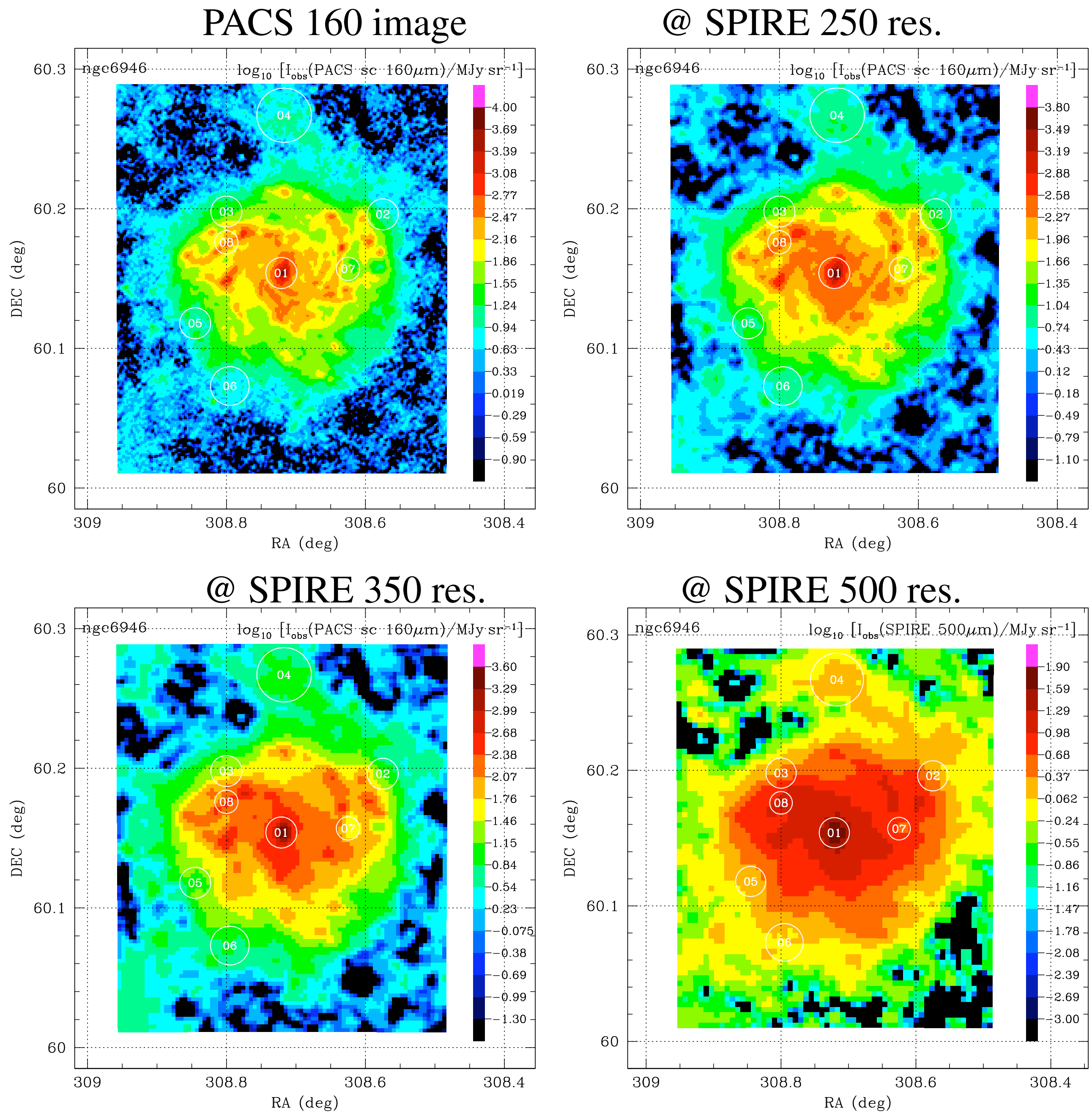
  - Fix $U_{\rm max} = 10^6$ and $\alpha = 2$
  - 4 adjustable parameters for each pixel:
    * $M_{\rm dust}$
    * $q_{\rm PAH}$
    * $U_{\rm min}$
    * γ

Spatial Resolution vs. Wavelength Coverage

Important to use data at common resolution (see Aniano poster on convolution kernels; (Aniano et al. 2011a)arXiv:1106.5065).

Tradeoff:

- Small pixels
  - Good spatial resolution
  - Cannot use data from low-resolution cameras, e.g. MIPS 160, SPIRE 500
- Large pixels
  - Poor spatial resolution
  - Can use longer-λ data
  - Increase S/N in shorter-λ data

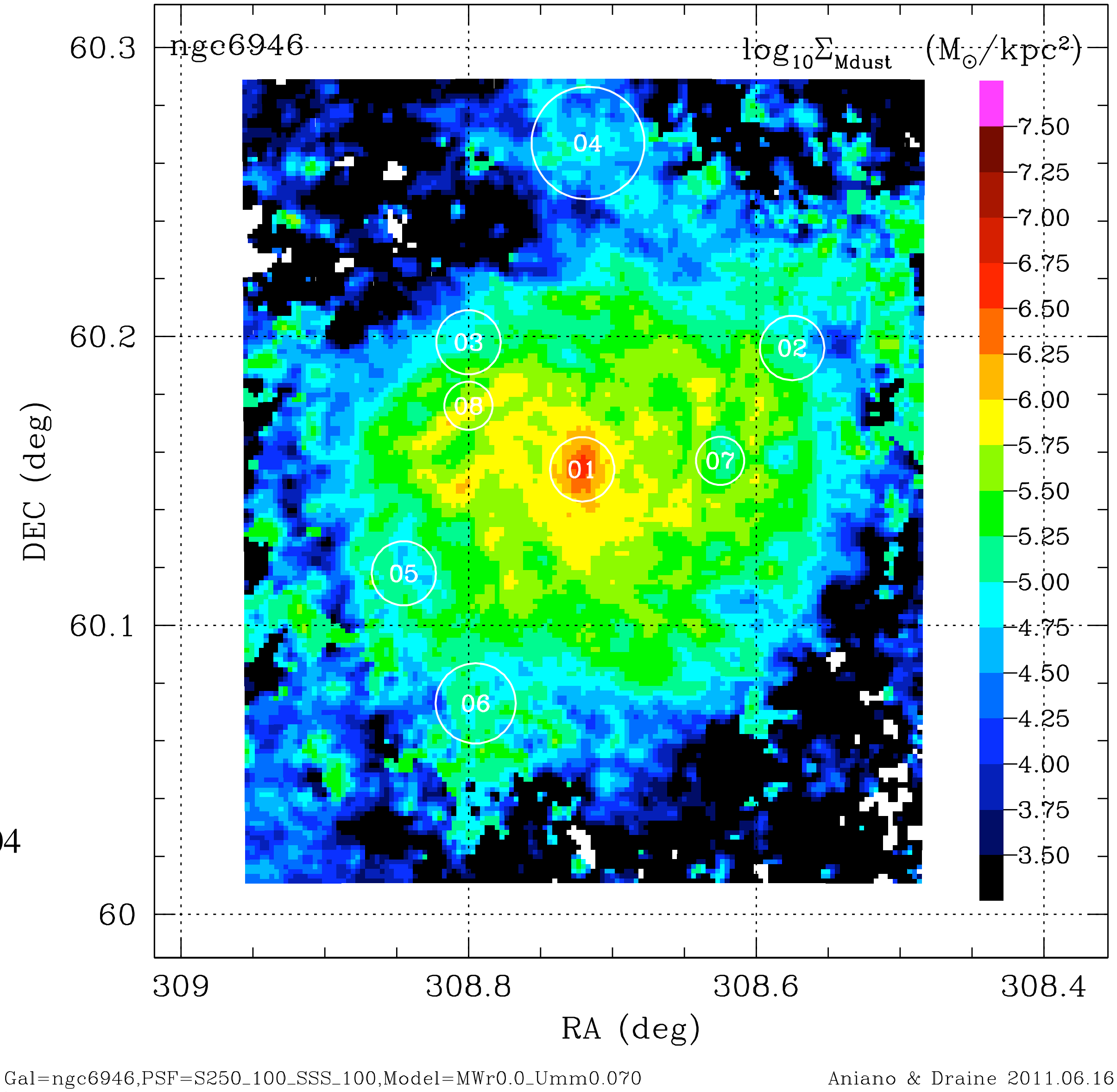


NGC 6946 (Aniano et al. 2011b)

