Magnetic Nanoparticles in the ISM

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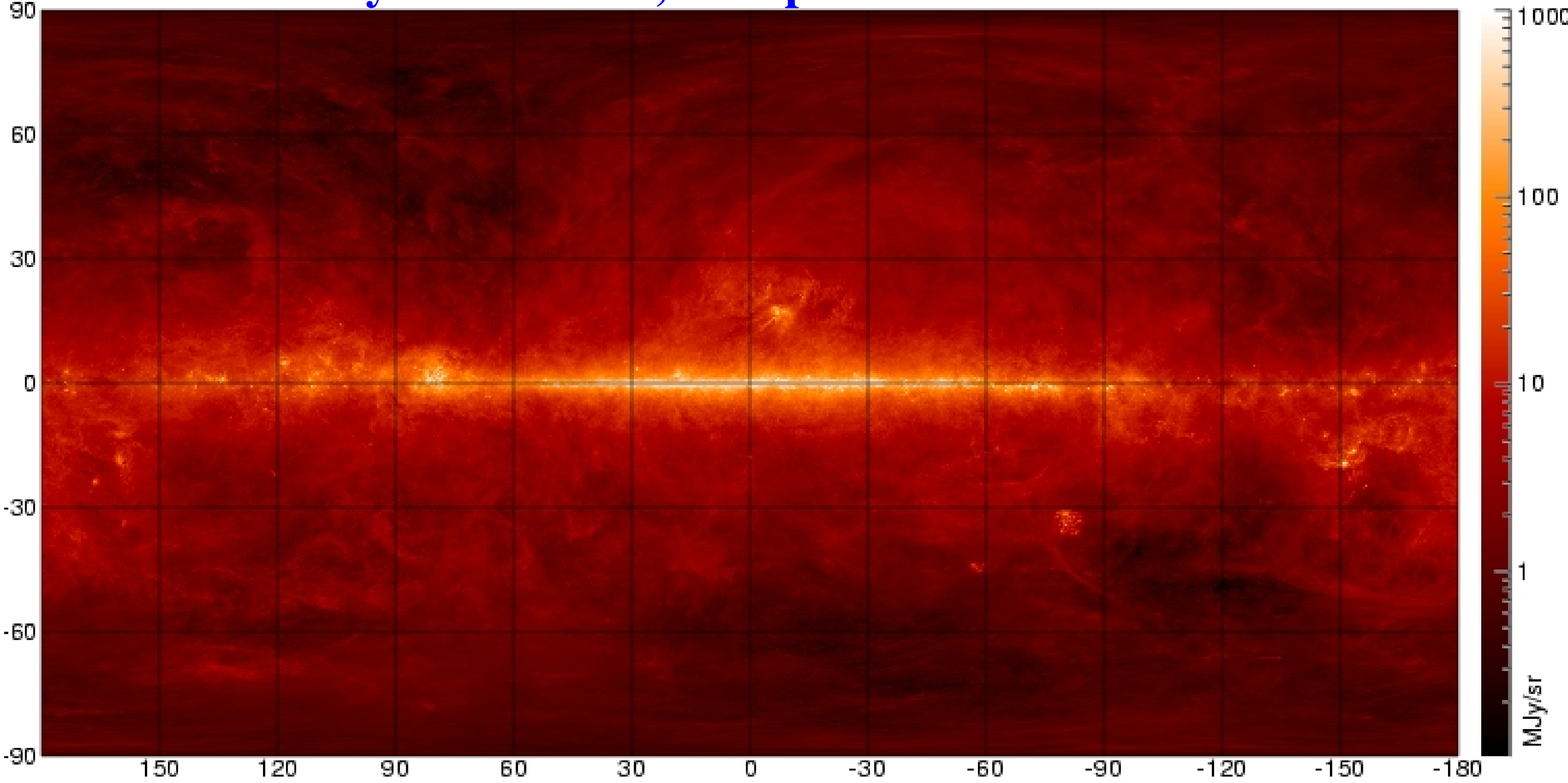
1. **Far-Infrared/Submm Opacities: Model vs. Observed in MW**
2. **Problem: mm-wave Excess in the Small Magellanic Cloud (SMC)**
3. **Magnetic Fe Nanoparticles in the SMC Dust Population?**
4. **Magnetic Nanoparticles in the Milky Way?**
5. **Polarization**

Acknowledgements:
Brandon Hensley (Princeton grad student)

FIR-Submm Dust Opacity
Physical Models; Compare with 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

The DL07 Dust Model

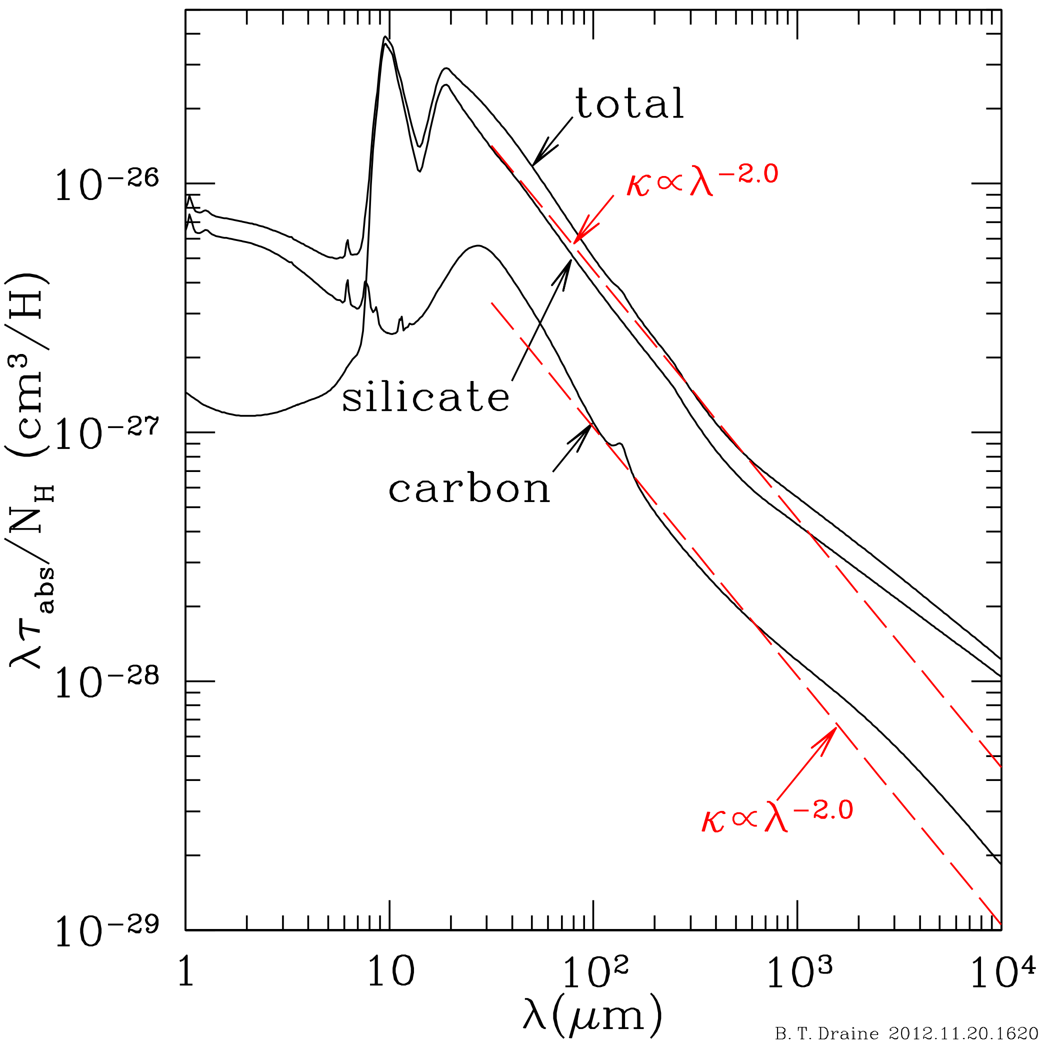
- PAH particles (25 – 10^4 C atoms)
  - abundance and size distribution to reproduce the "UIR" emission bands
    (3.3, 6.2, 7.7, 8.6, 11.3, 12.0, 12.7μm)
  - account for 2175Å extinction feature ($\pi \rightarrow \pi^*$ electronic excitation of PAHs)
  - rotational emission with spectrum and intensity of observed
    20–60 GHz Anomalous Microwave Emission
- Larger carbonaceous particles (up to $a \approx 0.5\,\mu\mathrm{m}$)
  - treat carbonaceous particles as a single population
    ad-hoc smooth transition from PAH-like to graphite-like
  - account for significant fraction of optical extinction
  - account for most of 2–8μm extinction
  - account for $\sim$50% of 100–500μm opacity
  - For $a > 0.01\,\mu\mathrm{m}$, opacity calculated assuming optical properties of graphite
    $\kappa \propto \nu^2$ for $\nu < 1\,\mathrm{THz}$ ($\lambda > 300\,\mu\mathrm{m}$)
    (Draine & Lee 1984; Li & Draine 2001; Draine & Li 2007).
- Amorphous silicate (composition $\sim$ MgFeSiO$_4$)
  - $\sim$2/3 of dust mass

