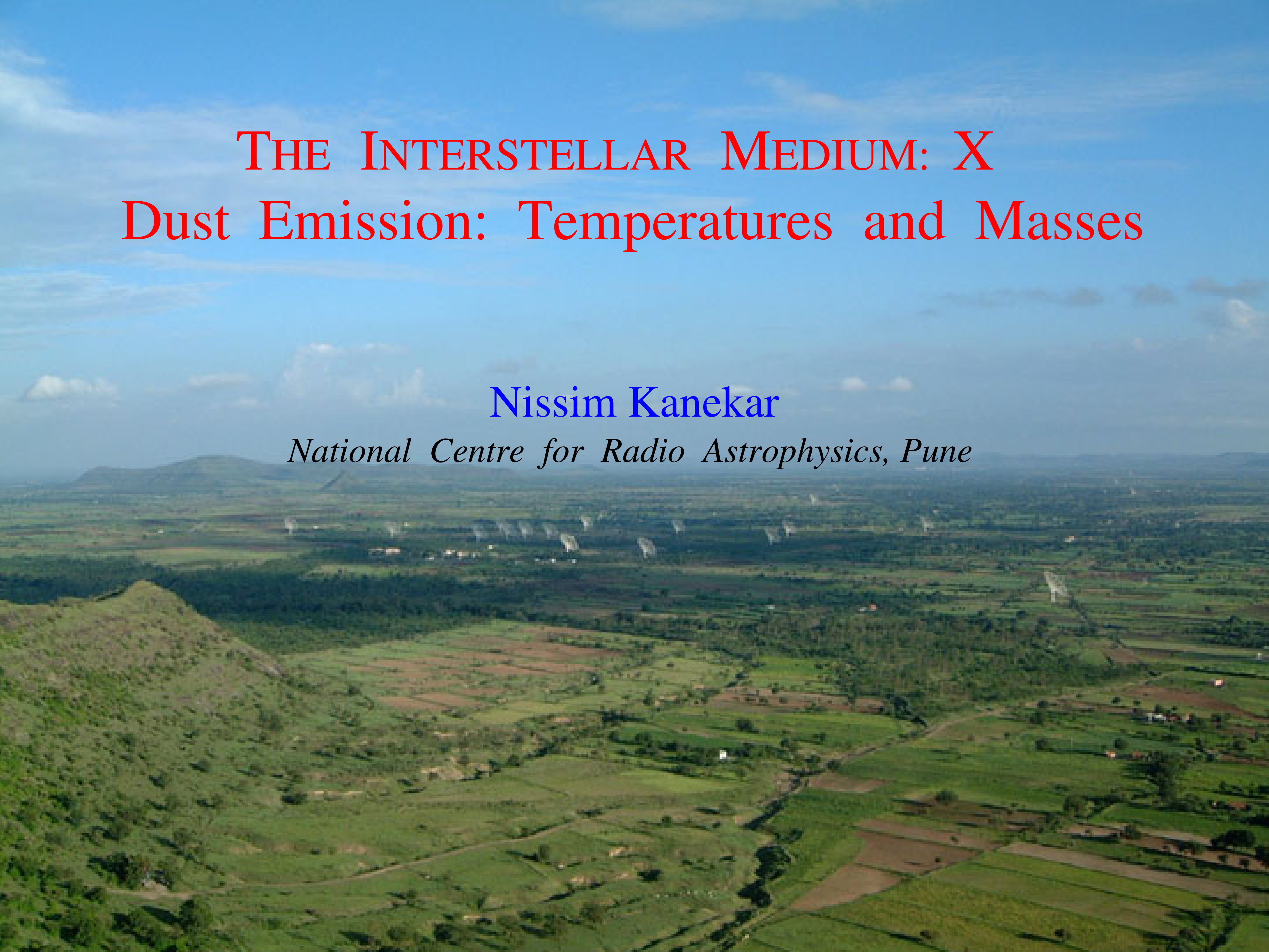
THE INTERSTELLAR MEDIUM: X
Dust Emission: Temperatures and Masses