0.1° = 12 kpc @ 6.8 Mpc

image credit: Kuzio de Naray & McGaugh 2004

dust map at SPIRE250 resolution, $18''$ pixel = 590 pc



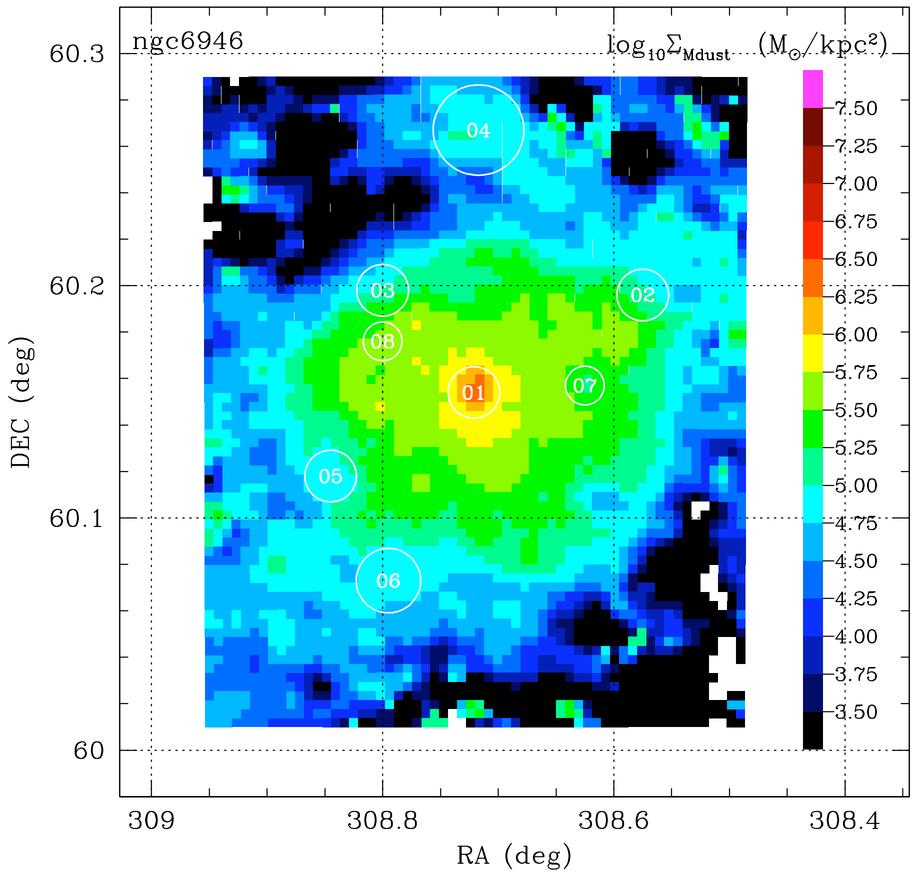
$N_{\rm H} = 10^{21}\,{\rm cm}^{-2} \rightarrow \Sigma_{\rm HI} = 10^{6.9} M_\odot\,{\rm kpc}^{-2}$ $\quad$ $A_V = \Sigma_{\rm dust}/10^{5.2} M_\odot\,{\rm kpc}^{-2}$

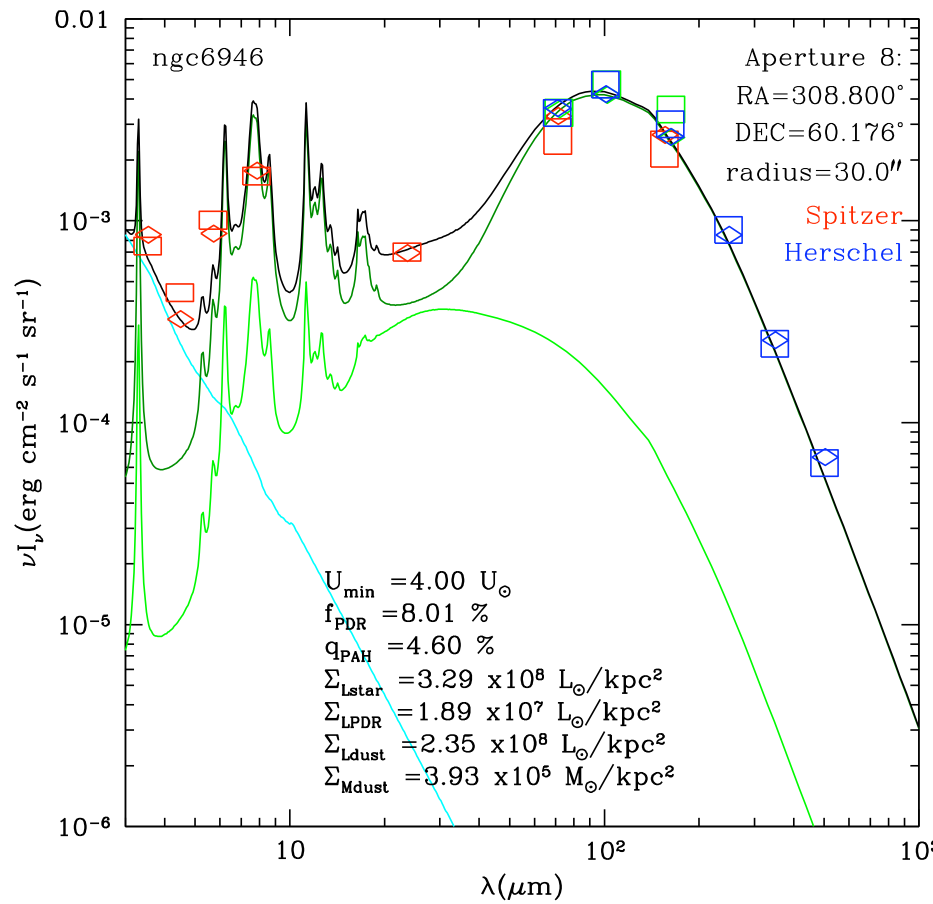
single-pixel detection limit $\sim 10^{4.7} M_\odot\,{\rm pc}^{-2}$**, or** $A_V \approx 0.3$ **mag**

Dust Map and SED for NG6946 @ SPIRE 500 resolution

(Aniano et al. 2011b)

