

Toward a Quantitative Understanding of Mid-IR Emission from Galaxies

Bojan Nikolic

Paul Alexander, Marcel Clemens, Malcolm Longair, Dominic Ford and Garret Cotter

`bnikolic@nrao.edu`

NRAO - Charlottesville and Green Bank

Scope

Using mid-IR observations to learn about:

- Energetics of galaxies (star formation / SMBH accretion)
- The conditions in the interstellar medium in active galaxies
- Astrophysics of dust

Outline

- Introduction
- Modelling mid-IR emission from galaxies
- Application of the models to a statistical sample
- Two case studies:
 - Moderate starburst NGC 520
 - Intense starburst Arp 220
- Conclusions

Intro

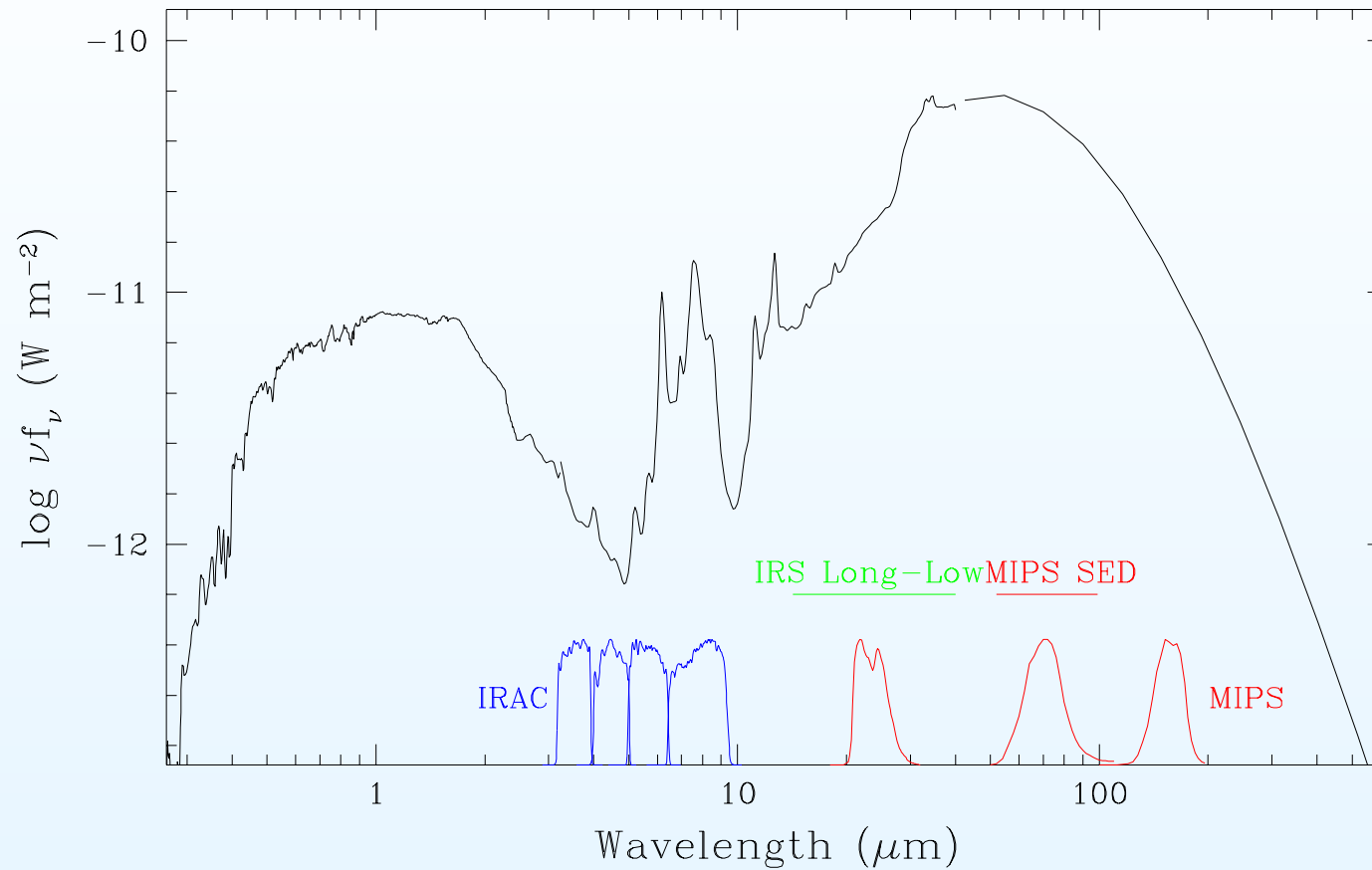


Figure: Composite spectrum of M82, [Kennicutt et al.(2003)]

- Mid-IR: 3 μm –30 μm

Why Mid-IR?