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OUTLINE

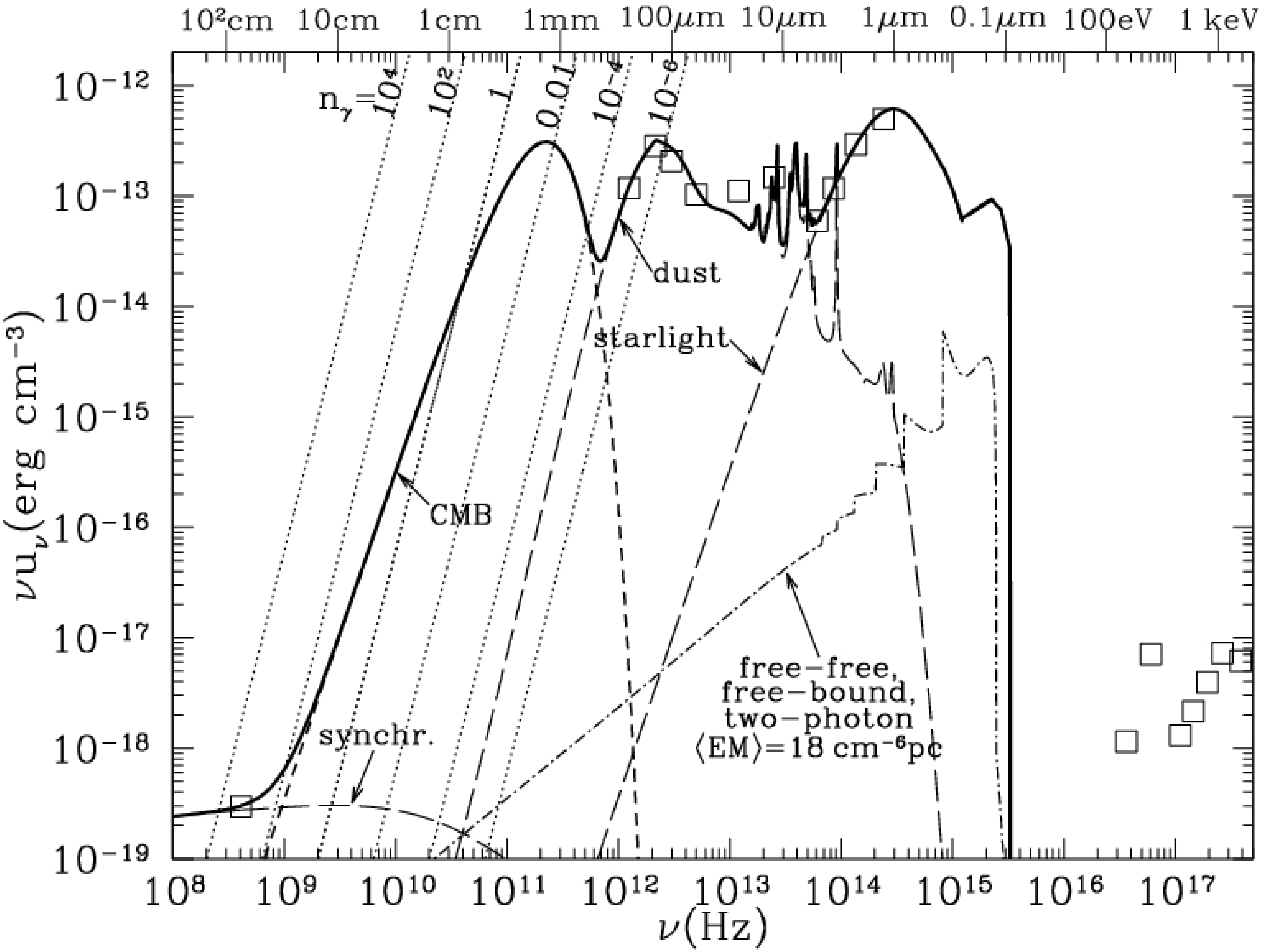
- Background.
- The interstellar radiation field.
- Heating and cooling of dust grains.
- The dust emission spectrum.
- Inferring the dust temperature and the dust mass.

BACKGROUND

- Depletion: {C, O, Mg, Fe, Si, Al} major constituents of dust.
- Dust/H mass ratio ~ 0.01: 28% in C, 72% in {O, Mg, Fe, Si}.
- 2175 Å bump: sp_2-bonded graphite grains or PAHs.
  Strong in Milky Way, absent in SMC: Different kinds of dust ?
- Other features: 9.7 μm Si–O stretch & 18 μm O–Si–O bend modes; 3.4 μm C–H stretch mode, 3.1 μm O–H stretch mode in H_20 ice.
- Strong PAH vibrational modes at 3.3, 6.2, 7.7, 8.6, 11.3, 12.7 μm.
- Constituents: graphite, silicates, PAHs, oxides, silicon carbide, Fe...
  Use size distributions to match to extinction/emission curves.
- MRN model: Good near-IR – UV fit. Size distribution, $dn/da \propto a^{-3.5}$.
- Modern models: Add PAHs. Good match to extinction curves, but problems with depletion: Over-consumption of Si and C!

THE INTERSTELLAR RADIATION FIELD (ISRF)

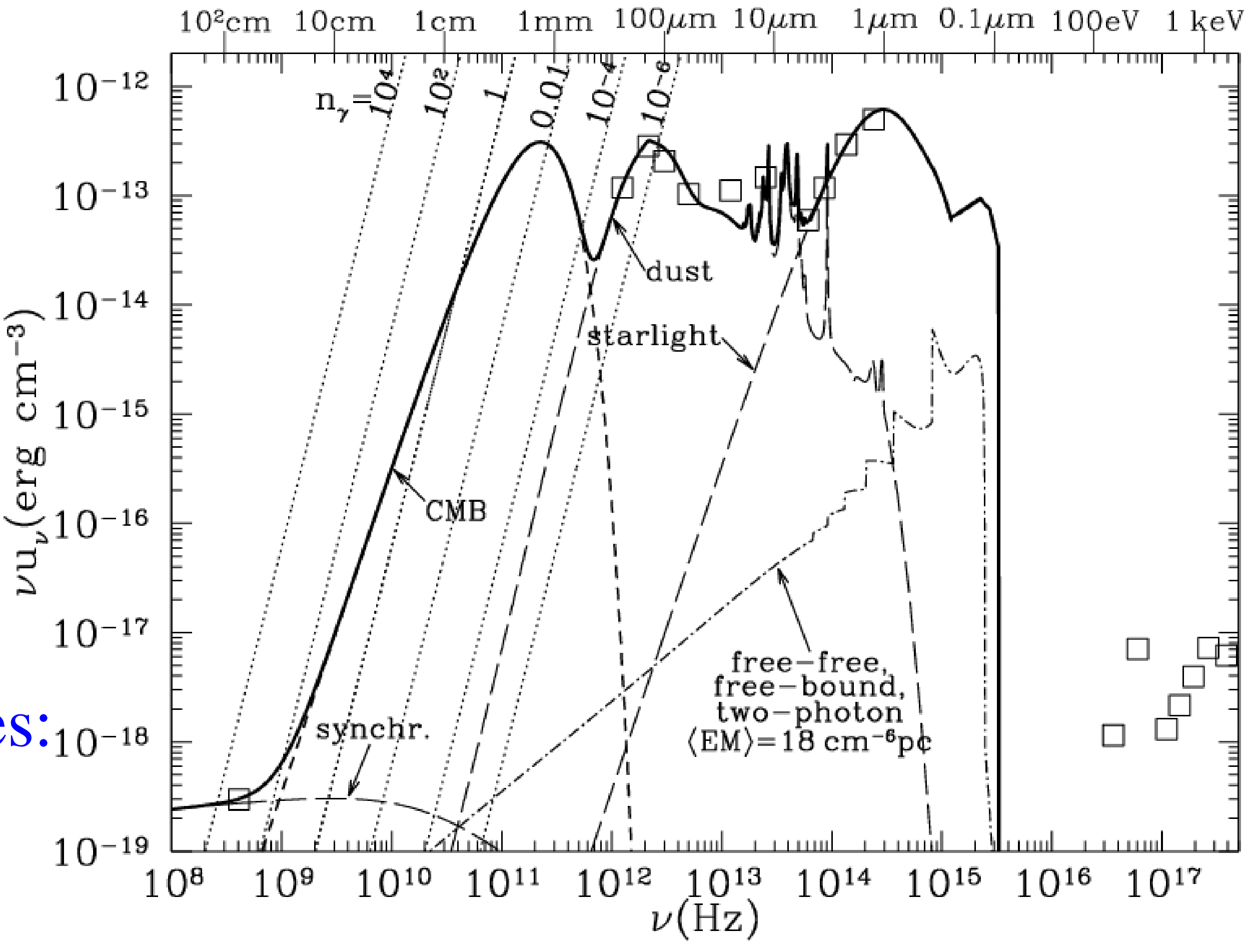
(Draine 2011)