The "Astrosilicate" Opacity

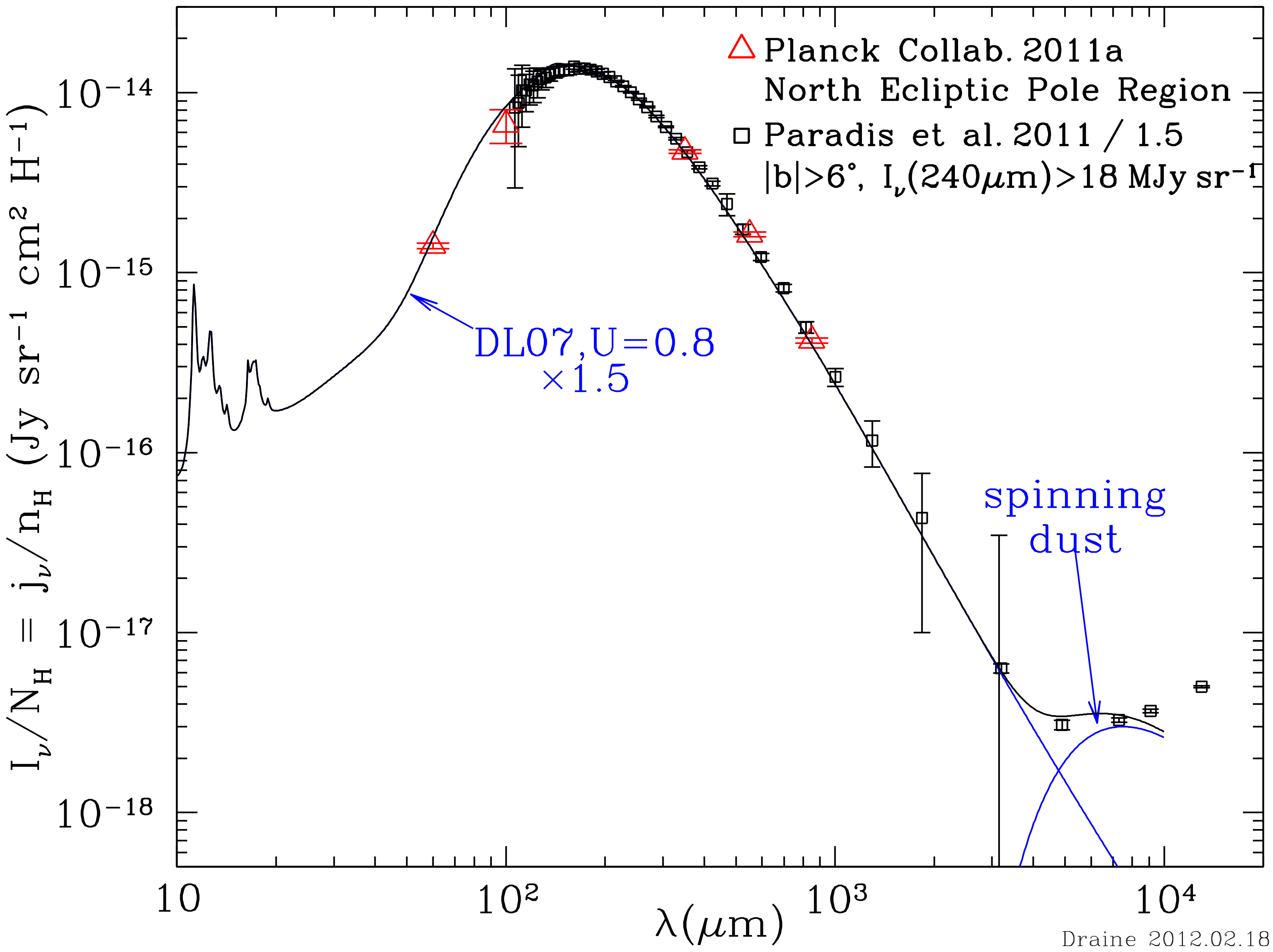
Amorphous silicate ("astrosilicate)
(composition ∼ $MgFeSiO_4$)

- ∼2/3 of dust mass
- needed to account for observed 10 and 18μm features
- original Draine & Lee (1984) model: $\kappa \propto \nu^2$ for $\nu < 3\,\mathrm{THz}$ ($\lambda > 100\,\mu\mathrm{m}$)
- FIRAS: $\nu < 1\,\mathrm{THz}$ spectrum deviates from $\nu^2 B_\nu(T \approx 18\,\mathrm{K})$
- Li & Draine (2001) modified astrosilicate Im(ϵ) at $\lambda > 250\mu$m to approximately reproduce FIRAS spectrum

DL07 Opacities



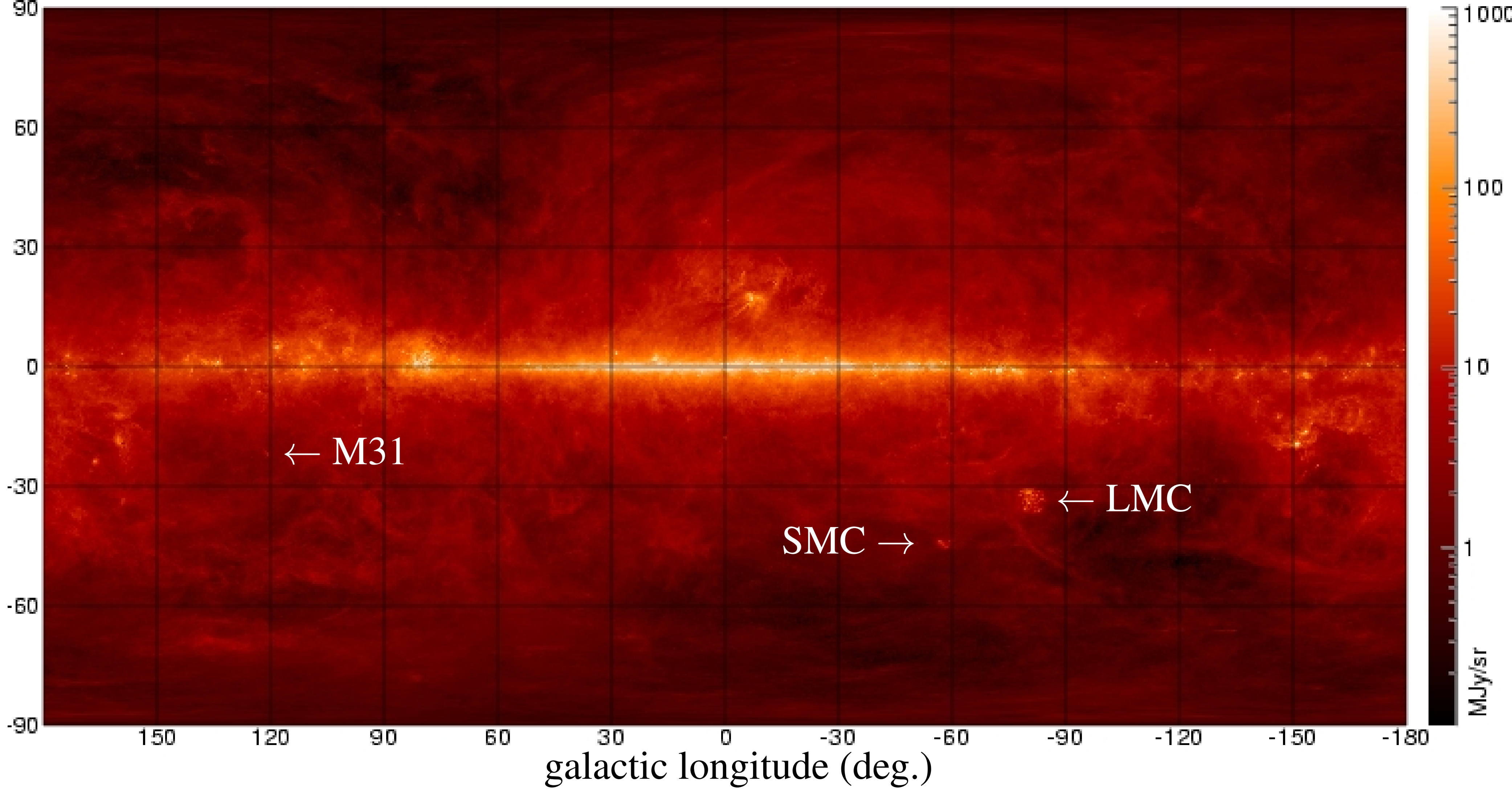
Comparison with FIR-Submm-μwave Observations in MW



How about Nearby Galaxies?

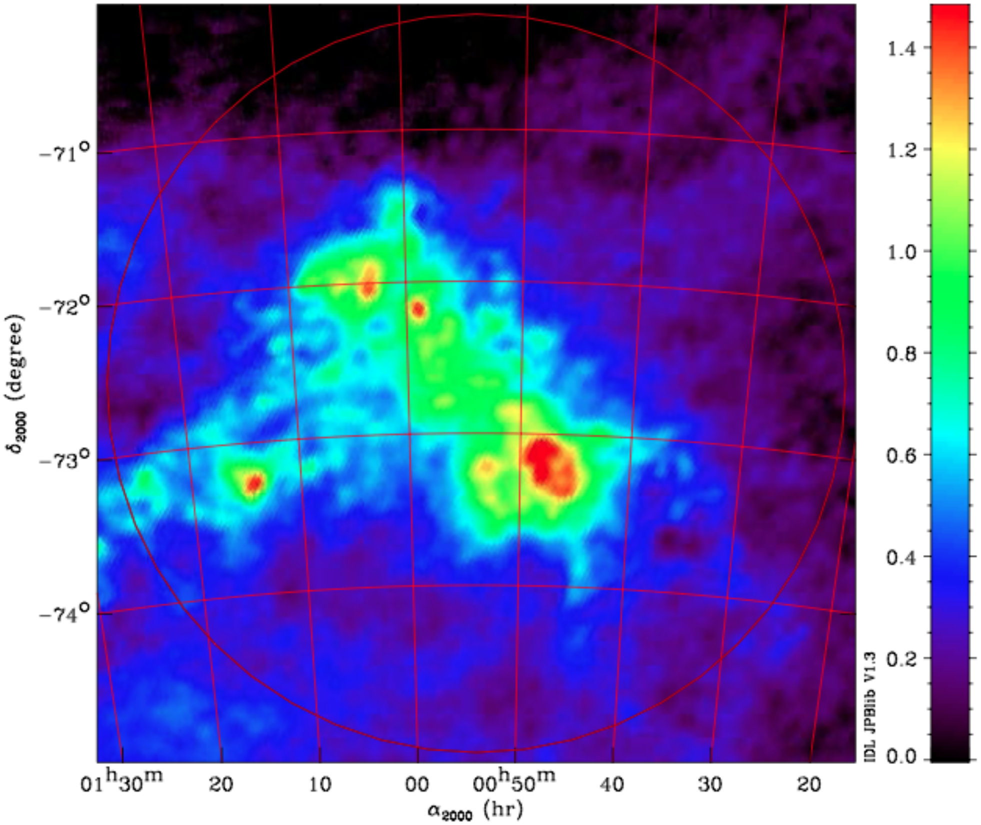
100 μm IRAS/COBE Map of Sky (after zodi subtraction)