Mid-IR compared to other tracers of star-formation: UV-light, H-recombination lines, far-IR, sub-mm, radio continuum

Advantages

- More information
- Less extinction than optical/near-IR
- High resolution
- Large format detectors

Disadvantages

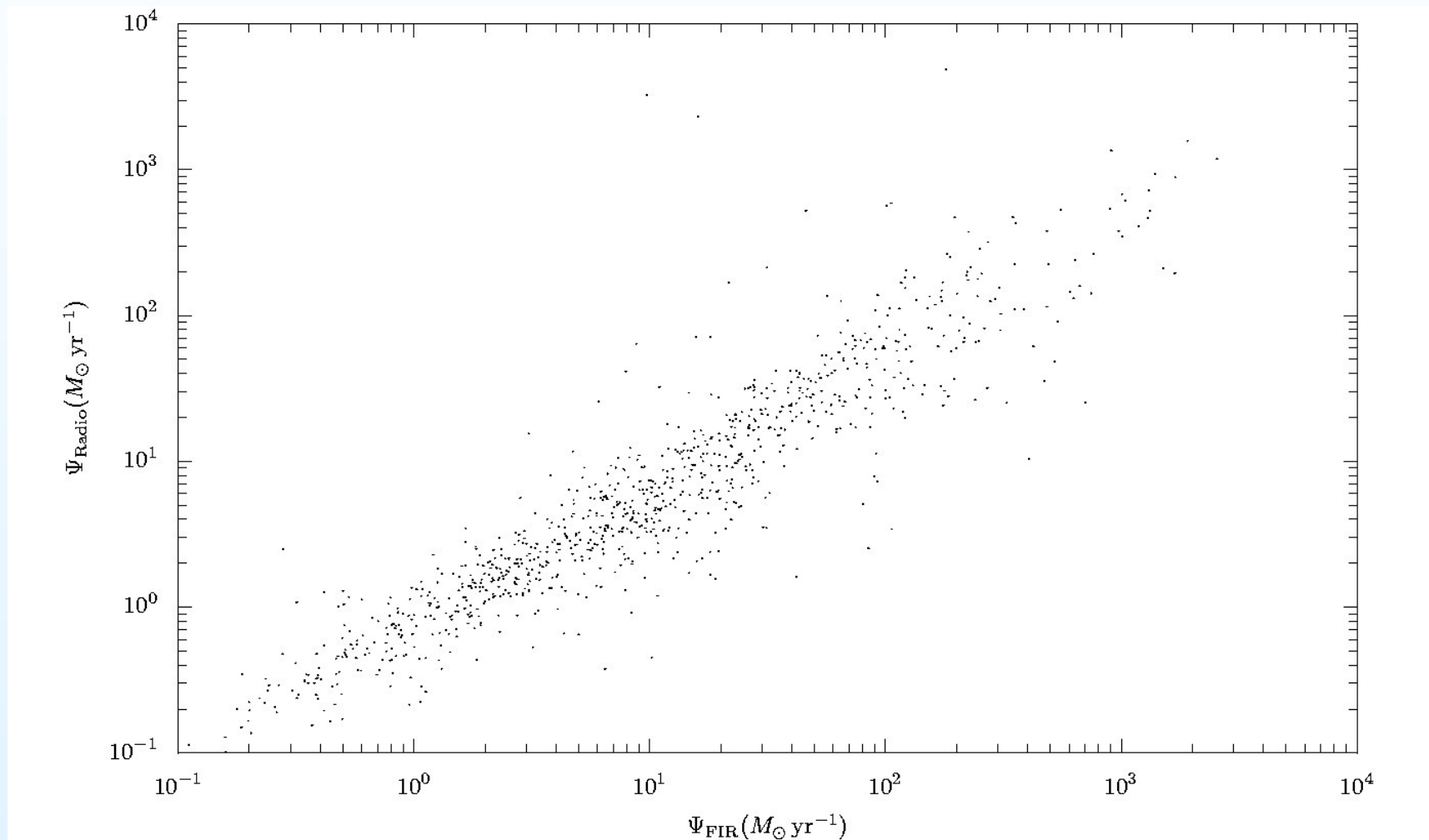
- More extinction than far-IR/sub-mm
- Most power comes out in far- not mid-IR
- More complex physics

Physics of far and mid IR emission

- Far-IR: treat as an bolometric measure of energy release in galaxy.