THE INTERSTELLAR RADIATION FIELD

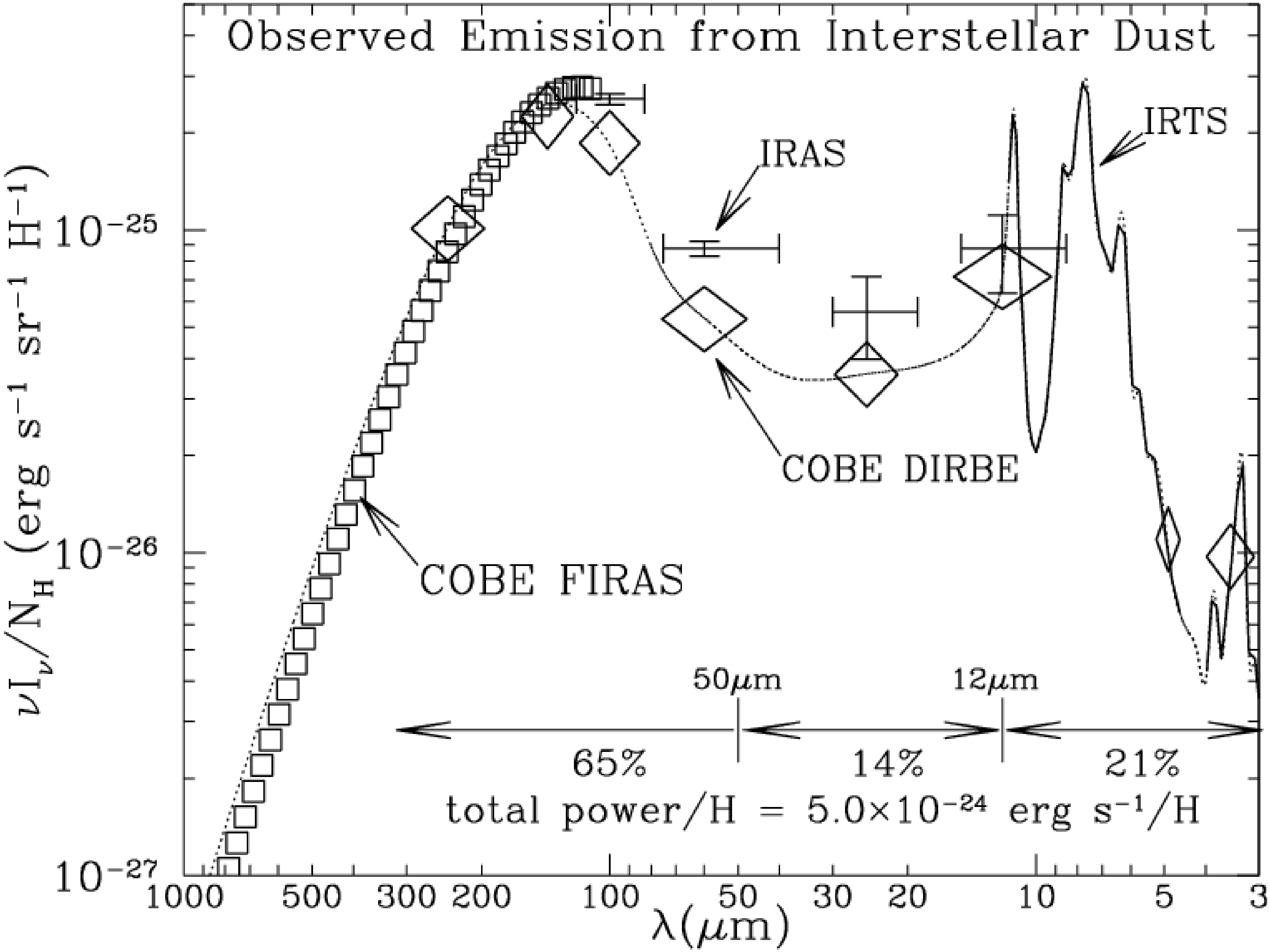
(Draine 2011)

- Starlight: UV – Optical.
- CMB: 1 mm – 1 cm.
- Synchrotron: < 1 GHz.
- Hot plasma: > 0.5 keV.
- Free-free emission + Hα + other recombination lines: Near-IR - Optical (mostly from HII regions).



- Dust: (1) Mid-IR: PAH emission bands, 3 – 12 μm.
  (2) Far-IR : Thermal emission, 50 – 500 μm.
  (3) Microwave, ~ 20 GHz: Emission from spinning dust.

OBSERVED DUST EMISSION



(Draine 2011)

HEATING OF DUST

- Radiative heating important in the diffuse ISM, collisional heating in dark clouds (no UV field).