Image credit: D. Finkbeiner



The Small Magellanic Cloud (SMC)

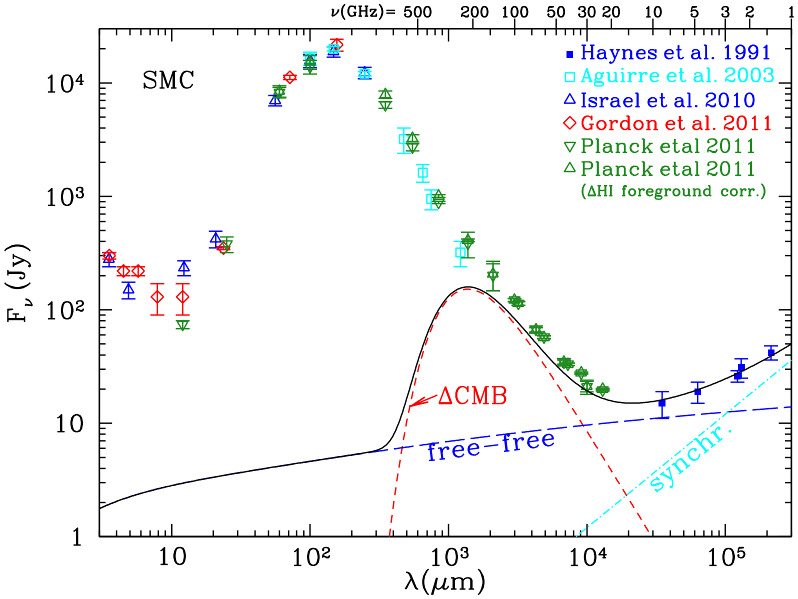
Optical (AAO)

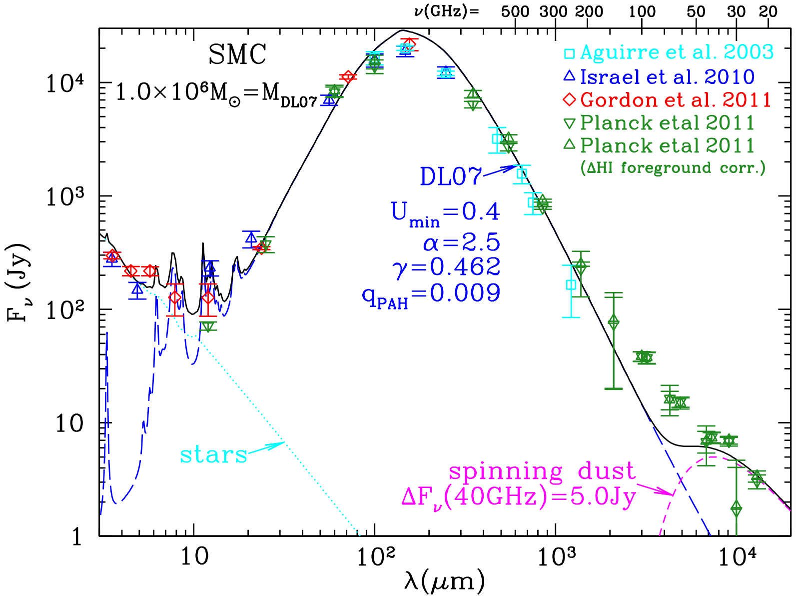


Planck 857GHz (Planck Collaboration et al. 2011)

- Interstellar gas less enriched with heavy elements (C, N, O, ..., Fe)
  SMC ∼25% “solar”)
- Dust composition differs from Milky Way
  - 2175Å extinction feature: very weak
  - PAH emission: very weak

Dust in the SMC: Excess 50–300 GHz Emission





- Photometry: Israel et al. (2010) and Planck Collaboration et al. (2011)
- $M_{\rm H}(SMC) \approx 4.8 \times 10^8 M_\odot$
- $Z(SMC) \approx 0.25 Z_\odot$
- $M_{\rm dust,max}(SMC) \approx 1.2 \times 10^6 M_\odot$
- After subtracting
  - *synchrotron emission*
  - *free-free (bremstrahhlung)*
  - *chance upward fluctuation of CMB*

  Can our dust model + starlight reproduce the observed emission?

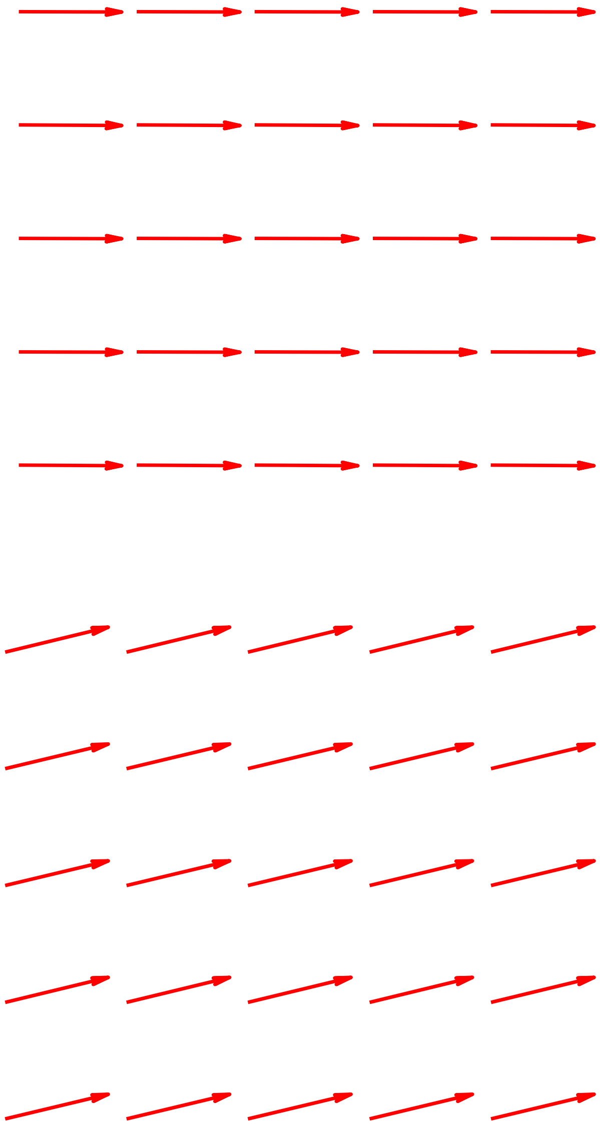
- Model with acceptable mass of dust, but **severe 50–200 GHz shortfall**.
- Spinning dust cannot explain this.
- **Dust in SMC is qualitatitively different from MW dust**... but in what way?
- At long wavelengths (particle size $\ll \lambda$), it is generally assumed that emission comes from thermal fluctuations in the electric dipole moment.

  Perhaps this isn't the only source of emission from dust....

Magnetic Dipole Emission from Magnetic Dust

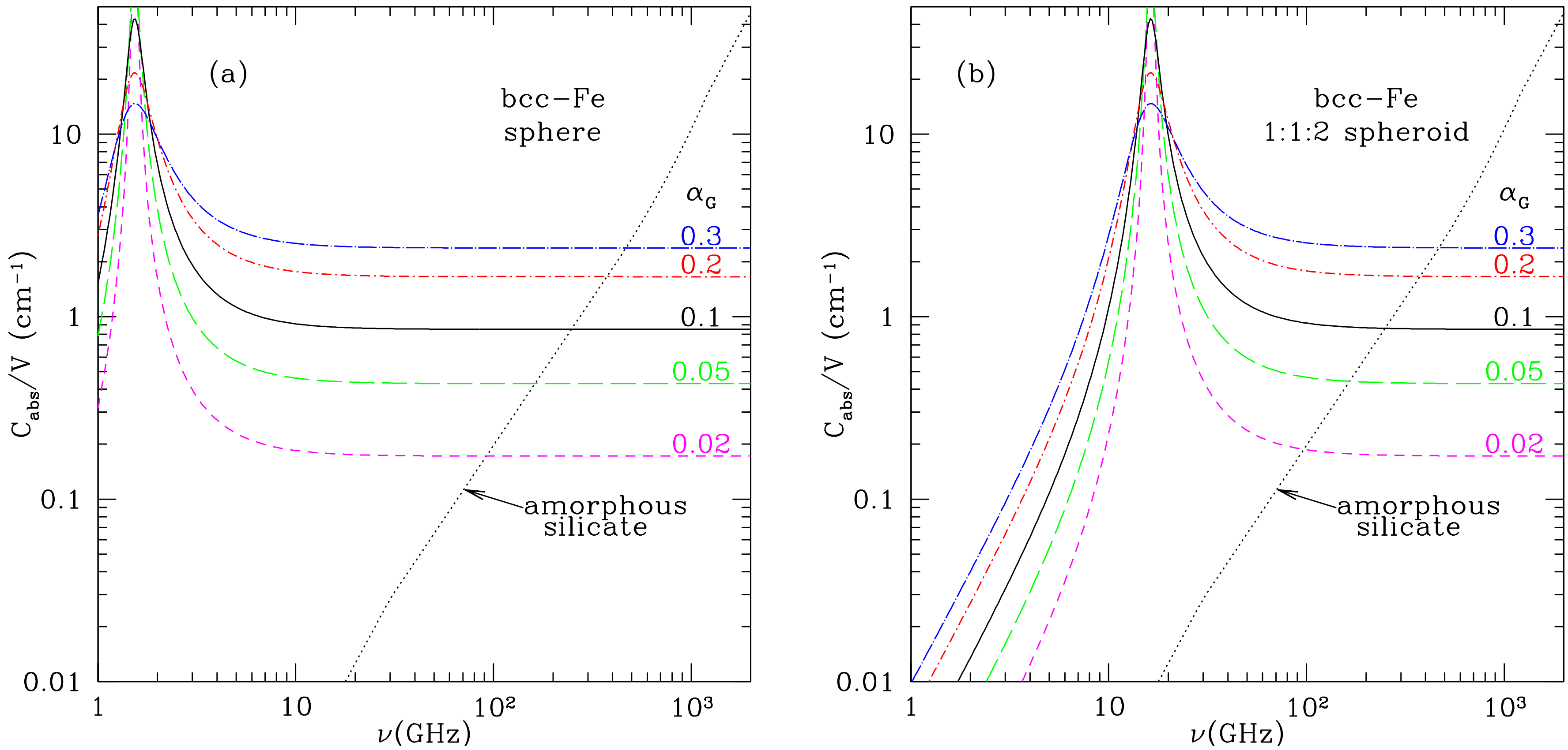
(Draine & Lazarian 1999; Draine & Hensley 2012b)