Physics of far and mid IR emission

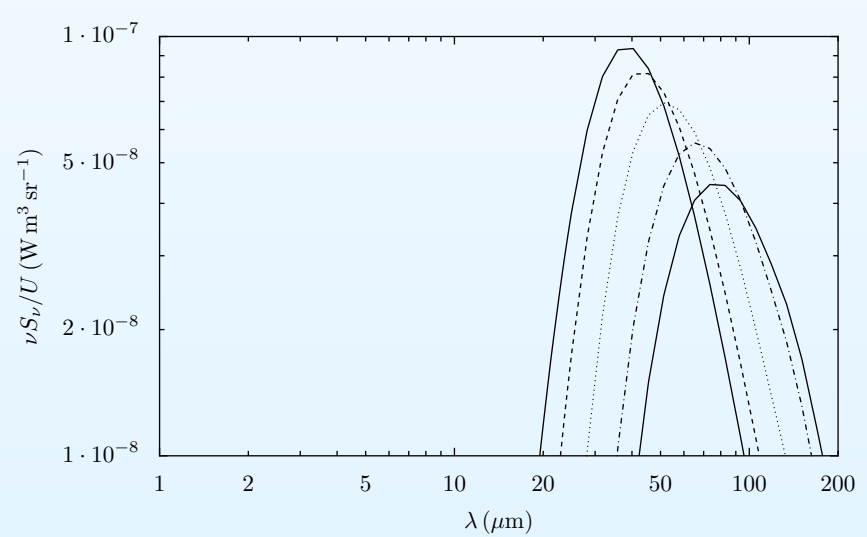
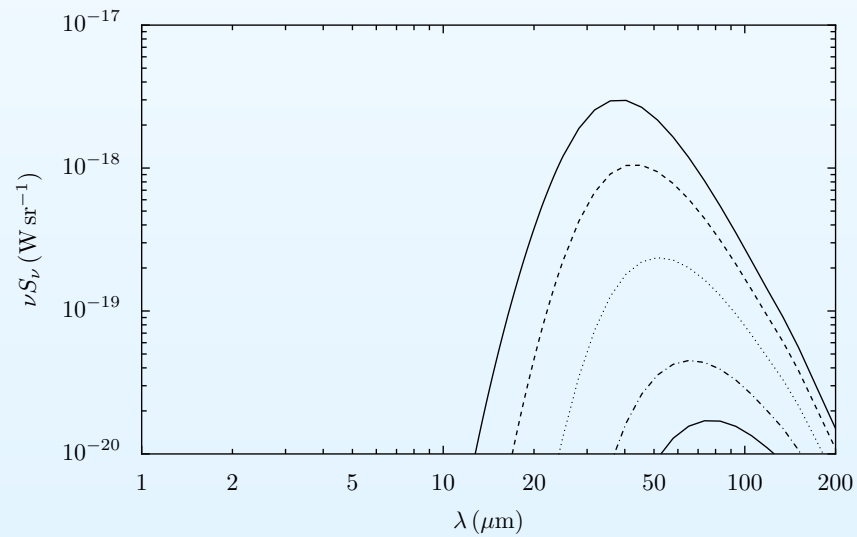
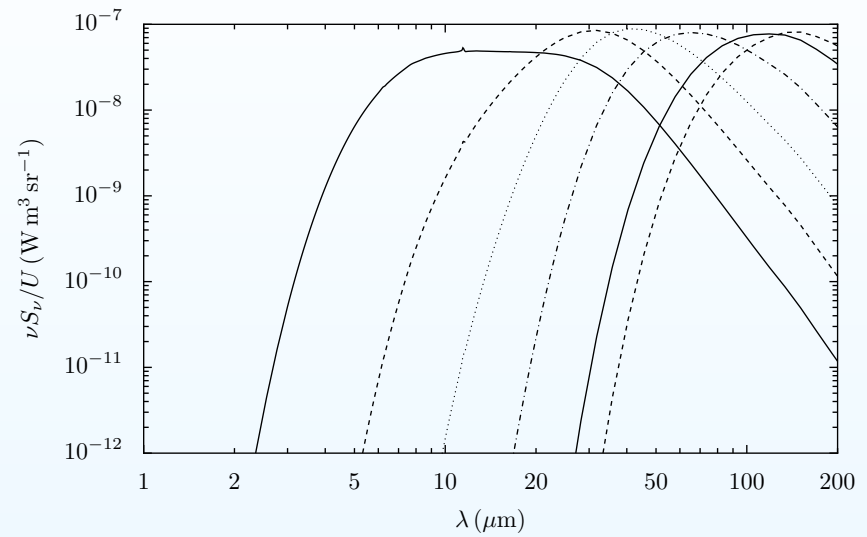
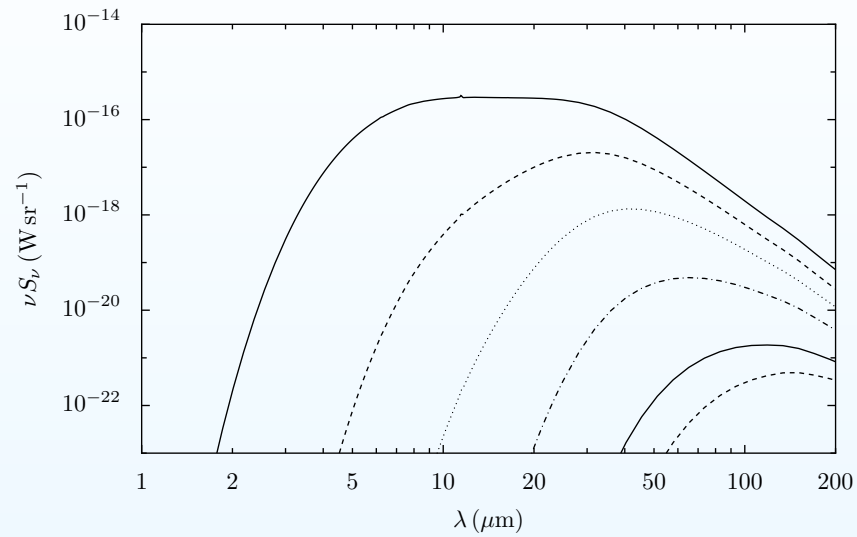
- Far-IR: treat as an bolometric measure of energy release in galaxy.