$\log[\Sigma_{\rm dust}(M_\odot/{\rm kpc}^2)]$

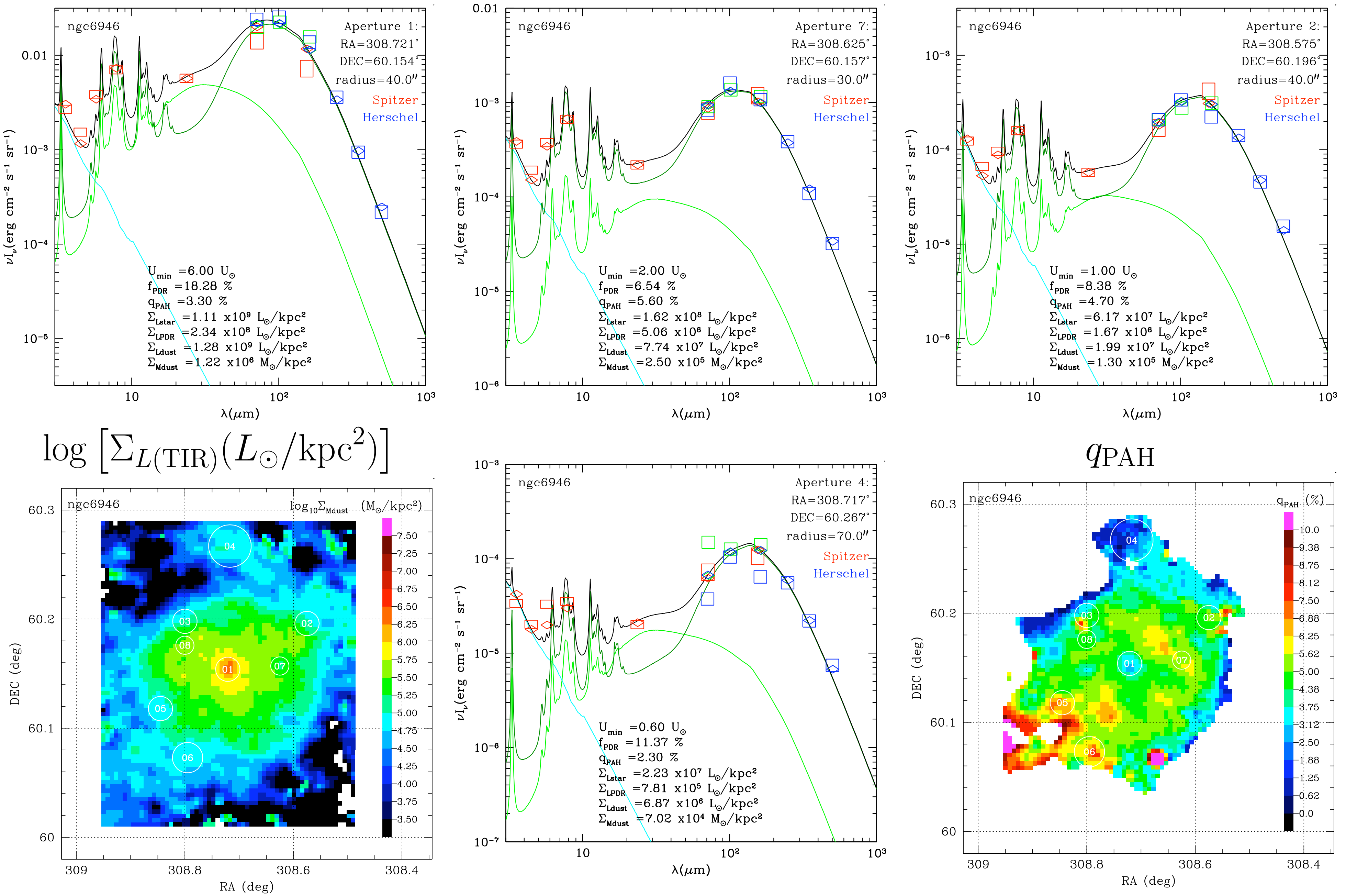




- For each pixel: find best-fit dust model (with $U_{\rm max} = 10^6$ and $\alpha = 2$ fixed)
  - dust surface density: $\Sigma_{\rm dust}$ **single-pixel detection limit** $\sim 10^{4.5} M_\odot\,{\rm kpc}^{-2}$ **or** $A_V \approx 0.2$.
  - PAH mass fraction: $q_{\rm PAH}$
  - Starlight intensity distribution: $U_{\rm min}$ and γ
- *Can reproduce observed SED with NO "cold" dust*

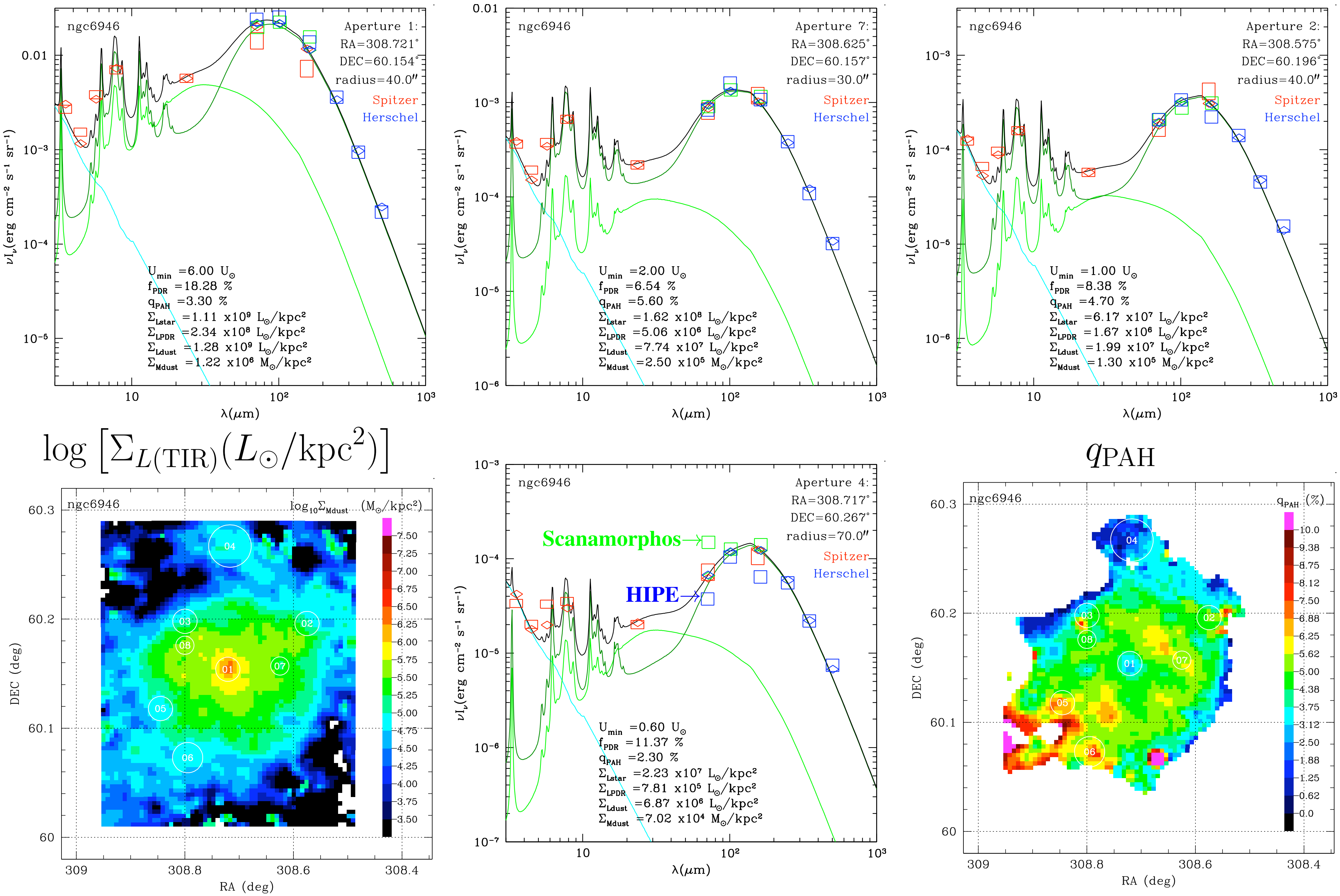
SEDs in Selected Apertures: NGC6946 @ SPIRE 500 resolution

(Aniano et al. 2011b)