- Absorption of a photon excites electron to higher states. Non-radiative de-excitation: Energy moves to vibrational modes.

- Heating dominated by the ISRF at UV/optical wavelengths:

$$(dE/dt)_{abs} = \int u_\nu \, (d\nu / h\nu) \times c \times h\nu \times Q_a(\nu) \times \pi a^2.$$

$$= \langle Q_a \rangle_\star \times \pi a^2 \times c \, u_\star$$

where $Q_a(\nu) \equiv$ The absorption efficiency,

$\langle Q_a \rangle_\star \equiv \int d\nu \, u_{\nu,\star} Q_a(\nu) \; / \int d\nu \; u_{\nu,\star}$ (Average Q_a).

and $u_\star \equiv \int d\nu \, u_{\nu,\star}$ (The starlight energy density).

- Need spectrum-averaged absorption efficiency, $\langle Q_a \rangle_\star$, at UV and optical wavelengths.

COOLING OF DUST

- Radiative cooling via IR thermal and vibrational band emission.

- Rate of energy loss due to radiative cooling:

$$(dE/dt)_{em} = \int d\nu\, 4\pi \times B_\nu(T) \times \pi a^2 \times Q_a(\nu) \;.$$

$$= \langle Q_a \rangle_T \times 4\pi a^2 \times \sigma T^4$$

where $Q_a(\nu) \equiv$ The emission efficiency,

and $\langle Q_a \rangle_T \equiv \int d\nu\, B_\nu(T)\, Q_a(\nu) \;/\; \int d\nu\, B_\nu(T)$ (Average Q_a).

- Need spectrum-averaged emission efficiency, $\langle Q_a \rangle_T$, in the IR.

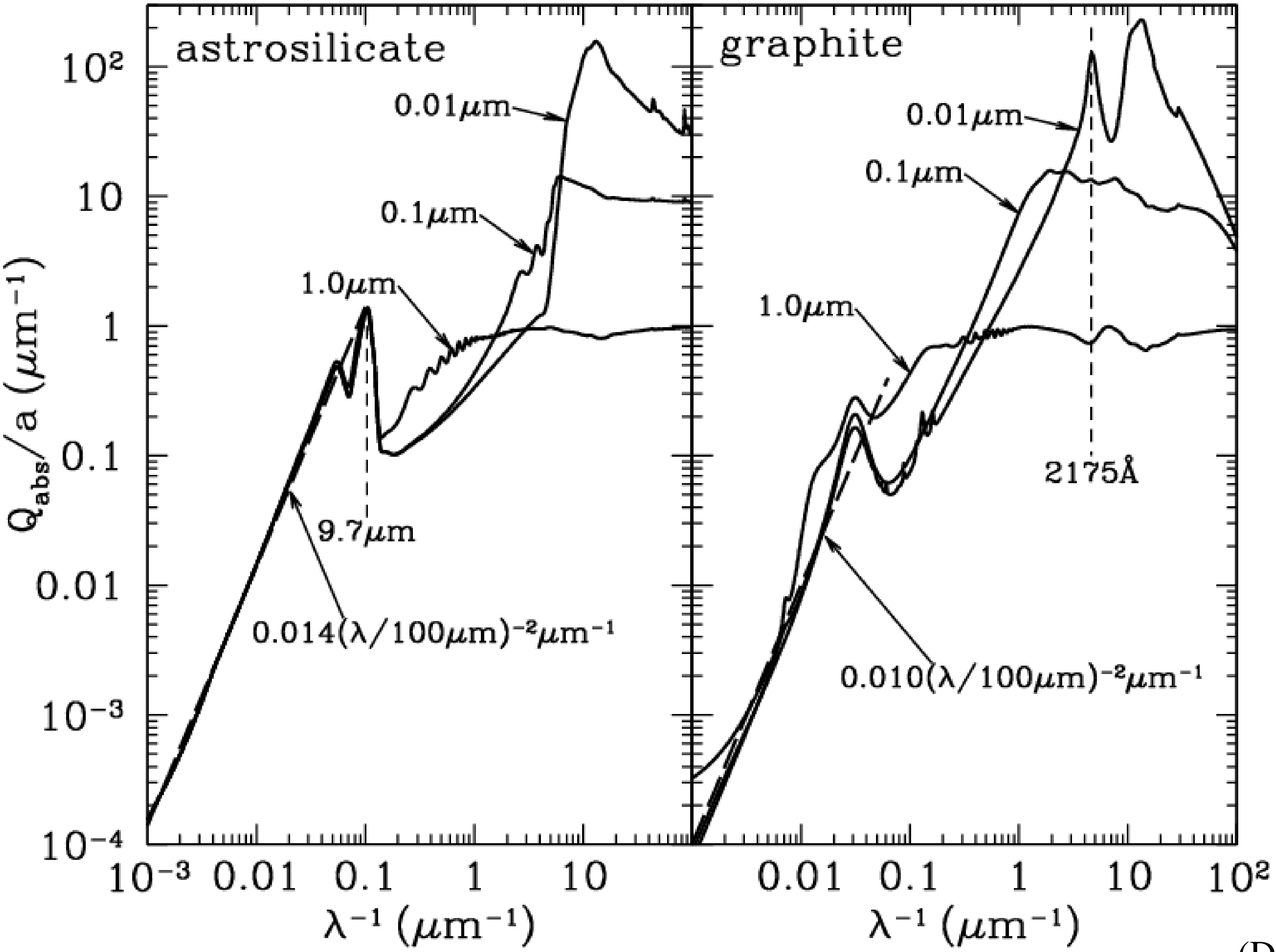
- For both heating and cooling, need the absorption efficiency as a function of frequency for the various types of grains!
  Mie scattering, different shapes, Monte Carlo simulations! Tough...