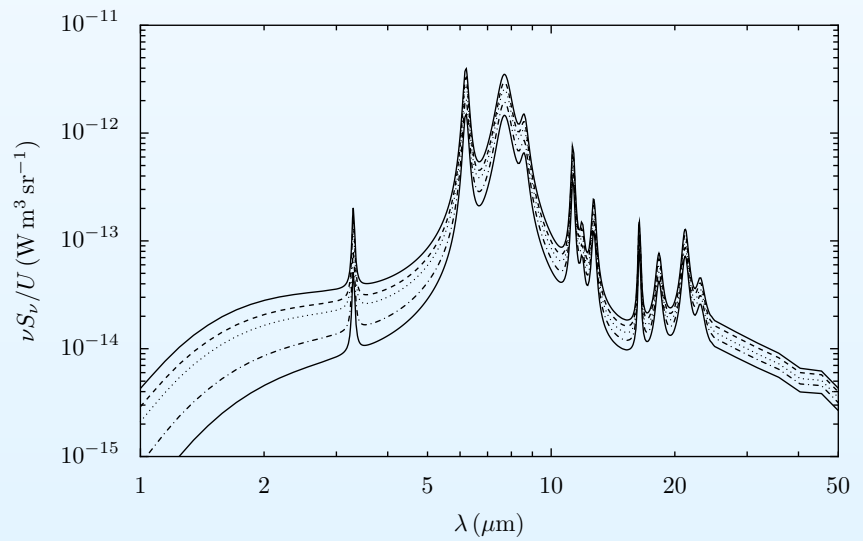
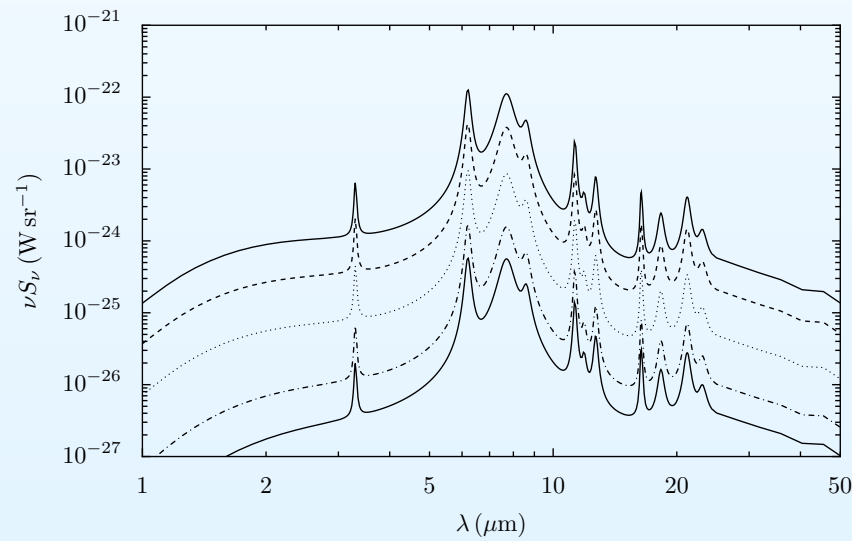
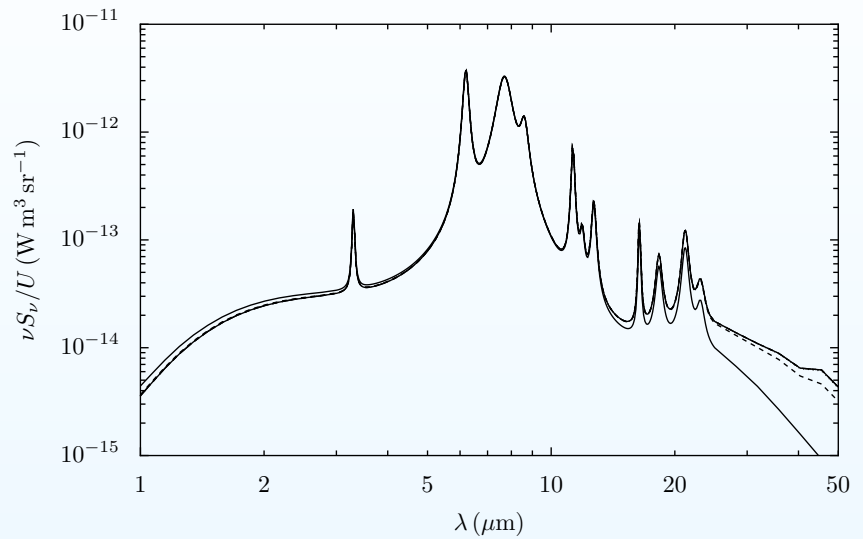
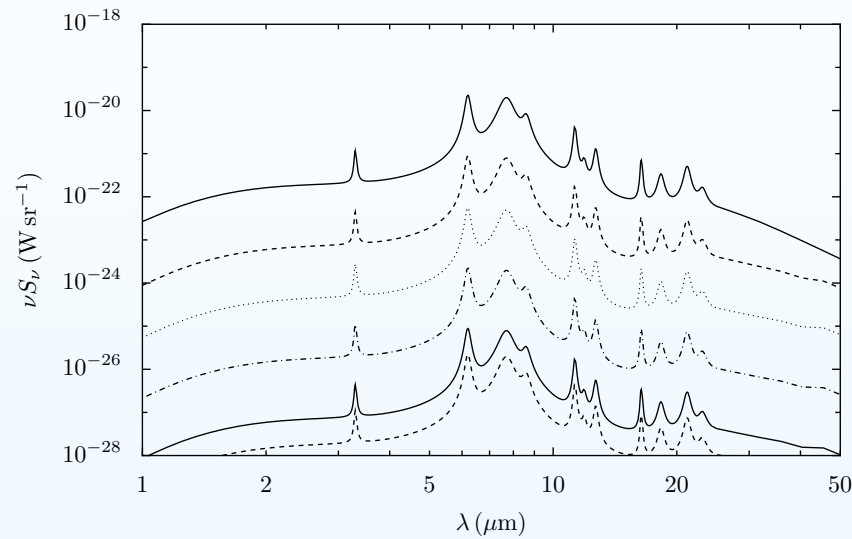
Physics of far and mid IR emission

- Far-IR: treat as an bolometric measure of energy release in galaxy.
- Shape of the far-IR spectrum constrains the relative geometry of dust and heating sources.
- Mid-IR: dominated by very small transiently heated grains (including PAHs).
 - For purely transiently heated grains, emission determined purely by the properties of the grain and hardness of the heating spectrum.