SEDs in Selected Apertures: NGC6946 @ SPIRE 500 resolution

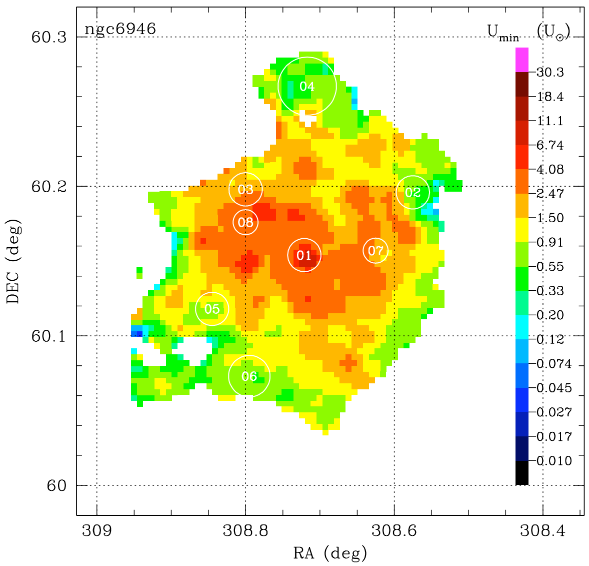
(Aniano et al. 2011b)



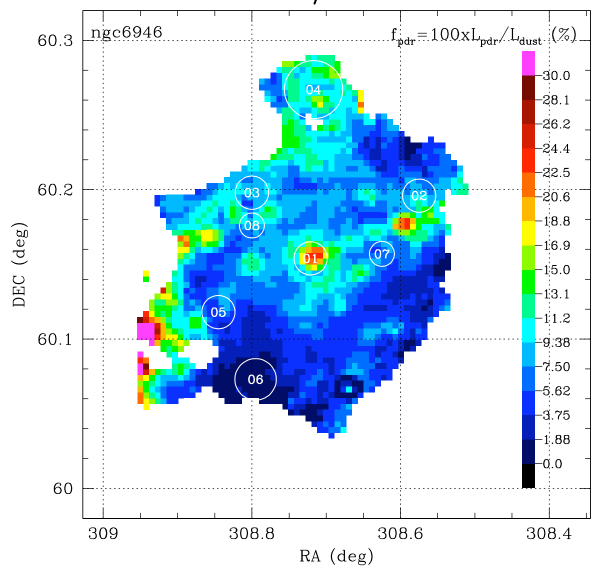
Starlight Properties: NGC 6946 @ SPIRE 500 resolution

(Aniano et al. 2011b)

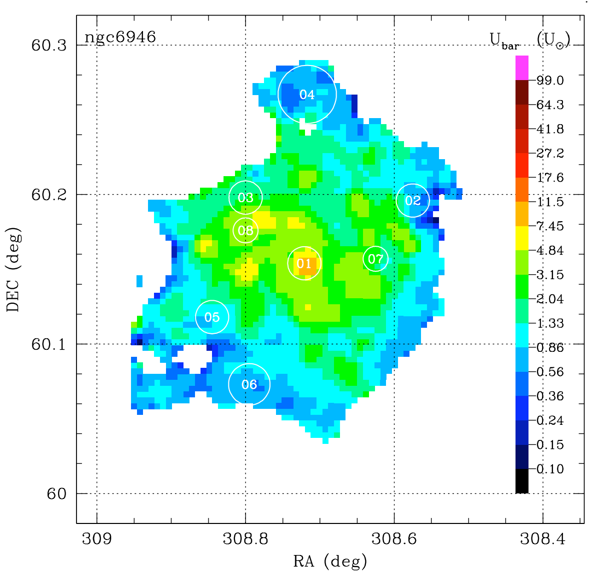
$U_{\rm min}$



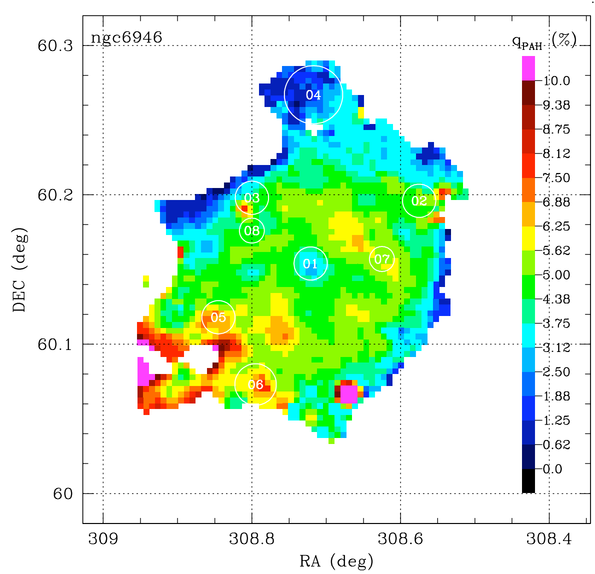
$L_{\rm PDR}/L_{\rm TIR}$



$\langle U \rangle$



$q_{\rm PAH}$



Starlight Properties

- Radial gradient in $U_{\rm min}$:
  - $U_{\rm min} \approx 4$ for central kpc
  - $U_{\rm min} \approx 1$ at $\sim$6 kpc
  - $U_{\rm min} \approx 0.3$ at $\sim$10 kpc
- Similar gradient in $\langle U \rangle$
- $L_{\rm PDR}/L_{\rm TIR} \approx 5 - 10\%$ over most of disk
- A few hot spots where $L_{\rm PDR}/L_{\rm TIR} \approx 15 - 25\%$

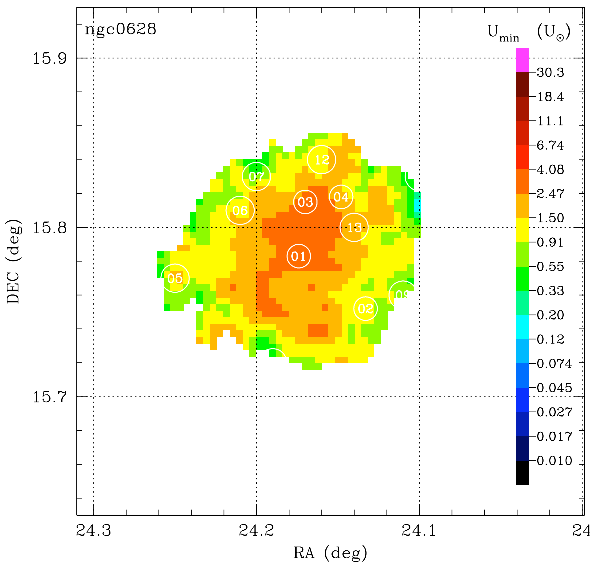
PAH Abundance

- Most of disk has $q_{\rm PAH} \approx 0.045$
- Apparent minimum in $q_{\rm PAH}$ in central kpc.