- Suppose much of the Fe is in magnetic material (e.g., metallic Fe, magnetite $\mathrm{Fe_3O_4}$, or maghemite γ–$\mathrm{Fe_2O_3}$)
- Lowest energy state of metallic Fe:
  - spins are parallel (magnetized),
  - magnetization $\vec{\mathrm{M}}$ is aligned with one of the crystal axes
- Excited state: spins parallel, but oriented away from crystal axis
- Oscillations in magnetization $\rightarrow$ magnetic dipole emission
- Finite temperature $\rightarrow$ **thermal** magnetic dipole emission



Magnetic Dipole Absorption Cross Section for Fe Nanoparticles

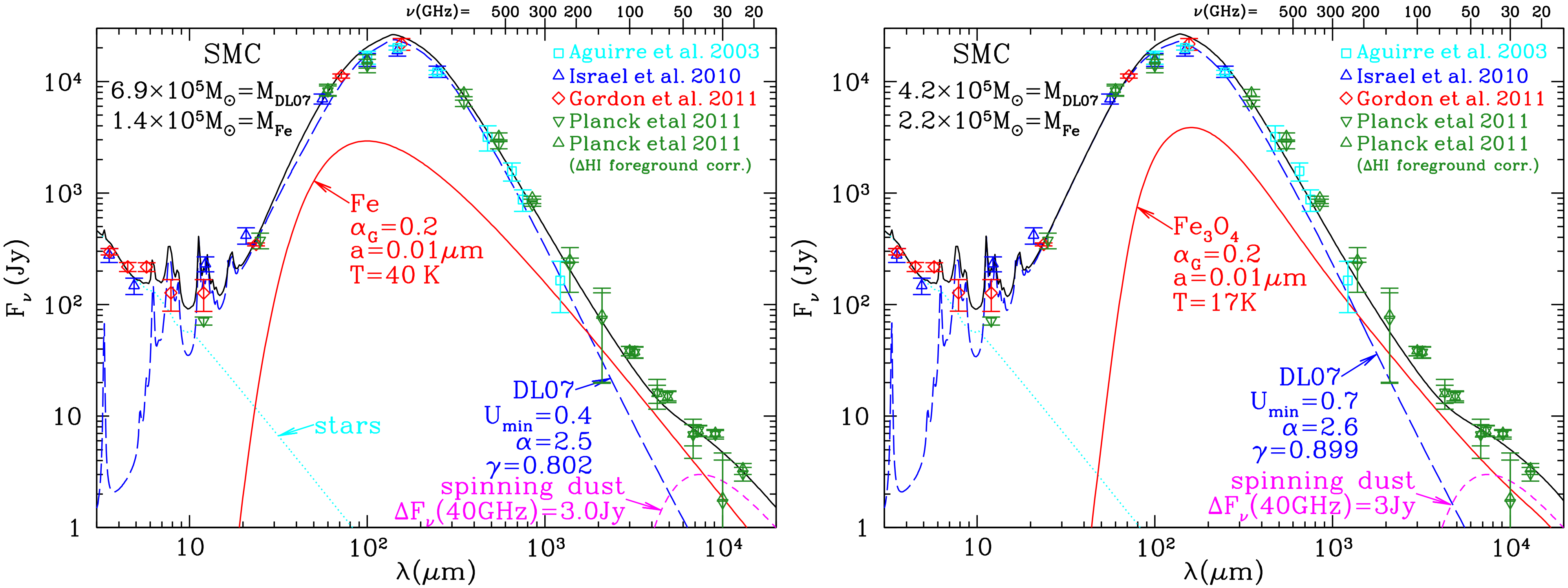
(Draine & Hensley 2012b)



- Magnetization dynamics: use Gilbert equation (*not* Landau-Lifshitz eq. or Bloch-Bloembergen eq.)
- Resonance frequency depends on particle shape.
- Absorption depends on uncertain “Gilbert damping parameter” α_G.
  $\alpha_G \approx 0.2$ may be realistic.

SMC Dust Models With Iron or Magnetite (Fe_3O_4) Nanoparticles

(Draine & Hensley 2012a)



- $M_{\rm dust} = 8.4 \times 10^5 M_\odot$ or $6.4 \times 10^5 M_\odot < M_{\rm dust,max} = 1.2 \times 10^5 M_\odot$
- magnetic dipole emission dominates for $\nu \lesssim 200\,{\rm GHz}$
- spinning dust component:
  - normal spectrum (peaking near 40 GHz)
  - has ∼expected strength (scaled with PAH abundance in SMC)

Metallic Fe Grains in ISM?

- Chemical form of solid-phase Fe in ISM not known – fraction in silicates is disputed.
- McDonald et al. (2010): low-metallicity AGB stars in globular clusters sometimes produce dust that is not silicate (IR spectrum is featureless);
  propose that **Fe metal grains** form in low-metallicity winds.
- Interplanetary dust particles known as "GEMS" contain **Fe nanoparticles** (Bradley 1994).
- "Inclusion-Rich Rims" on lunar soil grains contain **Fe nanoparticles** (Keller & McKay 1997).
- In lab, olivine irradiated by 2 keV He^{++} develops **Fe nanoparticles** (Loeffler et al. 2009).
- Reasonable to consider that there may be metallic Fe nanoparticles in ISM, either as inclusions or as "free-fliers" (released in shattering events)
- Different conditions in ISM in low-metallicity galaxies could conceivably lead to larger fraction of metallic Fe than in ISM of "normal" galaxies.

We don't really understand grain evolution in ISM, so it's hard to say....

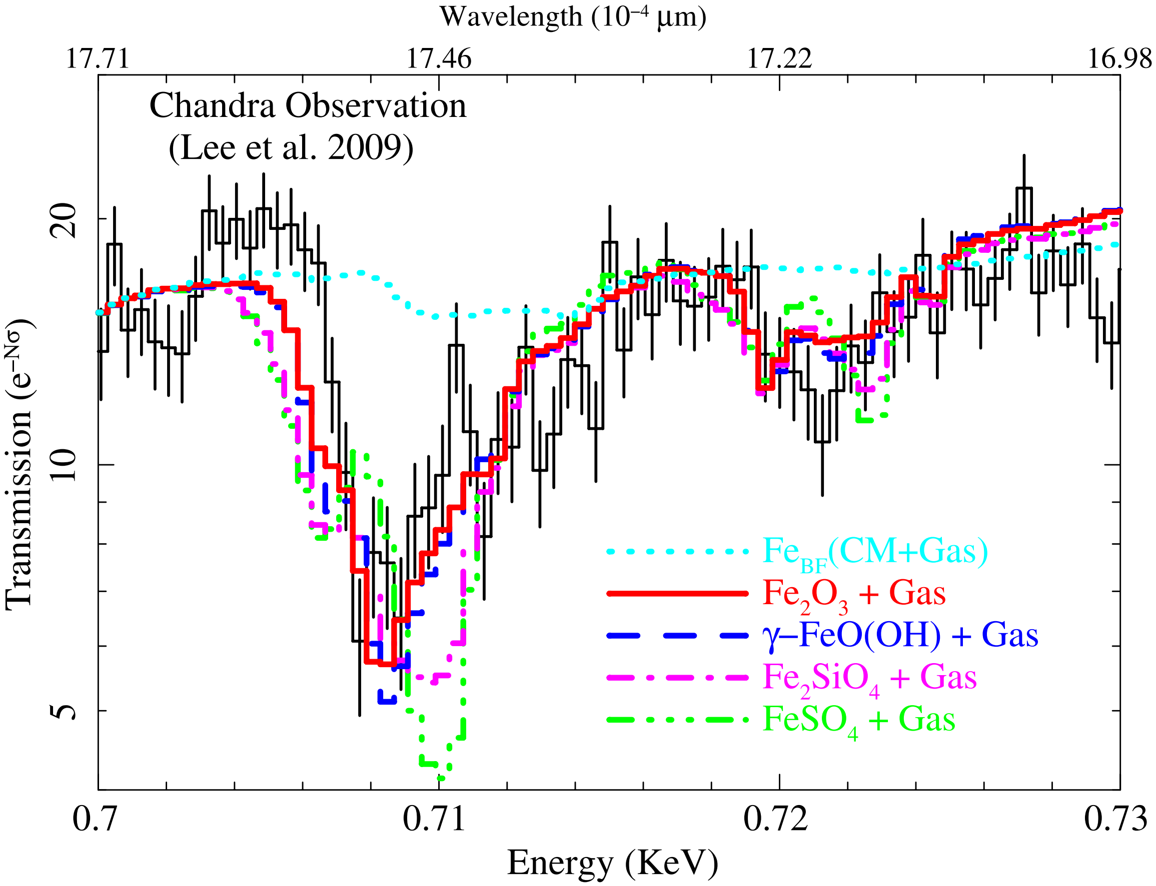
Magnetic Grains in ISM? Observational Tests

X-Ray Absorption

X-ray absorption fine structure could (in principle) identify chemical state of atoms in dust.

Example: Fe L edge (absorption from Fe 2s, 2p).
Especially L_2, L_3 (2p electrons)
Extinction profile depends on chemical state (metal, oxide, silicate) and on grain size (because extinction includes scattering).

Need ∼1 eV resolution and good S/N: Difficult.