Example: a grain in equilibrium (200 Å)

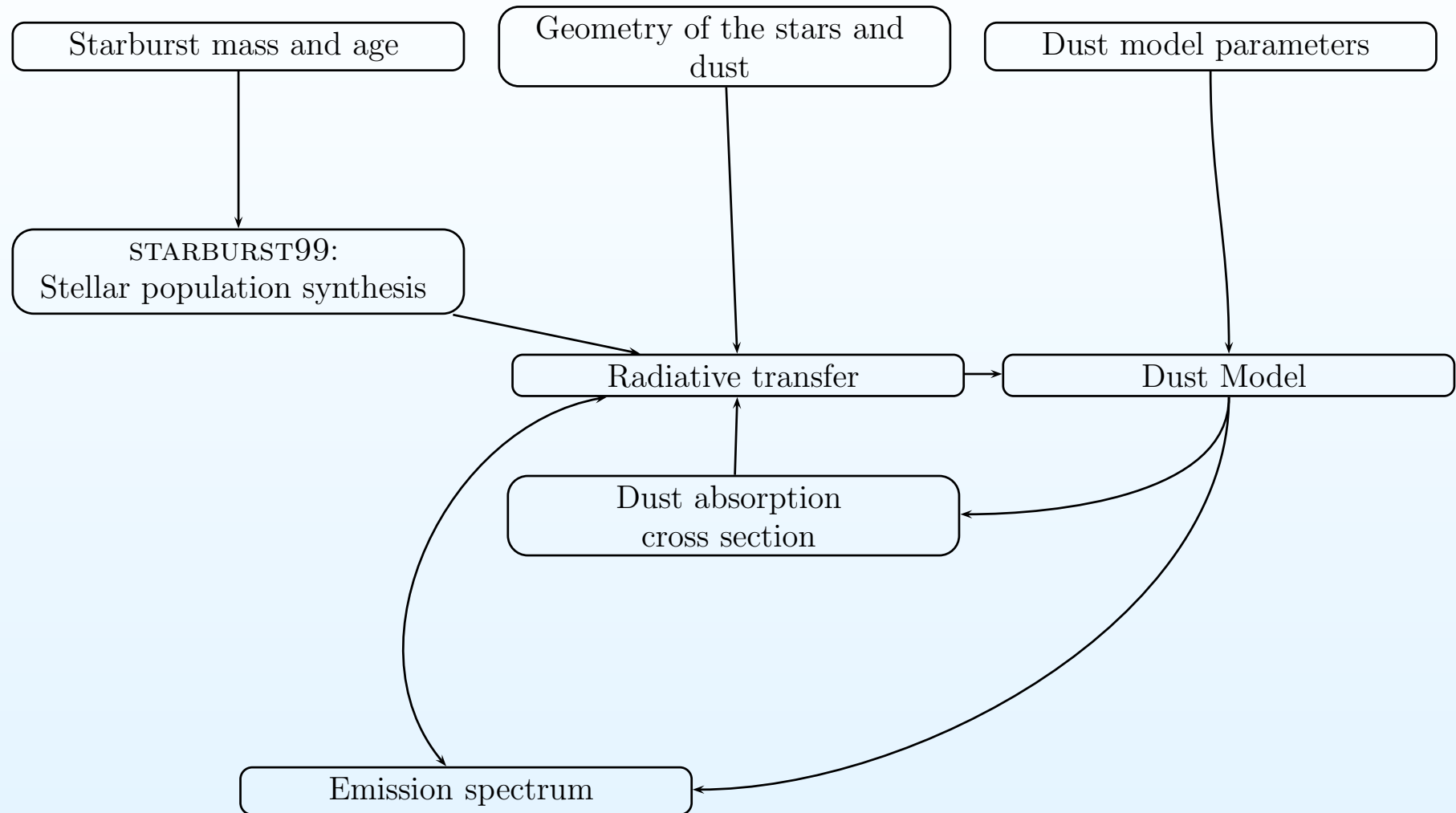


Example: a transiently heated grain (5 Å)