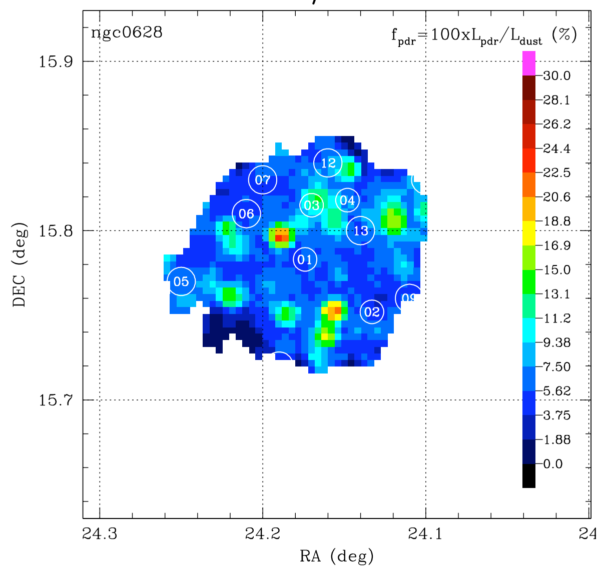
Starlight Properties: NGC 628 @ SPIRE 500 resolution

(Aniano et al. 2011b)

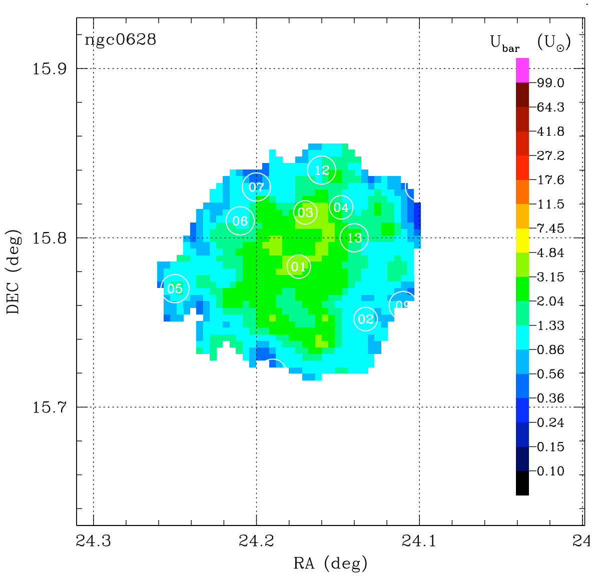
$U_{\rm min}$



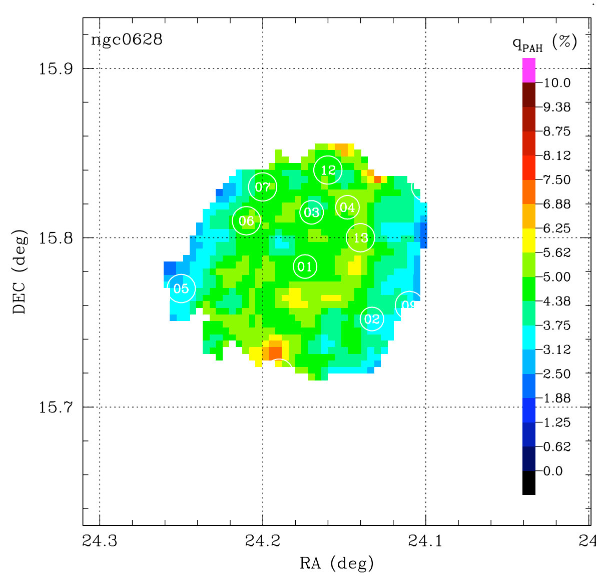
$L_{\rm PDR}/L_{\rm dust}$



$\langle U\rangle$



$q_{\rm PAH}$



Starlight Properties

- Radial gradient in $U_{\rm min}$:
  - $U_{\rm min} \approx 4$ for central kpc
  - $U_{\rm min} \approx 1$ at $\sim$6 kpc
  - $U_{\rm min} \approx 0.3$ at $\sim$10 kpc
- Similar gradient in $\langle U\rangle$
- $L_{\rm PDR}/L_{\rm TIR} \approx 5-10\%$ over most of disk.
- A few hot spots where $L_{\rm PDR}/L_{\rm TIR} \approx 15-25\%$

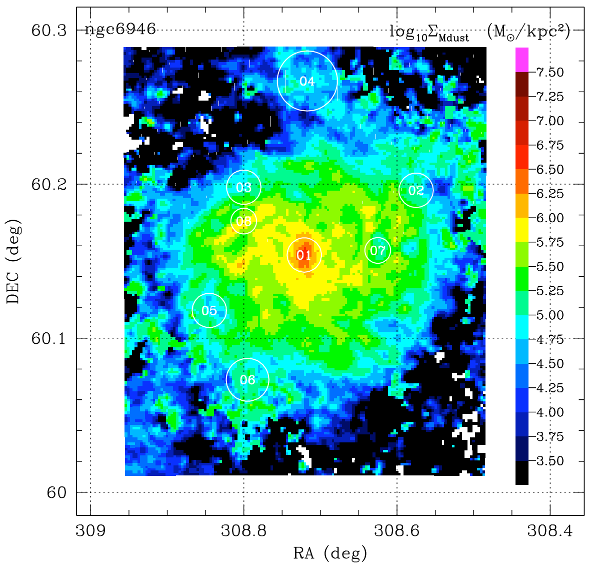
PAH Abundance

- Most of disk has $q_{\rm PAH} \approx 0.045$
- Do *not* have central minimum of $q_{\rm PAH}$

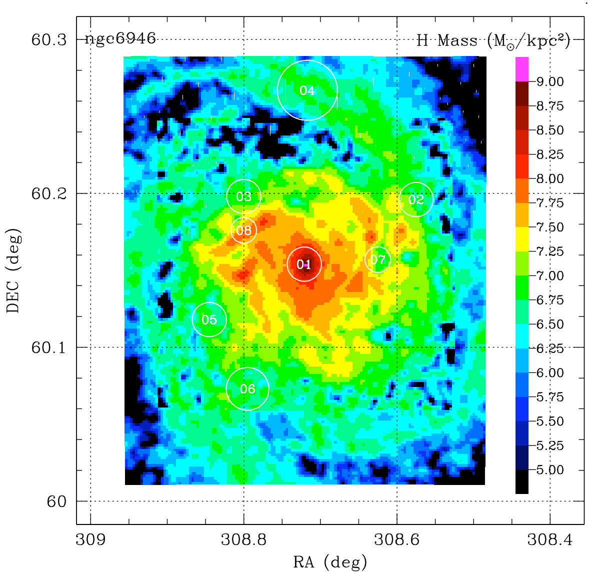
Dust-to-Gas Ratio in NGC 6946 at Spire 250 resolution

(Aniano et al. 2011b)