(e.g. Draine & Li 2001)

- Power-law behaviour in the IR: $Q_a(\lambda) = Q_0\, (\lambda/\lambda_0)^{-\beta}$, with $\beta \approx 2$.

COOLING OF DUST

- Power-law for $\lambda \geq 20\ \mu\text{m}$: $Q_a(\lambda) = Q_0\,(\lambda/\lambda_0)^{-\beta}$, with $\beta \approx -2$.



(Draine 2011)

THERMAL BALANCE

- In thermal balance, heating rate = cooling rate.

⇨ $\langle Q_a \rangle_\star \times \pi a^2 \times c\, u_\star = \langle Q_a \rangle_T \times 4\pi a^2 \times \sigma T^4$

⇨ $T_D = [\, \langle Q_a \rangle_\star \times (c/4\pi) \times u_\star / \langle Q_a \rangle_T \,]^{1/4}$

- For the ISRF spectrum and using Q_a for graphites and silicates:

$T_D = 16.4\, (a/0.1\mu m)^{-1/15}\, U^{1/6}$ K : Silicates, $0.01\ \mu m \leqslant a \leqslant 1\ \mu m$.

$T_D = 22.3\, (a/0.1\mu m)^{-1/40}\, U^{1/6}$ K : Graphite, $0.005\ \mu m \leqslant a \leqslant 0.15\ \mu m$.

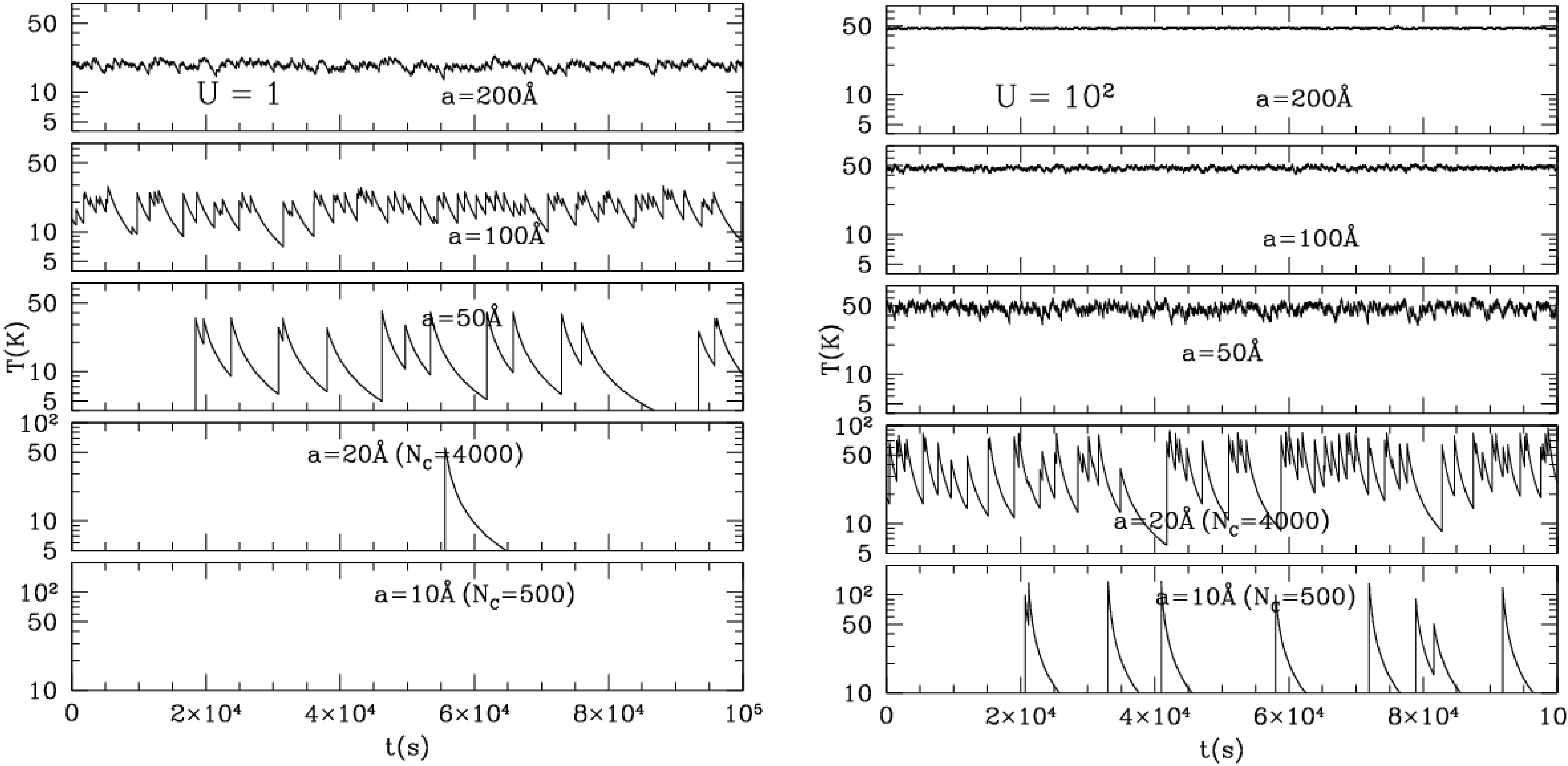
⇨ Dust temperatures of ~ 20 K for the ISRF!

- Serious caveat to the above: *Small grains*, with very large rise in the dust temperature, followed by rapid cooling to a *few* K:

⇨ Never achieve equilibrium with the radiation field!
Require non-equilibrium methods, with a temperature probability distribution function.