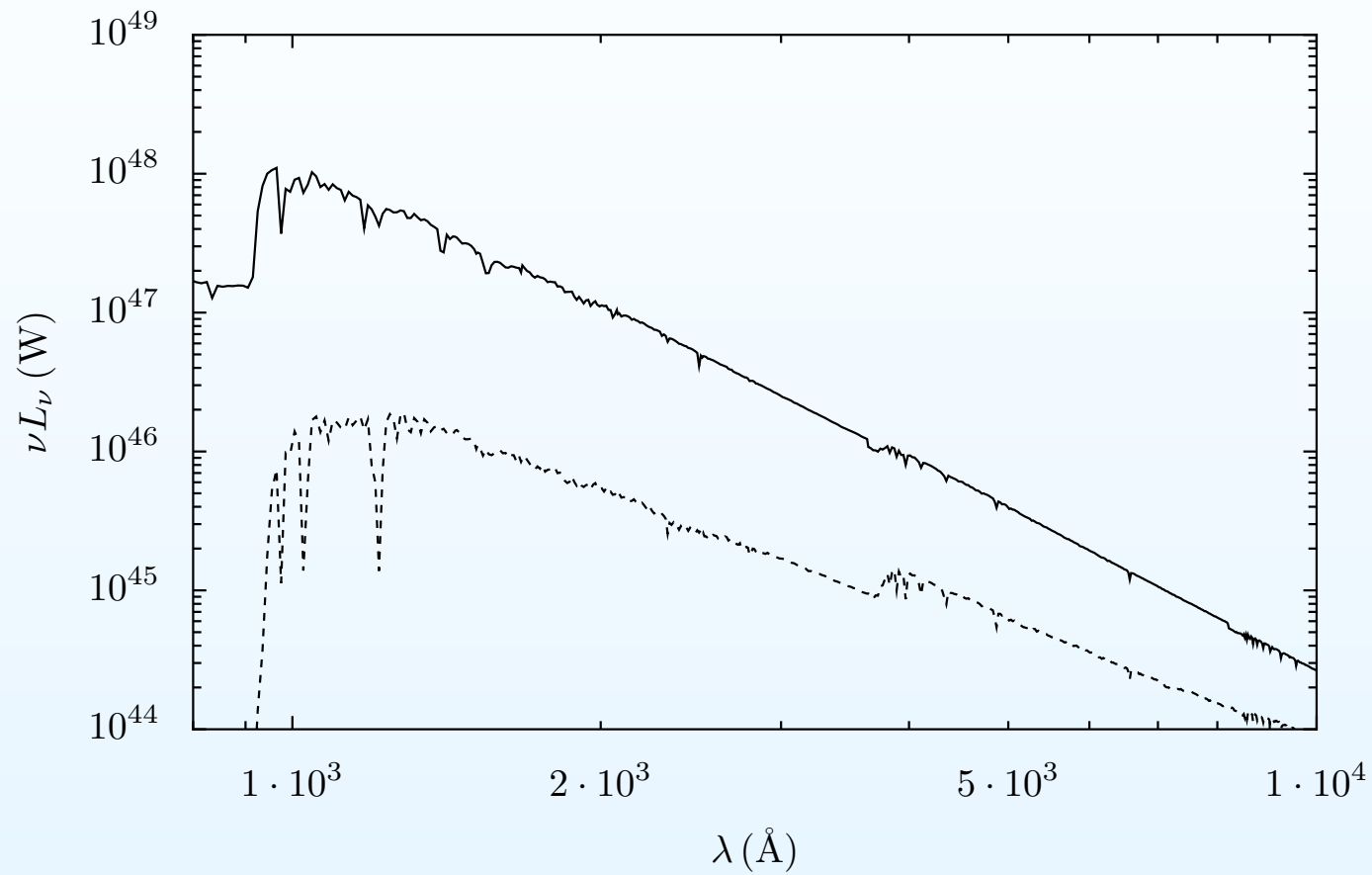


Modelling mid-IR emission from galaxies

Modelling mid-IR emission from galaxies



Stellar heating: Starburst99



Luminosity of a starburst of mass $10^6 M_\odot$ and age 5 Myr and 50 Myr.

Dust Model

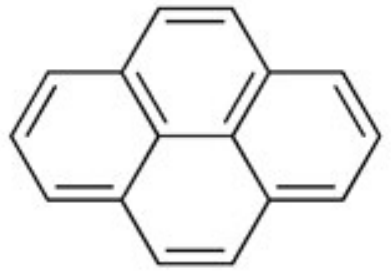
Want:

- Dust absorption cross section
- Emission from dust given a heating spectrum

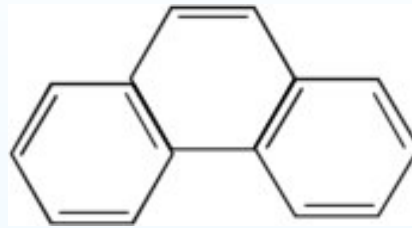
Need to consider:

- Three types of dust grains: silicate, graphitic and PAHs.
- Absorption cross section:
 - For PAHs use empirical cross section
 - For others Mie theory
- Transient heating:
 - Single temperature no longer appropriate; must calculate the probability distribution of grain energies.
 - Also must know the heat capacities of grains over a wide range of energies.
- The full size distribution of each family of grains