Chandra observation of Cyg X-1 (Lee 2010)

Metallic Fe Grains in ISM? Observational Tests

Polarization

Polarization of emission from silicates with randomly-oriented magnetic inclusions:
At THz frequencies, electric dipole emission polarized with

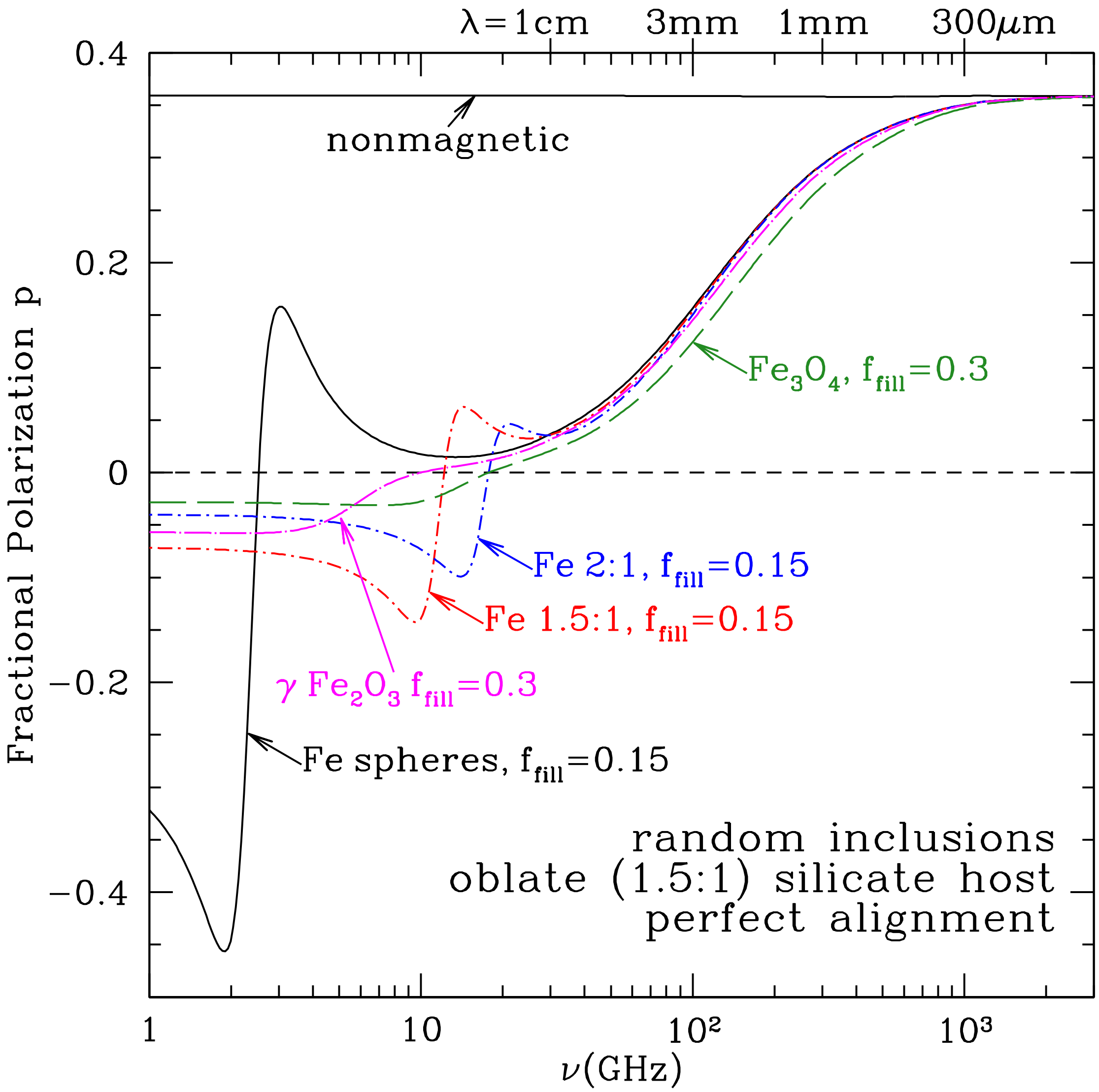
$$\vec{\mathbf{E}}_\omega \perp \vec{\mathbf{B}}_0$$

Magnetic dipole contribution is polarized with

$$\vec{\mathbf{B}}_\omega \perp \vec{\mathbf{B}}_0$$

In ISM, this polarization will be diluted by emission from other components

- Carbonaceous grains
- Spinning dust (20-60 GHz)
- Free-free
- Synchrotron



∼30% drop in polarization between 353 and 143 GHz
Draine & Hensley (2012a)

Summary

- In normal galaxies: Can successfully model SED using physical dust model with "amorphous silicate", graphitic carbon, and PAHs
- SMC dust appears to be qualitatively different from dust in Milky Way: relatively more emission in 50–300 GHz range
- **SMC SED can be explained by magnetic dipole radiation if much of the interstellar Fe in the SMC is in nanoparticles (free-flying or inclusions) of metallic Fe, magnetite $\mathrm{Fe_3O_4}$, or maghemite γ-$\mathrm{Fe_2O_3}$.**
  This may also be the case for other low-metallicity dwarf galaxies.
- Magnetic grains may also be present in Milky Way – some of the $\nu < 350\,\mathrm{GHz}$ ($\lambda > 850\,\mu\mathrm{m}$) opacity that has been attributed to "amorphous silicates" may in fact be magnetic dipole absorption (Hensley & Draine 2013, work in progress)
- If magnetic nanoparticles contribute appreciable emission at $\nu < 350\,\mathrm{GHz}$, polarization will be function of frequency: testable by *Planck*
  - Polarization of the SMC
  - Polarization of the MW cirrus

THANK YOU

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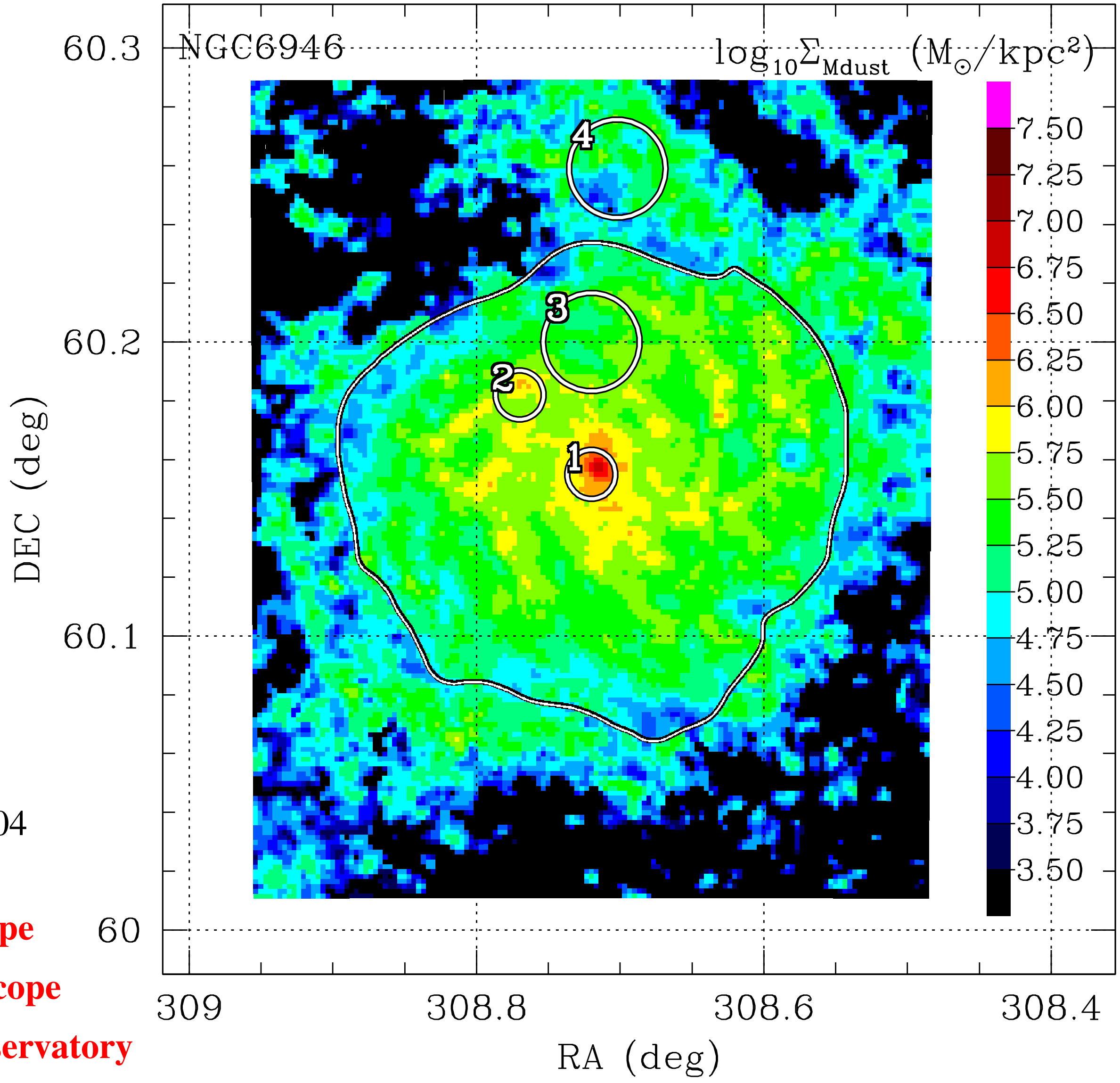
NGC 6946 (Aniano et al. 2012)

0.1° = 12 kpc @ 6.8 Mpc

image credit: Kuzio de Naray & McGaugh 2004

dust map at SPIRE250 resolution, 18″ pixel = 590 pc



IR Observations:

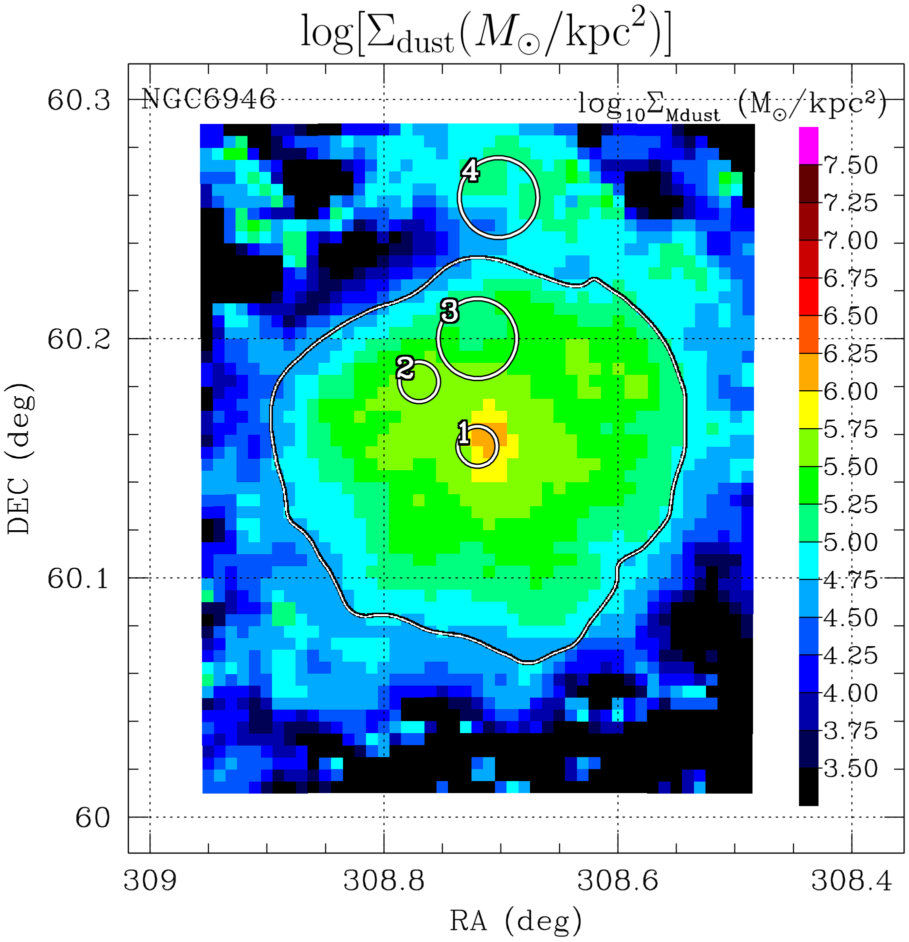
- **IRAC (3.6–8μm) on Spitzer Space Telescope**
- **MIPS (24–160μm) on Spitzer Space Telescope**
- **PACS (70–160μm) on Herschel Space Observatory**
- **SPIRE (250–500μm) on Herschel Space Observatory**

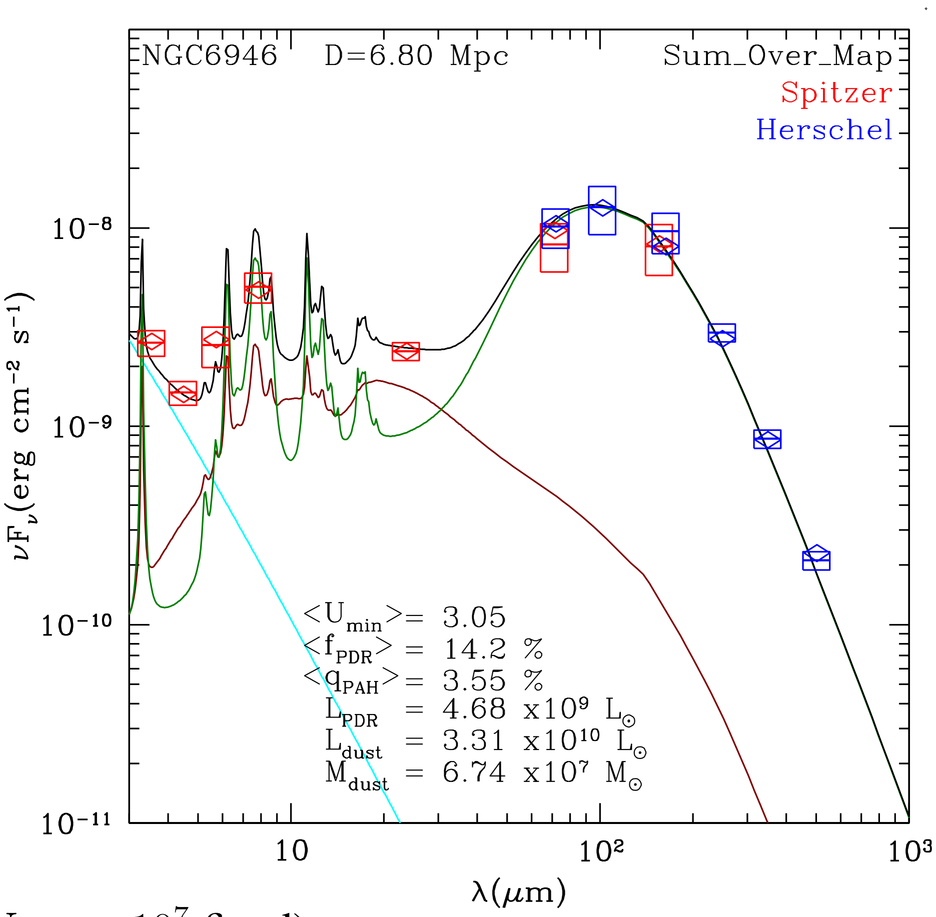
$N_{\rm H} = 10^{21}\,{\rm cm}^{-2} \rightarrow \Sigma_{\rm H} = 10^{6.9} M_\odot\,{\rm kpc}^{-2}$ $\qquad$ $A_V = \Sigma_{\rm dust}/10^{5.2} M_\odot\,{\rm kpc}^{-2}$

single-pixel detection limit $\Sigma_{\rm dust} \approx 10^{4.75} M_\odot\,{\rm pc}^{-2}$**, or** $A_V \approx 0.4$ **mag**

Dust Map and SED for NG6946 @ MIPS160 resolution

(Aniano et al. 2012)

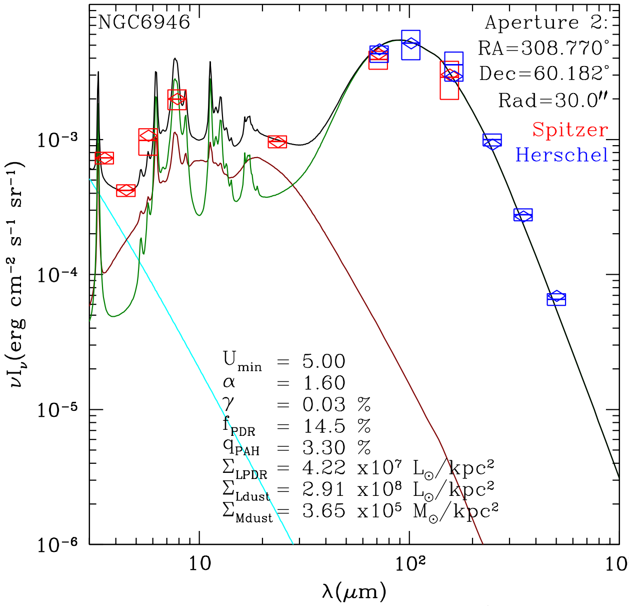


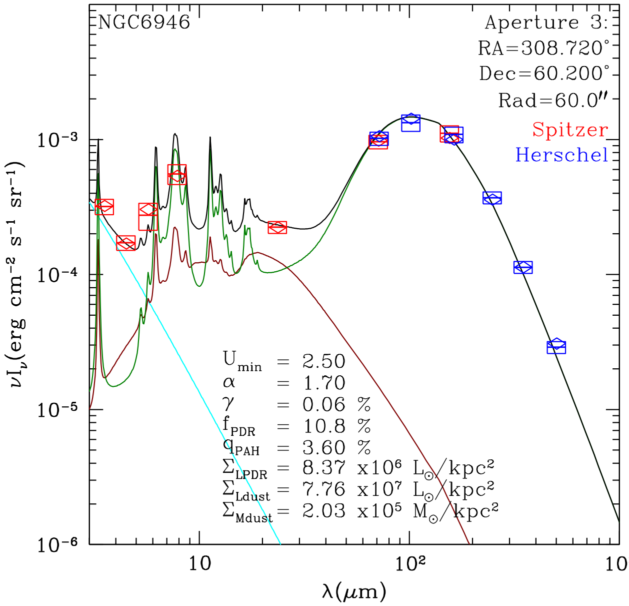


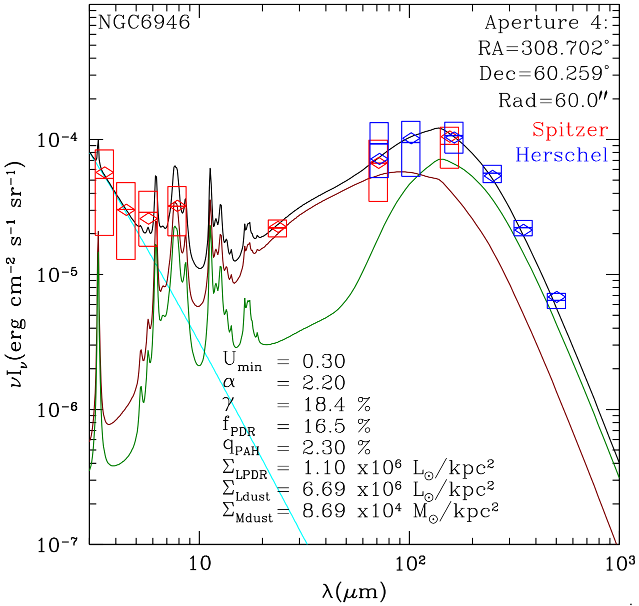
- For each pixel: find best-fit dust model (with $U_{\rm max} = 10^7$ fixed)
  - dust surface density: $\Sigma_{\rm dust}$ **single-pixel detection limit** $\sim 10^{4.75} M_\odot\,{\rm kpc}^{-2}$ **or** $A_V \approx 0.4$.
  - PAH mass fraction: $q_{\rm PAH}$
  - Starlight intensity distribution: $U_{\rm min}$, γ, α
- *Can reproduce observed SED out to 500 μm with NO "cold" dust*