GRAIN SIZE AND TEMPERATURE

(Draine 2011)

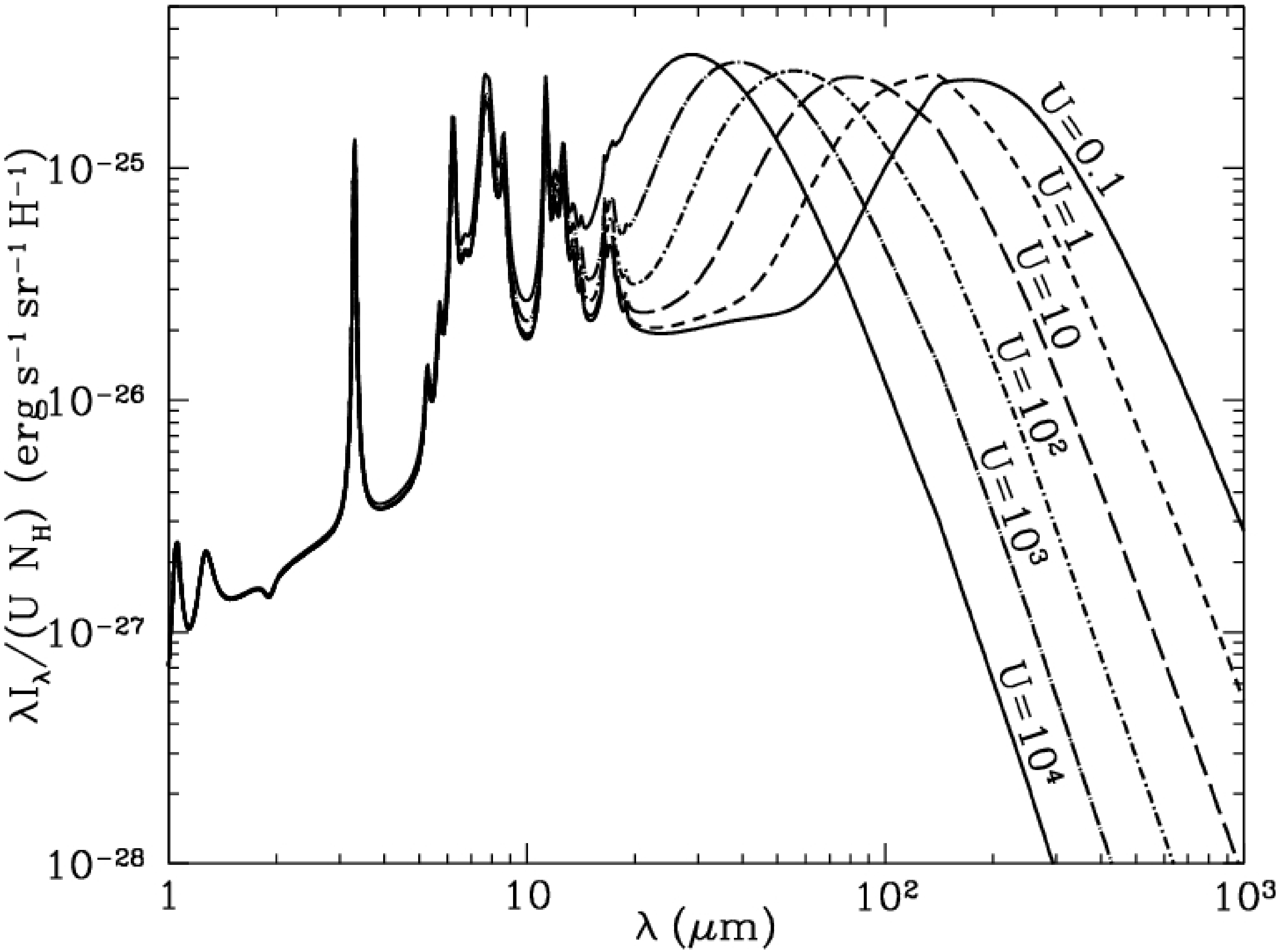


- Small grains: Low vibrational energy ⇨ Rare single photon absorptions cause large temperature rise, followed by rapid fall.
- Large temperature range and *hotter* (mid-IR) radiation!
- Strong emission at $1-4$ μm from reflection nebulae.

(Sellgren et al. 2011)

THE INTERSTELLAR RADIATION FIELD

(Draine 2011)