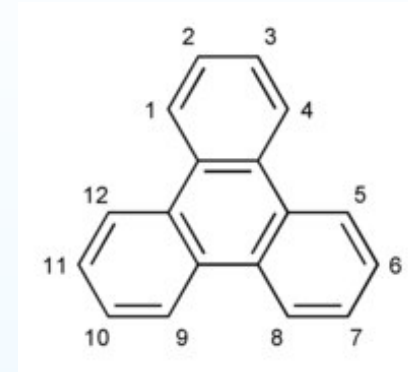
Polycyclic Aromatic Hydrocarbons



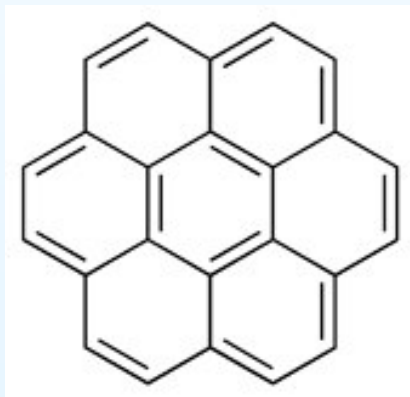
Pyrene



Phenanthrene



Triphenylene

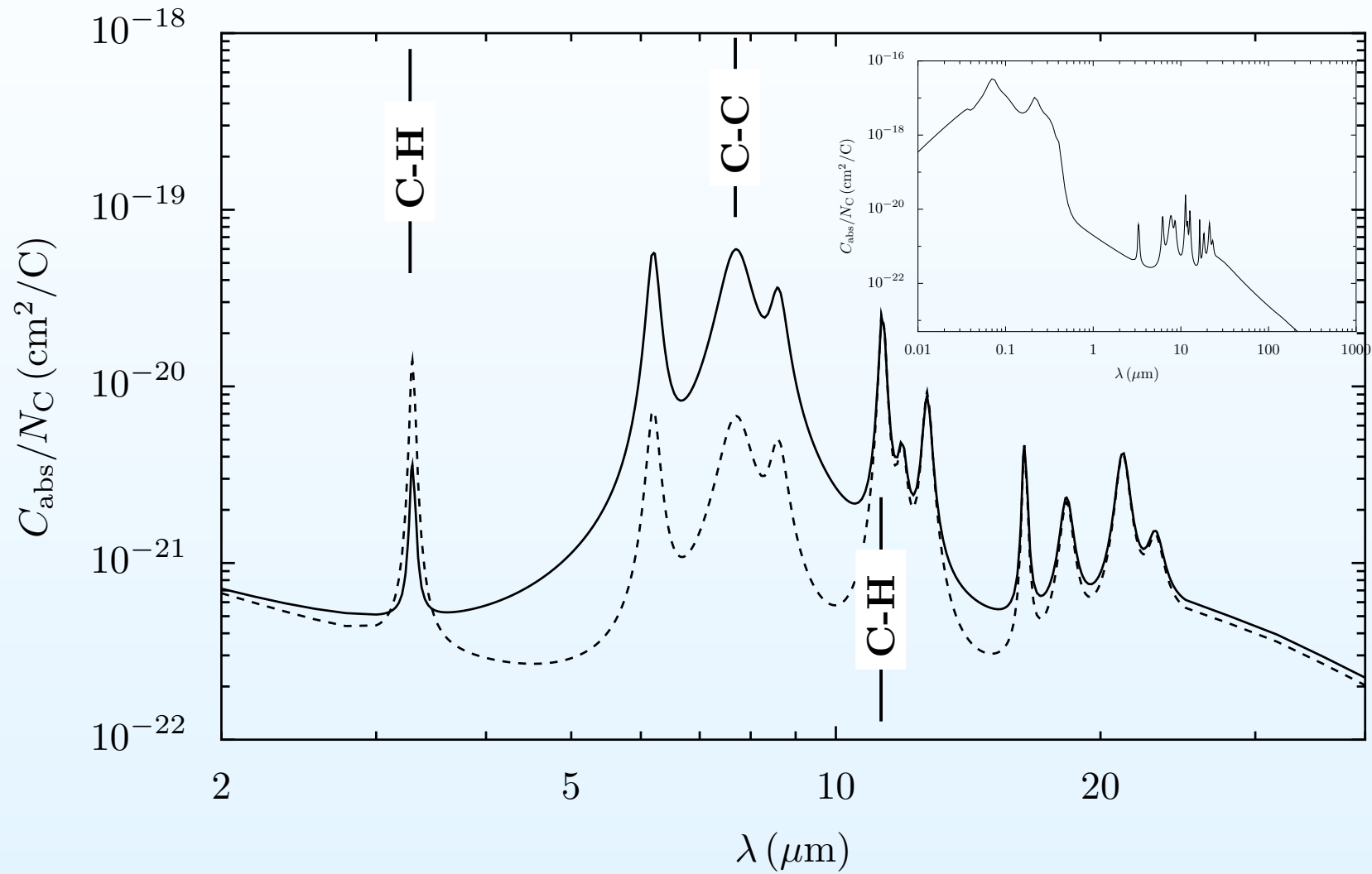


Coronene

Coronene has a radius of $\approx 3.5 \text{ \AA}$ — about the smallest particles included in the models.

Images source: Wikipedia

PAH cross sections



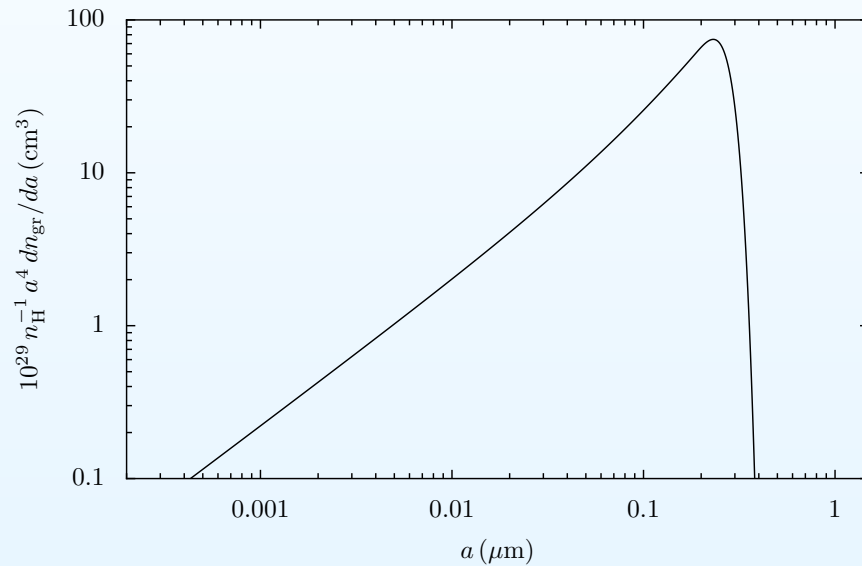
Cross section of ionised and neutral PAHs