$\Sigma_{\rm dust}$

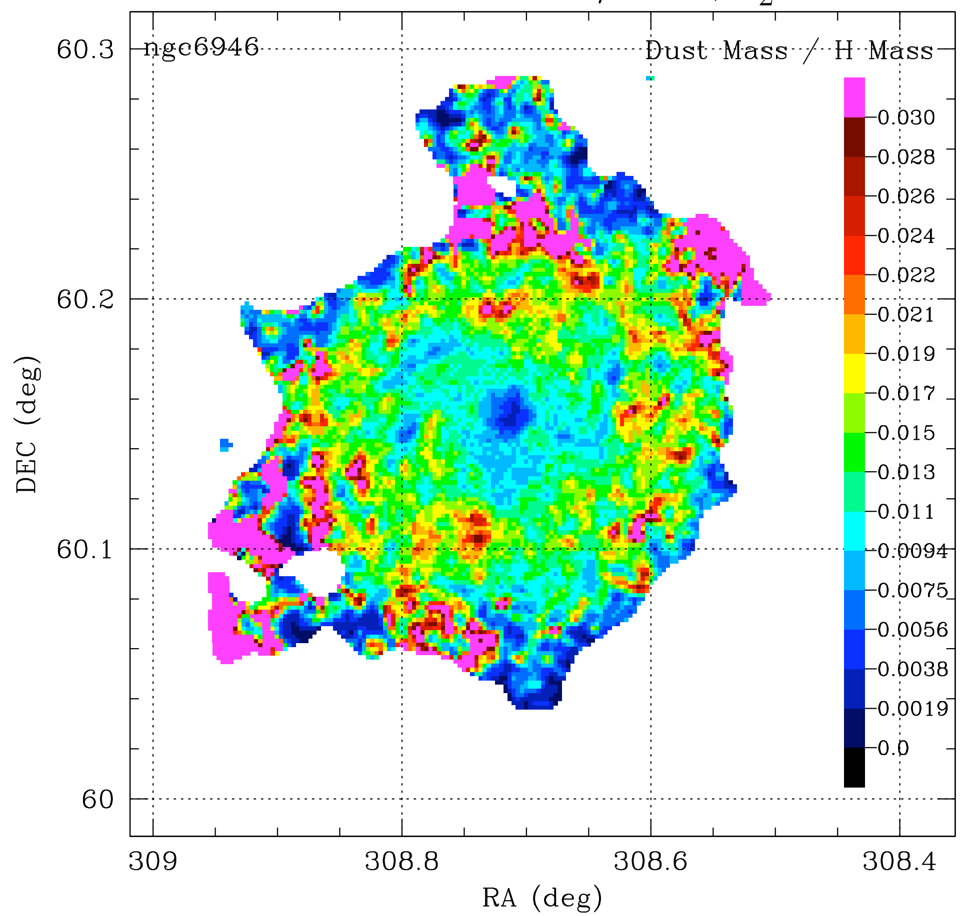


$\Sigma_{\rm H\,I+H_2}$



$X_{\rm CO} = 3\times10^{20}\,{\rm H_2\,cm^{-2}/(K\,km\,s^{-1})}$

$\Sigma_{\rm dust}/\Sigma_{\rm HI+H_2}$

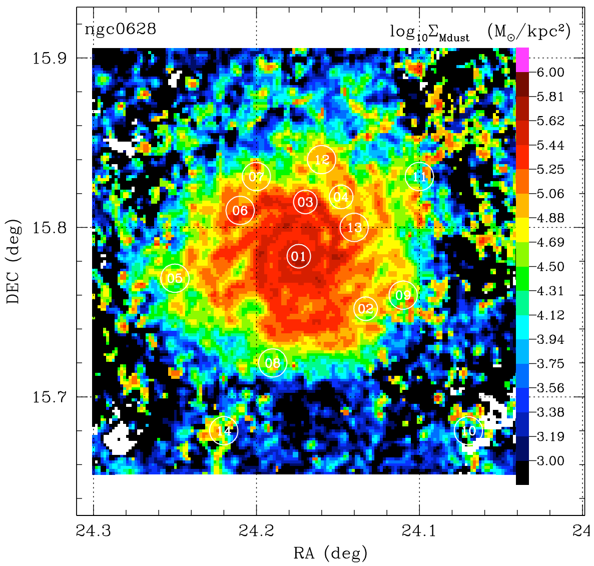


- Low dust/gas ratio within ∼2 kpc of center: indication that $X_{\rm CO}$ **should be lower near center?**
- $M_{\rm dust}/M_{\rm H} \approx 0.012 \pm 0.004$ over most of disk
- A few places with high $M_{\rm dust}/M_{\rm H}$ – bad data?

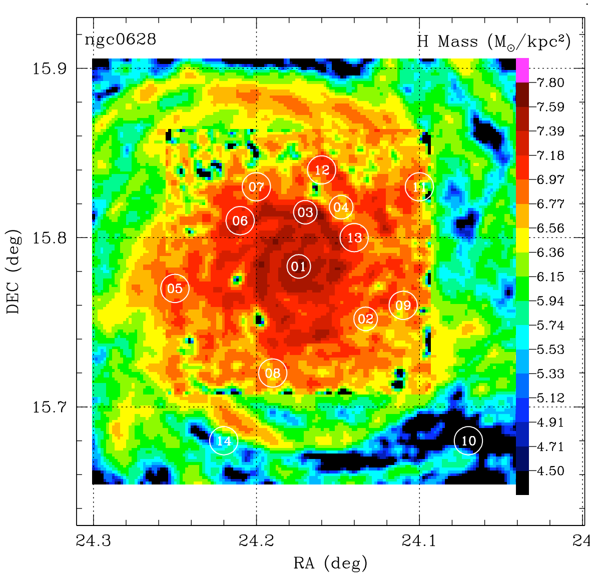
Dust-to-Gas Ratio in NGC 628 at Spire 250 resolution

(Aniano et al. 2011b)