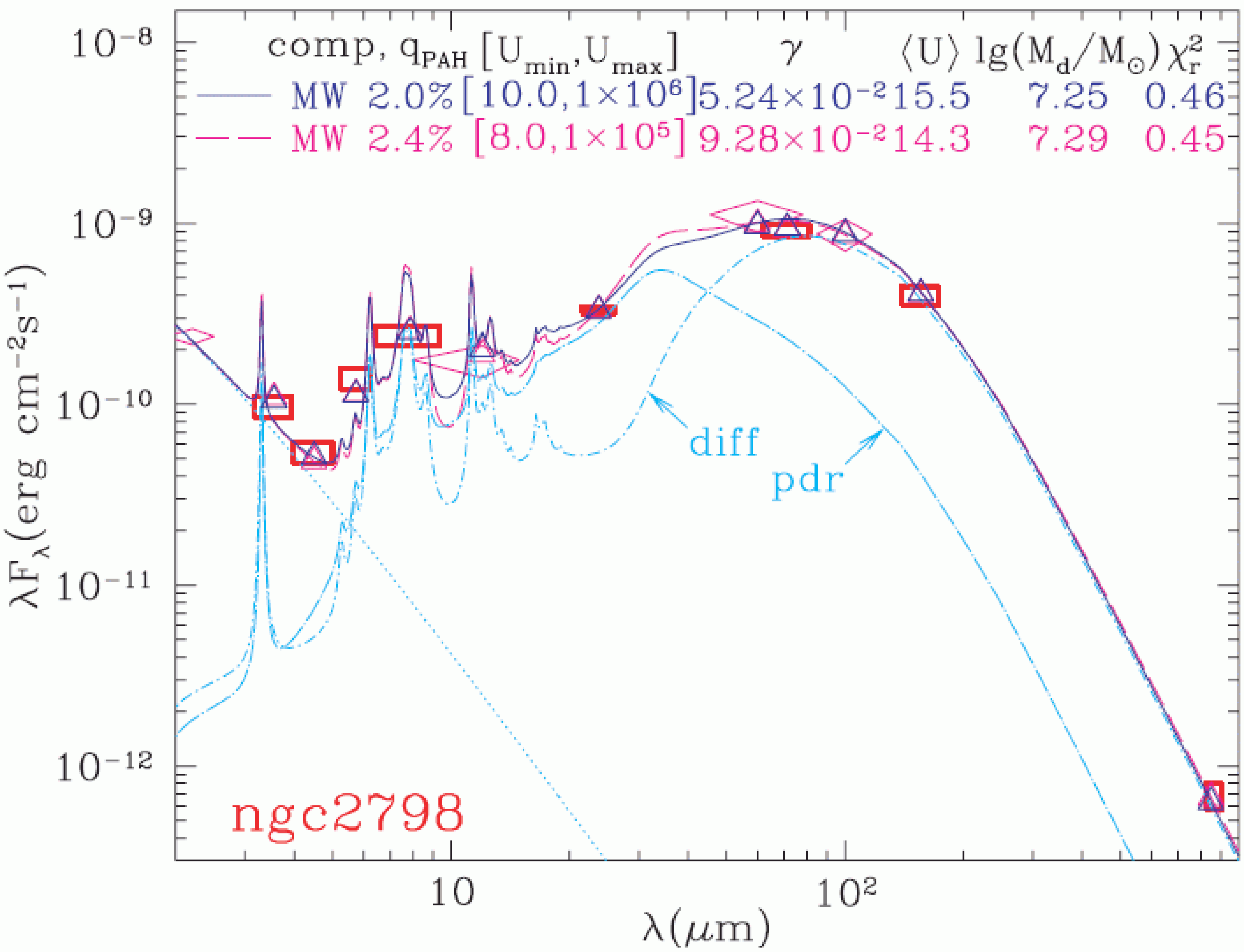


- Far-IR thermal peak at *shorter* wavelengths for stronger ISRF!
- Stronger radiation field ⇨ Higher dust temperatures! But not much change in the strengths of the PAH features.

EXTERNAL GALAXIES: EXPENSIVE APPROACH

- Multi-parameter fits, allowing for variations in dust composition, PAH fraction, size/temperature distribution, ISRF, diffuse/PDR type.

(e.g. Draine et al. 2007;
Dale et al. 2012)



(Draine et al. 2007)

- Requires exquisite sampling of the IR spectral energy distribution!

EXTERNAL GALAXIES: CHEAP APPROACH

- Cheaper approach *if* high-quality sub-mm data are available: "Modified black-body fits", assuming single dust temperature.

(e.g. Davis et al. 2012)

- Power emitted per unit frequency:

$$P_\nu = 4\pi B_\nu(T) \times \pi a^2 \times Q_{abs}(\nu) = 4\pi B_\nu(T) \times C_{abs}(\nu)$$

$$\Rightarrow \text{Flux density, } F_\nu = (P_\nu/4\pi D^2) = (M_D/D^2) \times B_\nu(T) \times \kappa_{abs}(\nu)$$

where $\kappa_{abs}(\nu)$ is the grain absorption cross-section per unit mass.

- *Assume* $\kappa_{abs}(\lambda) = \kappa_0\,(\lambda/\lambda_0)^{-\beta}$, with $\beta \approx 2$ & κ_0 from a dust model.

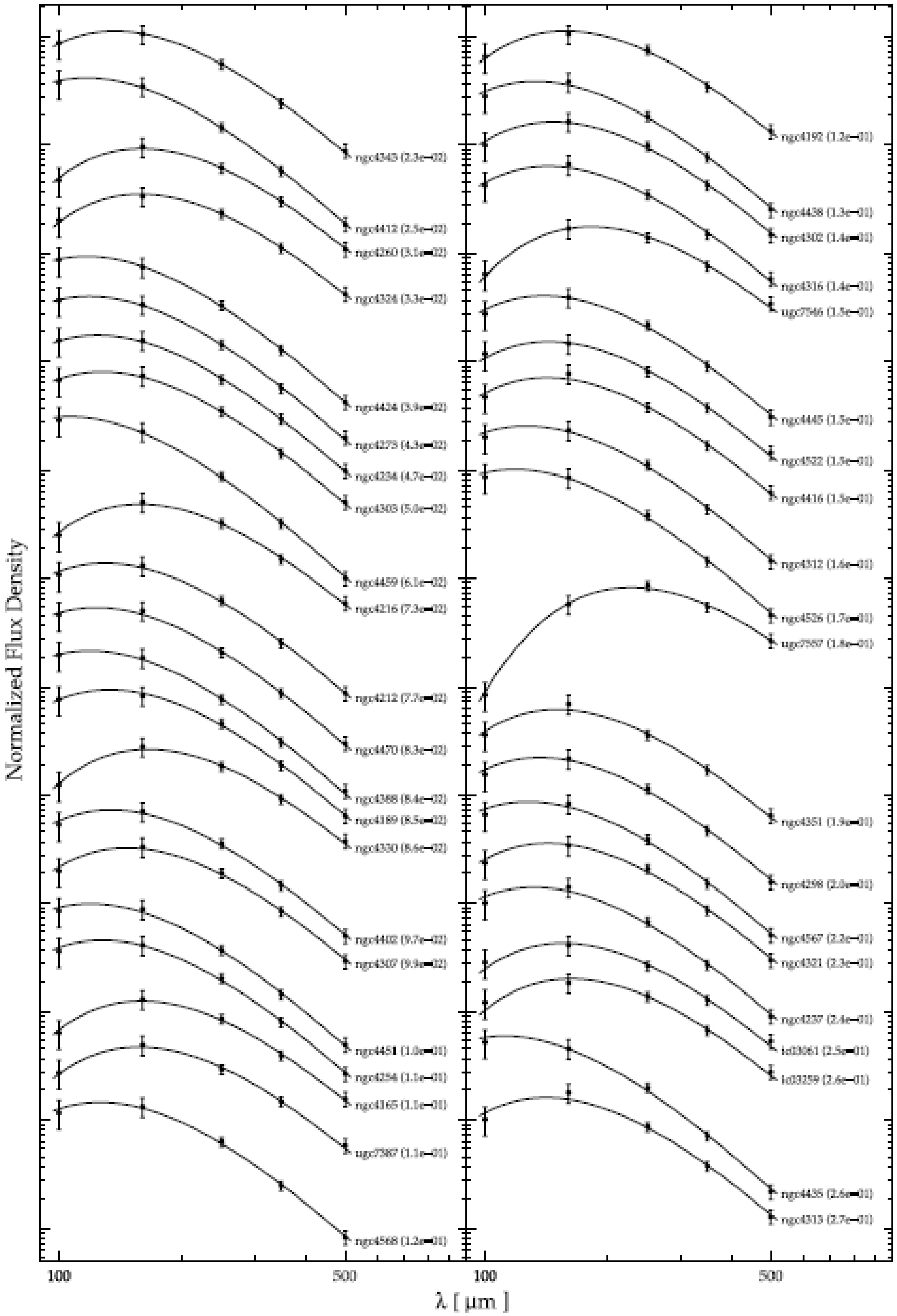
- Fit sub-mm ($> 100\ \mu$m) data for dust mass and "temperature" !