SEDs in Selected Apertures: NGC6946 @ MIPS160 resolution

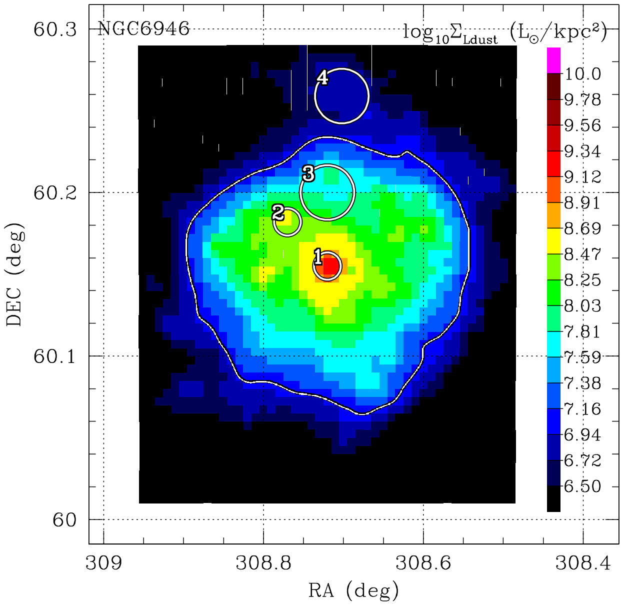
(Aniano et al. 2012)

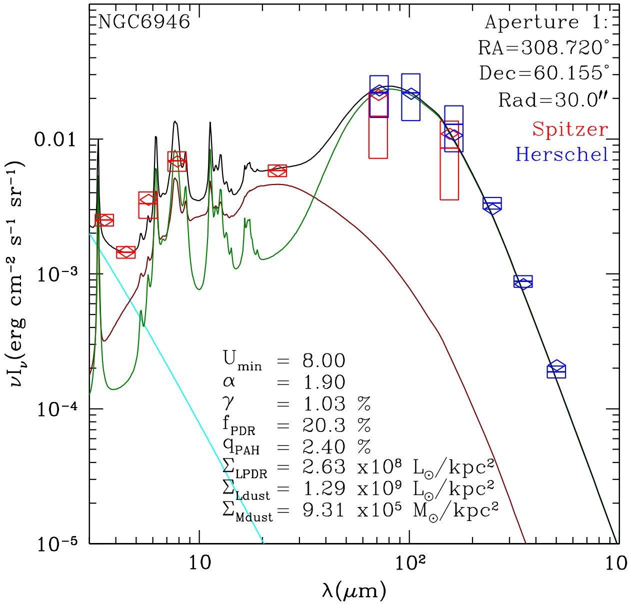


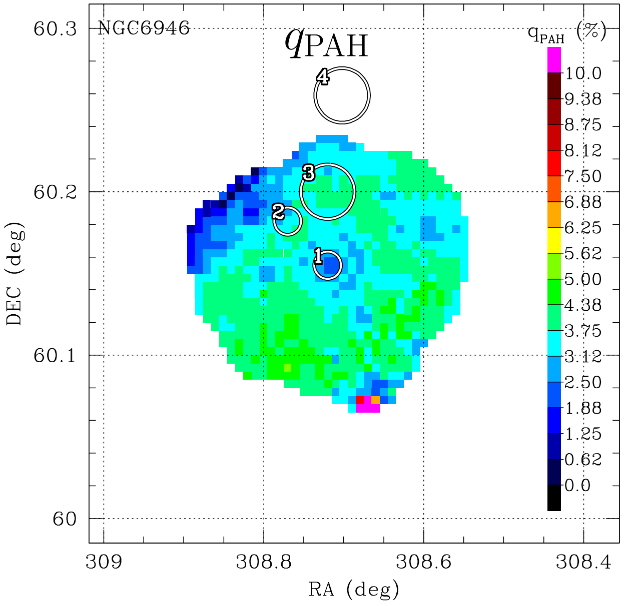




$$\log\left[\Sigma_{L(\mathrm{TIR})}(L_\odot/\mathrm{kpc}^2)\right]$$



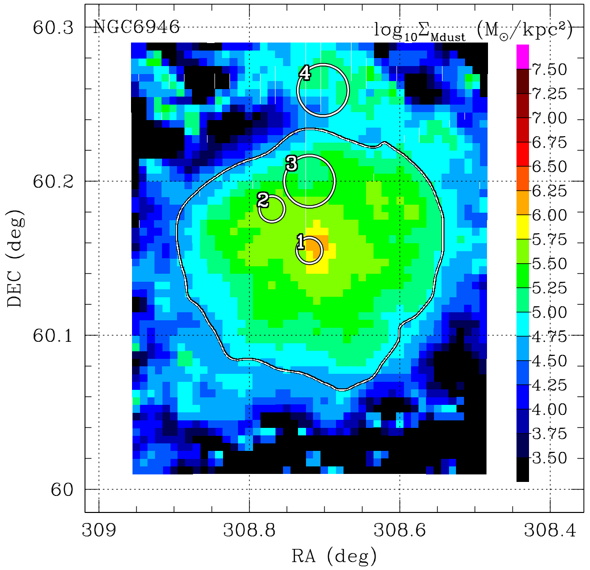




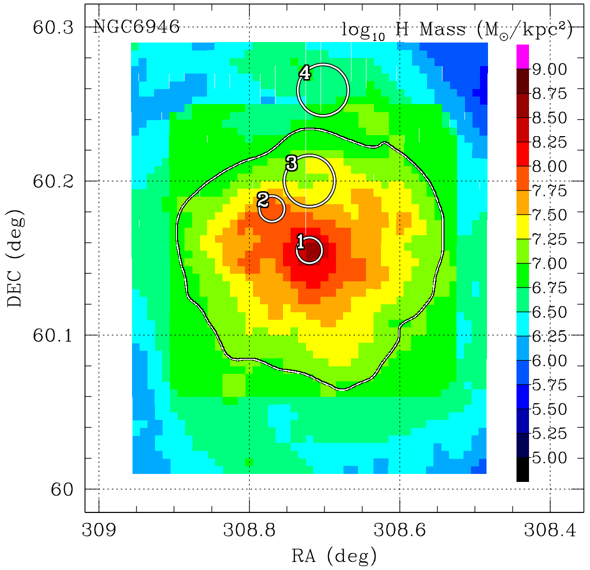
Dust-to-Gas Ratio in NGC 6946 at MIPS 160 resolution

(Aniano et al. 2012)