$\Sigma_{\rm dust}$

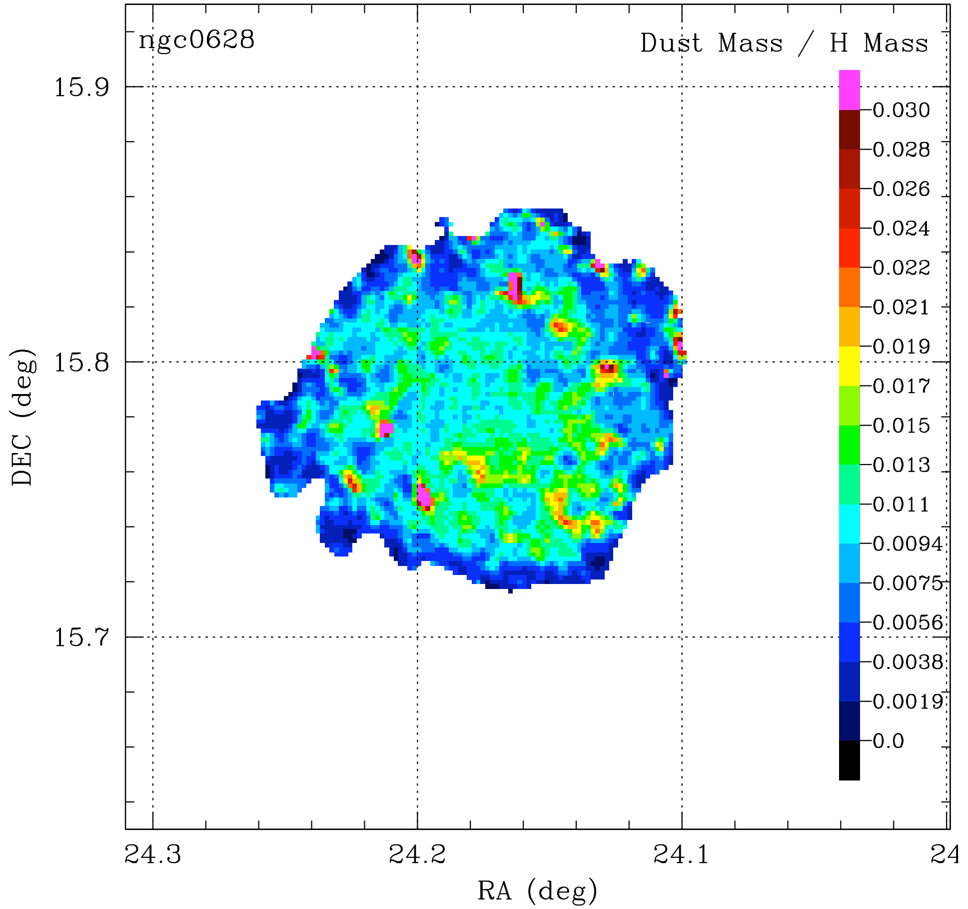


$\Sigma_{\rm H\,I+H_2}$



$X_{\rm CO} = 4\times 10^{20}\,{\rm H_2\,cm^{-2}/(K\,km\,s^{-1})}$

$\Sigma_{\rm dust}/\Sigma_{\rm HI+H_2}$



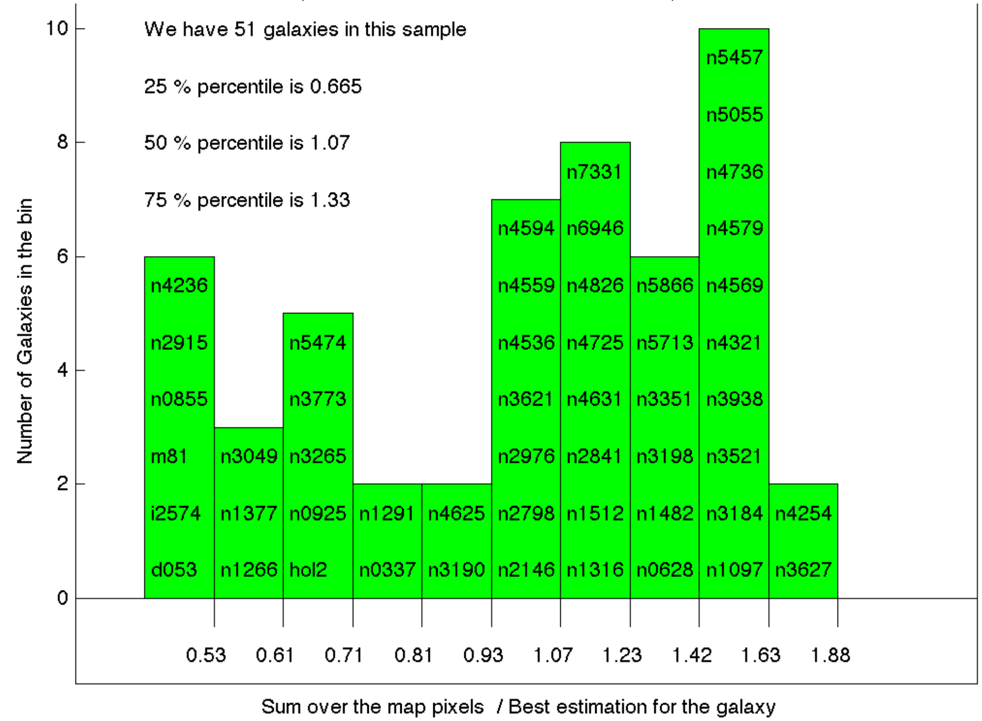
- Normal dust/gas ratio within ~2 kpc of center.
- $M_{\rm dust}/M_{\rm H} \approx 0.010 \pm 0.003$ over most of disk
- A few places with high $M_{\rm dust}/M_{\rm H}$ – bad data?
- Dust/gas ratio is **LOW** (~0.005) in outer regions.

Dust Mass Estimation with Different Camera Sets

- Σ_{dust} is obtained by fitting model to observations: Σ_{dust} estimate will depend on data set employed.
- Q: How do dust masses estimated using IRAC + MIPS only differ from dust masses obtained with more complete photometry?

Sample: 51 KINGFISH galaxies with complete (IRAC, MIPS, PACS, SPIRE) imaging Kennicutt & the KINGFISH team (2011).
Adopted "Gold Standard": Σ_{dust} estimated from complete (IRAC + MIPS + PACS + SPIRE) photometry at MIPS 160 resolution.
Compare estimates of M_{dust} obtained by summing over pixels.

IRAC + MIPS only vs. "Gold Standard"
(Aniano et al. 2011c)



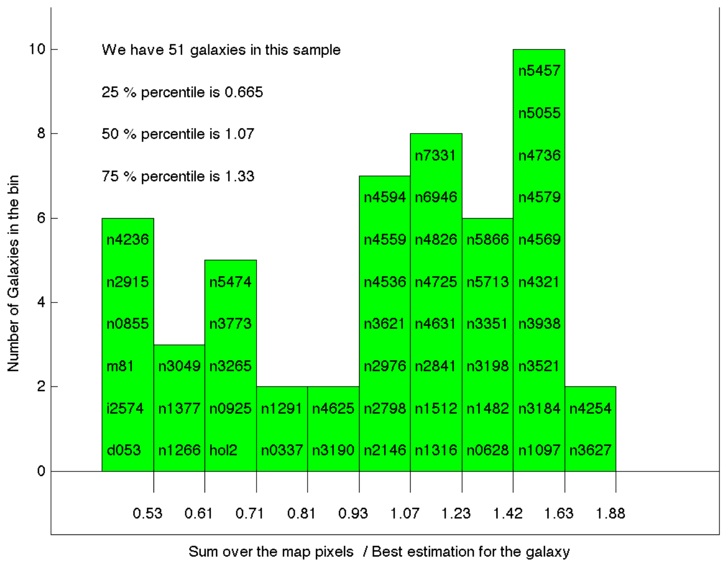
- median galaxy has dust mass estimate *decrease* by 7% when PACS and SPIRE data are added.
- 50% of the cases have M_{dust} changing by **less than a factor 1.33 when PACS and SPIRE are added**.
- Worst cases: factors of $\sim$1.7 (up and down)
- **At least for normal galaxies, dust mass estimates based only on Spitzer data appear to be reliable.**

Dust Mass Estimation with Different Camera Sets

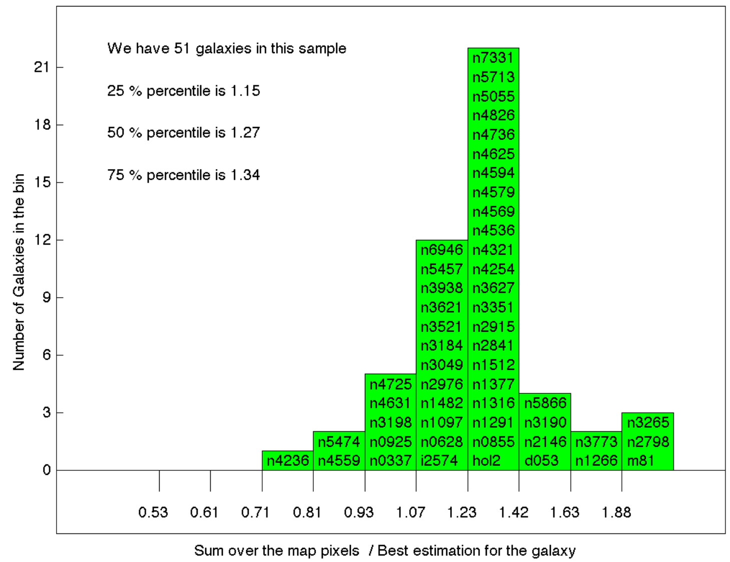
(Aniano et al. 2011c)

Gold standard: sum over pixel-by-pixel mass estimate at resolution of MIPS160, using all cameras (IRAC, MIPS, PACS, SPIRE).