- Results for dust mass within 20% of results from general fit!

(e.g. Bianchi 2013; but see Dale et al. 2012)

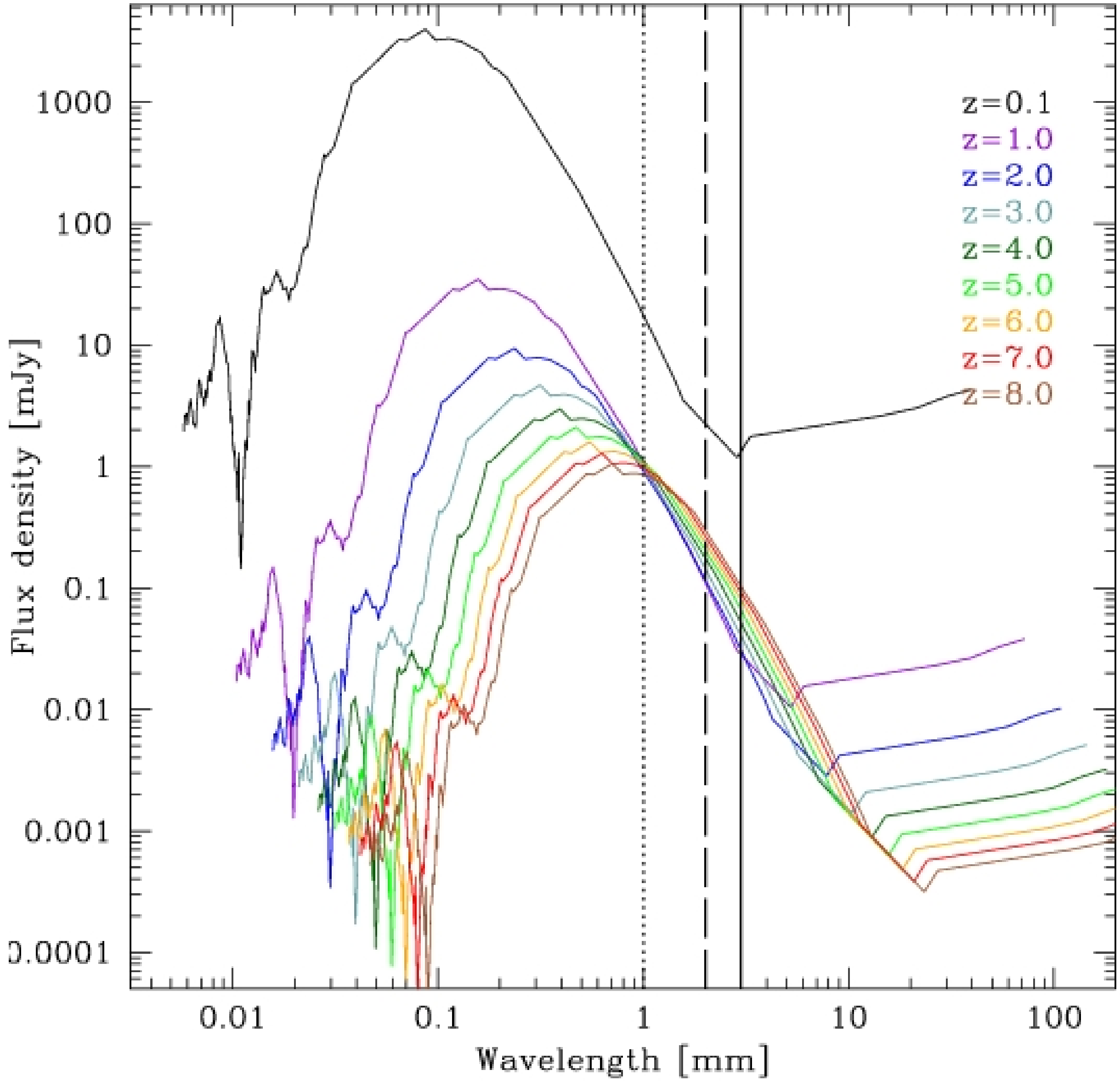
- Often applied to high-redshift galaxies, taking advantage of the negative k-correction in the dust spectrum!

EXTERNAL GALAXIES: CHEAP APPROACH



(Davis et al. 2012)

THE NEGATIVE K-CORRECTION AT HIGH REDSHIFTS



(From Robert Decarli)

- Negative K-correction: As easy to detect a galaxy at 1 – 3 mm at $z \sim 8$ as at $z \sim 1$!