$\Sigma_{\rm dust}$

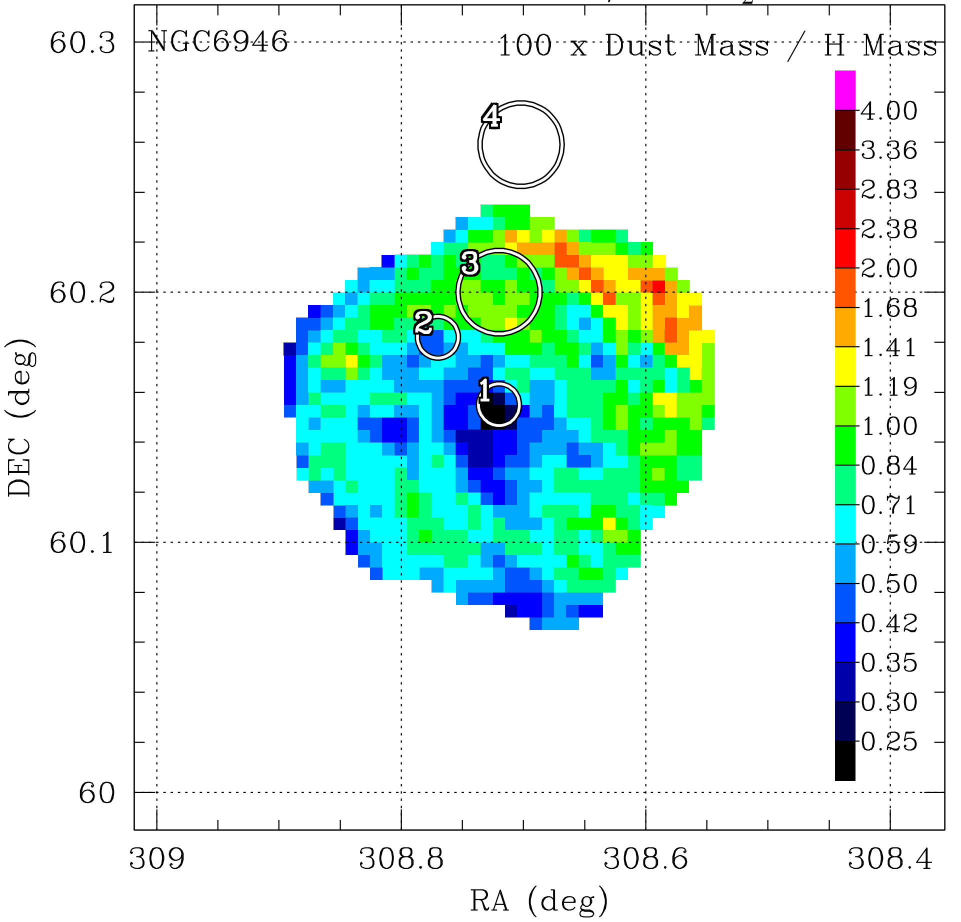


$\Sigma_{\rm H\,I+H_2}$



$$X_{\rm CO} = 4\times10^{20}\,{\rm H_2\,cm^{-2}/(K\,km\,s^{-1})}$$

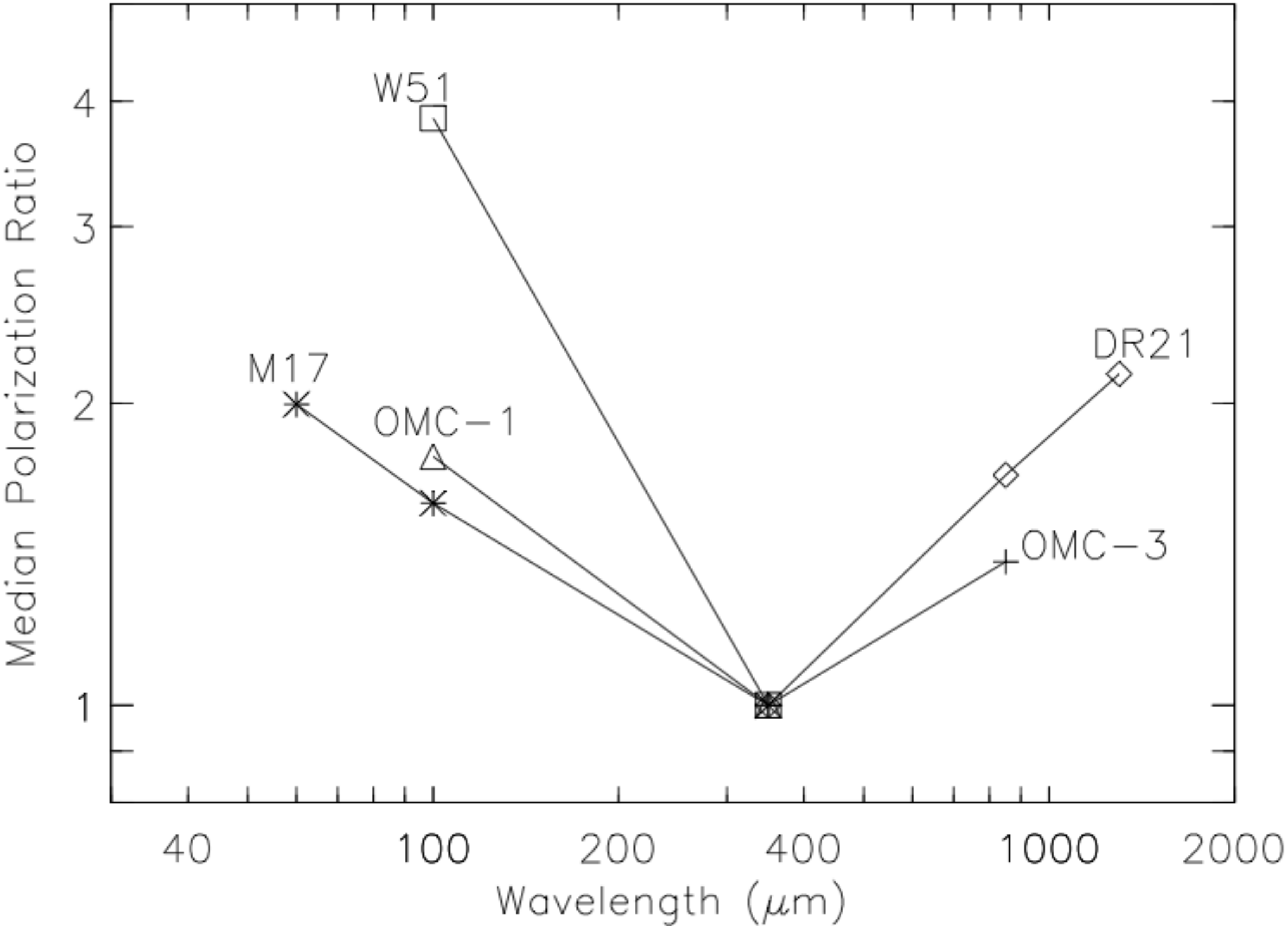
$\Sigma_{\rm dust}/\Sigma_{\rm HI+H_2}$



- Low dust/gas ratio within ~2 kpc of center: indication that $X_{\rm CO}$ **should be lower near center** (Meier & Turner 2004; Donovan Meyer et al. 2012)
- $M_{\rm dust}/M_{\rm H} \approx 0.010 \pm 0.004$ over most of disk
- A few places with high $M_{\rm dust}/M_{\rm H}$ – bad data?

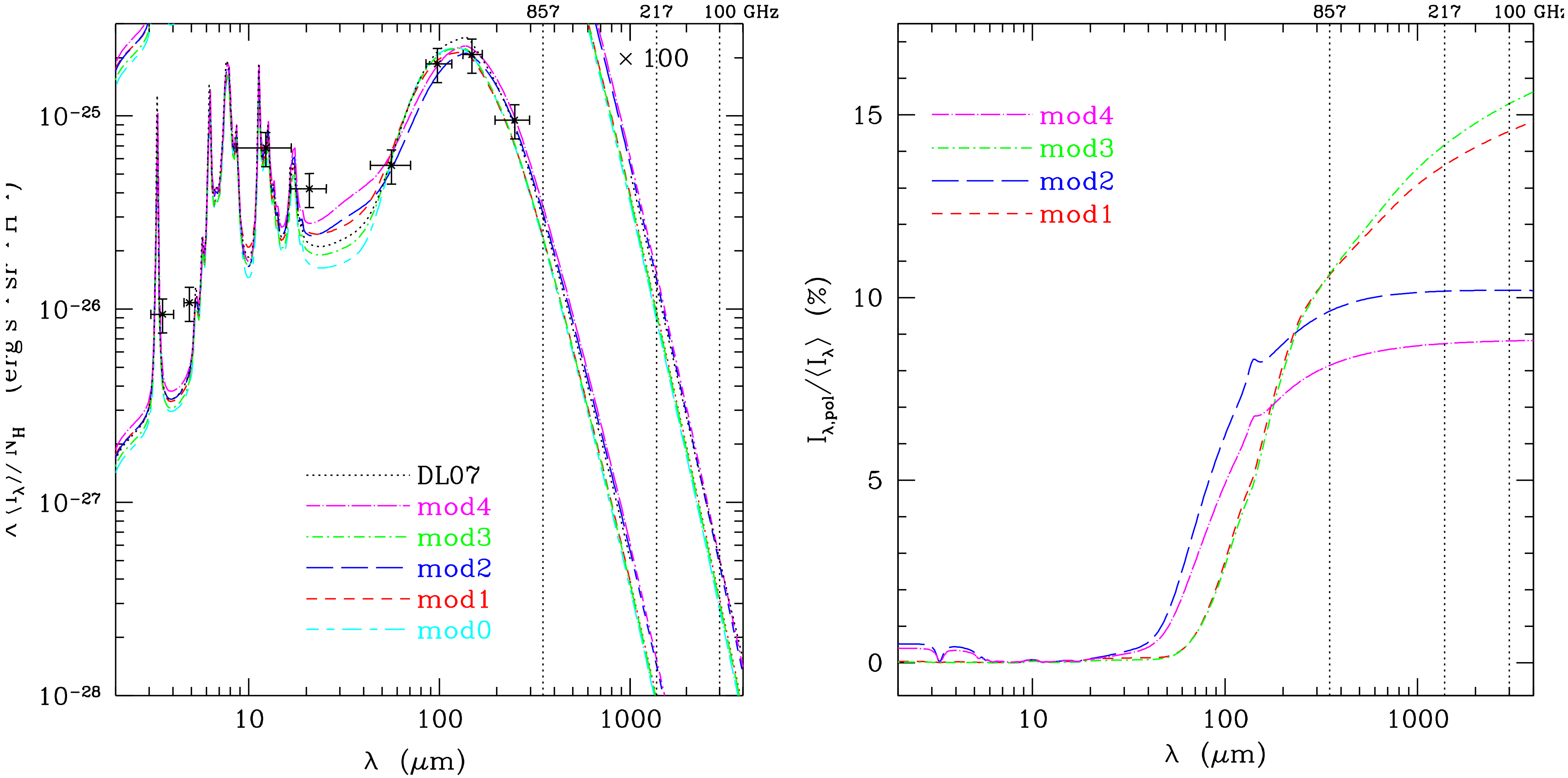
Far-Infrared Polarimetry of Star-Forming Molecular Clouds

Unexpected dependence on λ:



From Vaillancourt (2002)

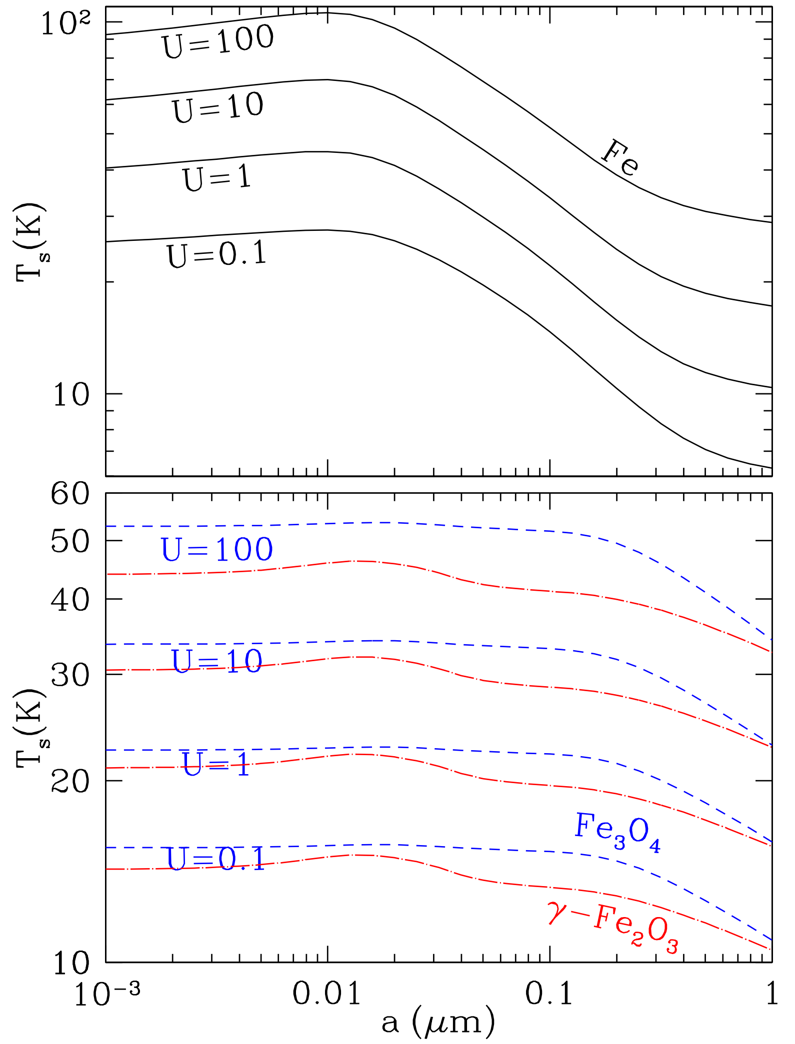
Predicted Polarization for the DL07 Model



from Draine & Fraisse (2009)

- mod1 and mod3: only silicate grains are aligned
- mod2 and mod4: both silicate and graphite grains are aligned

Temperatures of Fe Grains Heated by Starlight



from Draine & Hensley (2012a)

- Fe nanoparticles $a \lesssim 0.03\,\mu\mathrm{m}$ are heated to $\sim 40\,\mathrm{K}$ in regions where "normal" grains would have $T \approx 20\,\mathrm{K}$.
- If present as inclusions, will have same temperature as host.