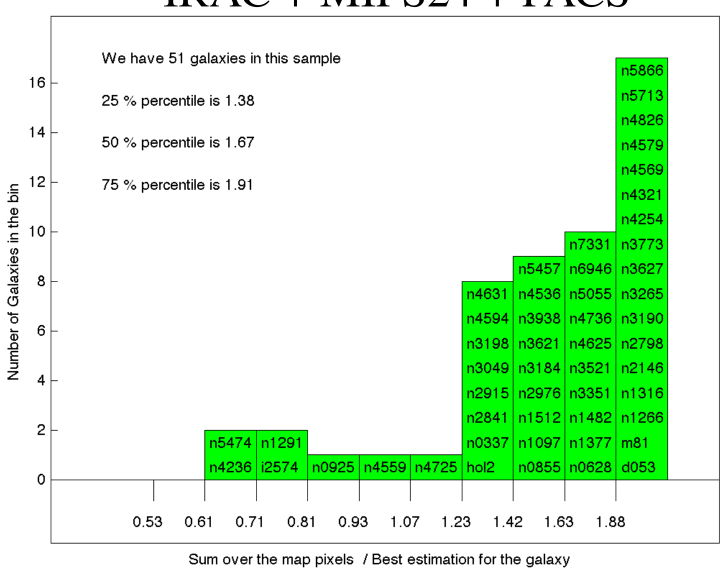
IRAC + MIPS only



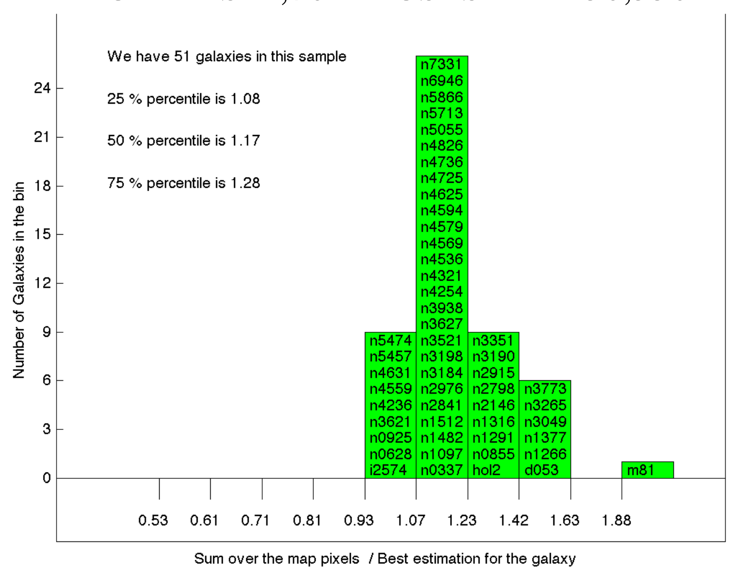
IRAC + MIPS24 + PACS + SPIRE250



IRAC + MIPS24 + PACS



IRAC+MIPS24,70+PACS+SPIRE250,350

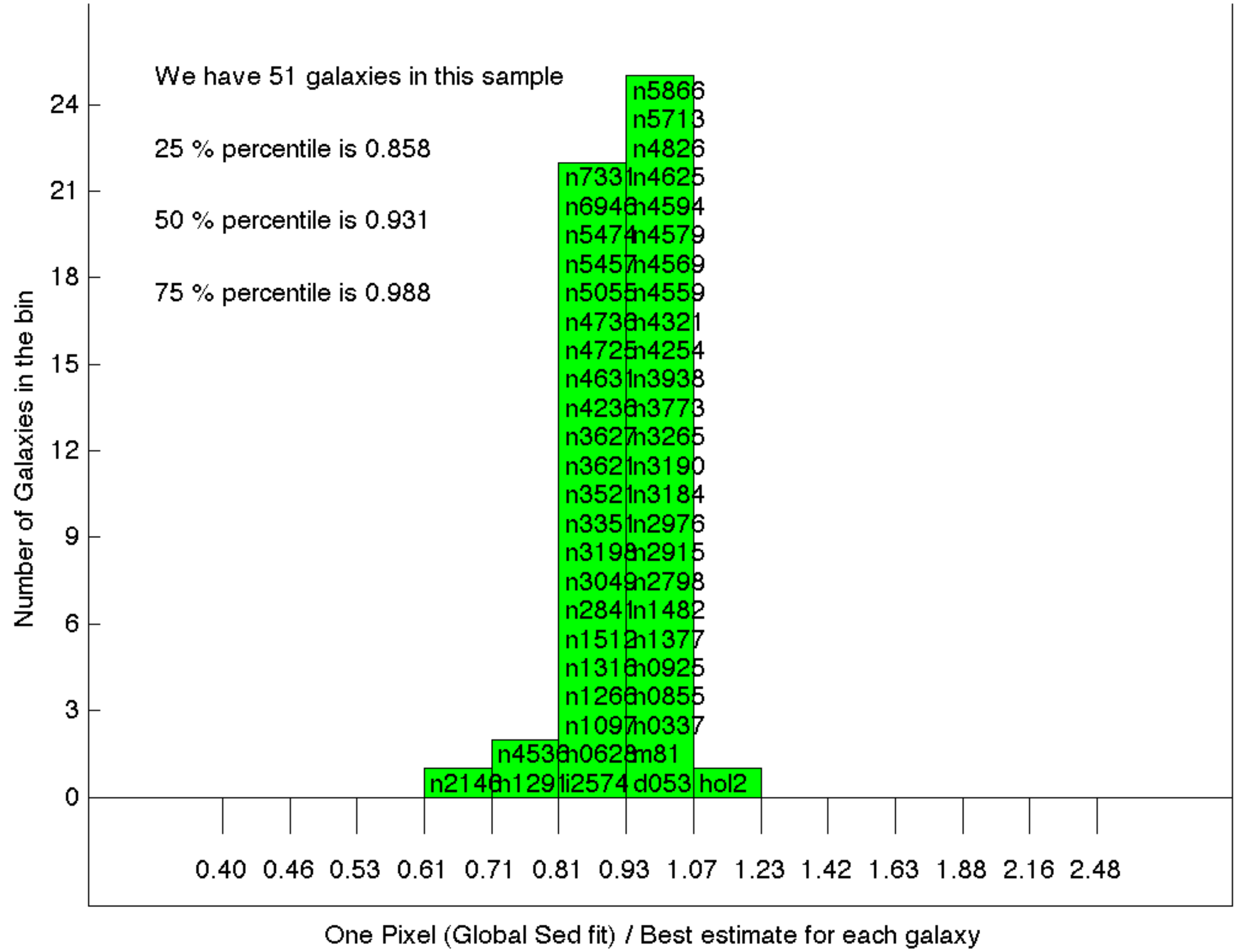


As longer-λ data is added, $M_{\rm dust}$ converges

- Spitzer data only (MIPS160 res.): median error= **-33.5%** and **+33%**
- IRAC + MIPS24 + PACS (PACS160 res.): median error= **+36%** and **+91%**
- IRAC + MIPS24 + PACS + SPIRE250 (SPIRE250 res.): median error= **+15%** and **+34%**
- IRAC + MIPS24,70 + PACS + SPIRE250,350: median error= **+8%** and **+28%**

Dust Mass from Global Flux vs. Sum over Pixels

Using IRAC+MIPS+PACS+SPIRE



Gold standard: sum over pixel-by-pixel mass estimate at resolution of MIPS160, using all cameras (IRAC, MIPS, PACS, SPIRE).

Fit to global flux (with all cameras) typically underestimates mass only slightly: 50% of the galaxies are within 0.86 and 0.99 of "gold standard" estimate.

Summary

- Important to allow for *distribution of starlight heating rate* within pixels.
- In normal galaxies: Can successfully model SED using T-*in*dependent opacities.
- In normal galaxies: Ad-hoc starlight distribution function proposed by DL07 (δ-func. + power-law) appears to work well.
- In normal galaxies with IRAC, MIPS, PACS, SPIRE imaging (to SINGS and KINGFISH depths): Sensitivity limit for SPIRE250 pixels
  - NGC 6946: $\Sigma_{\rm dust} \approx 10^{4.7} M_\odot\,{\rm pc}^{-2}$ ($A_V \approx 0.3\,$mag)
  - NGC 628: $\Sigma_{\rm dust} \approx 10^{4.5} M_\odot\,{\rm pc}^{-2}$ ($A_V \approx 0.2\,$mag).
- Dust mass estimated from Spitzer data only is typically within $\sim 35\%$ of the value obtained using all Spitzer + Herschel bands.
- Resulting dust/gas ratios ($M_{\rm dust}/M_{\rm H} \approx 0.010$ in NGC 628 and NGC 6946) are consistent with dust mass expected for MW depletion pattern.
- Dust mass estimated at SPIRE250 res. (no SPIRE350,500 or MIPS160) is generally within ~30% of dust masses estimated using all Spitzer and Herschel bands.
- Dust mass obtained from *global* SED is close to that obtained from modeling resolved SED.


THANK YOU

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