PAH cross sections

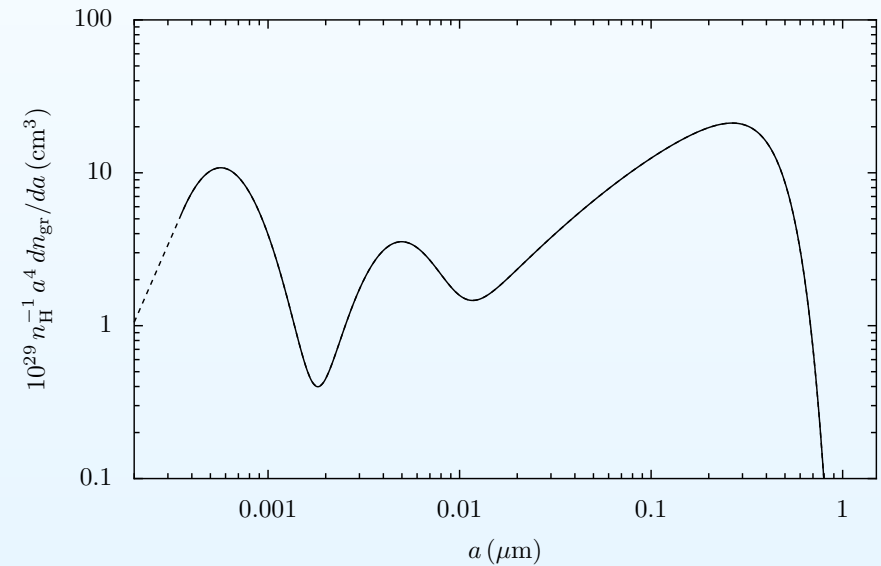
- The cross section is a strong function of neutral/ionised state.
 - Ionisation of grains a function of $\chi\sqrt{T}/n_e$: for PDRs ionisation typically high to complete (Draine & Li 2001).
- Fudge factors to reconcile the strength of the features with astronomical observations.
 - Adjustable parameters in the present models are E_{62} , E_{77} and E_{86} .
 - Fitting to diffuse galactic emission suggests $E_{62} = 3.0$, $E_{77} = 2.0$ and $E_{86} = 2.0$.
- Hydrogenisation? Here, complete hydrogenisation is assumed.

Grain size distributions

Best fit size distributions to the Galactic diffuse ISM
[Weingartner & Draine(2001)]: $R_V = 3.1$, Galactic metallicity.

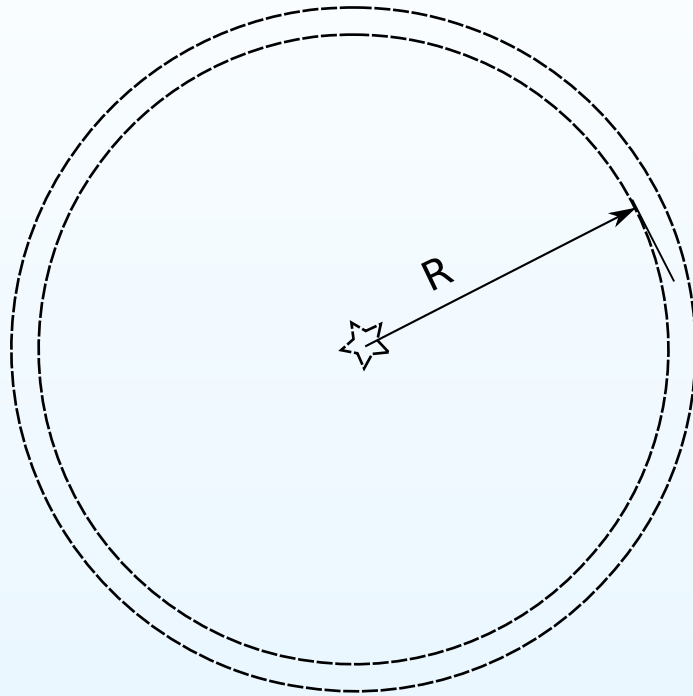


Size distribution of silicate grains

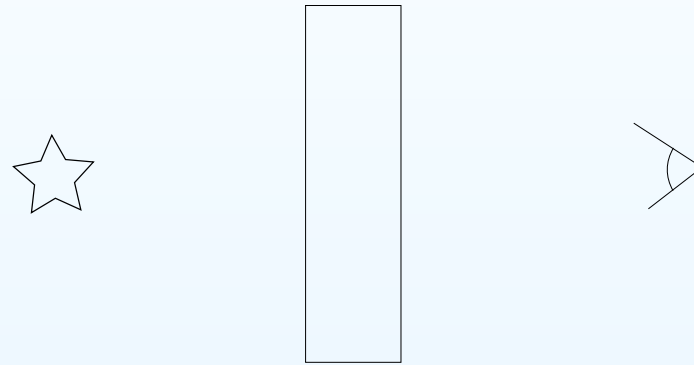


Size distribution of carbonaceous grains
(graphitic spheres and PAHs)

Radiative transfer



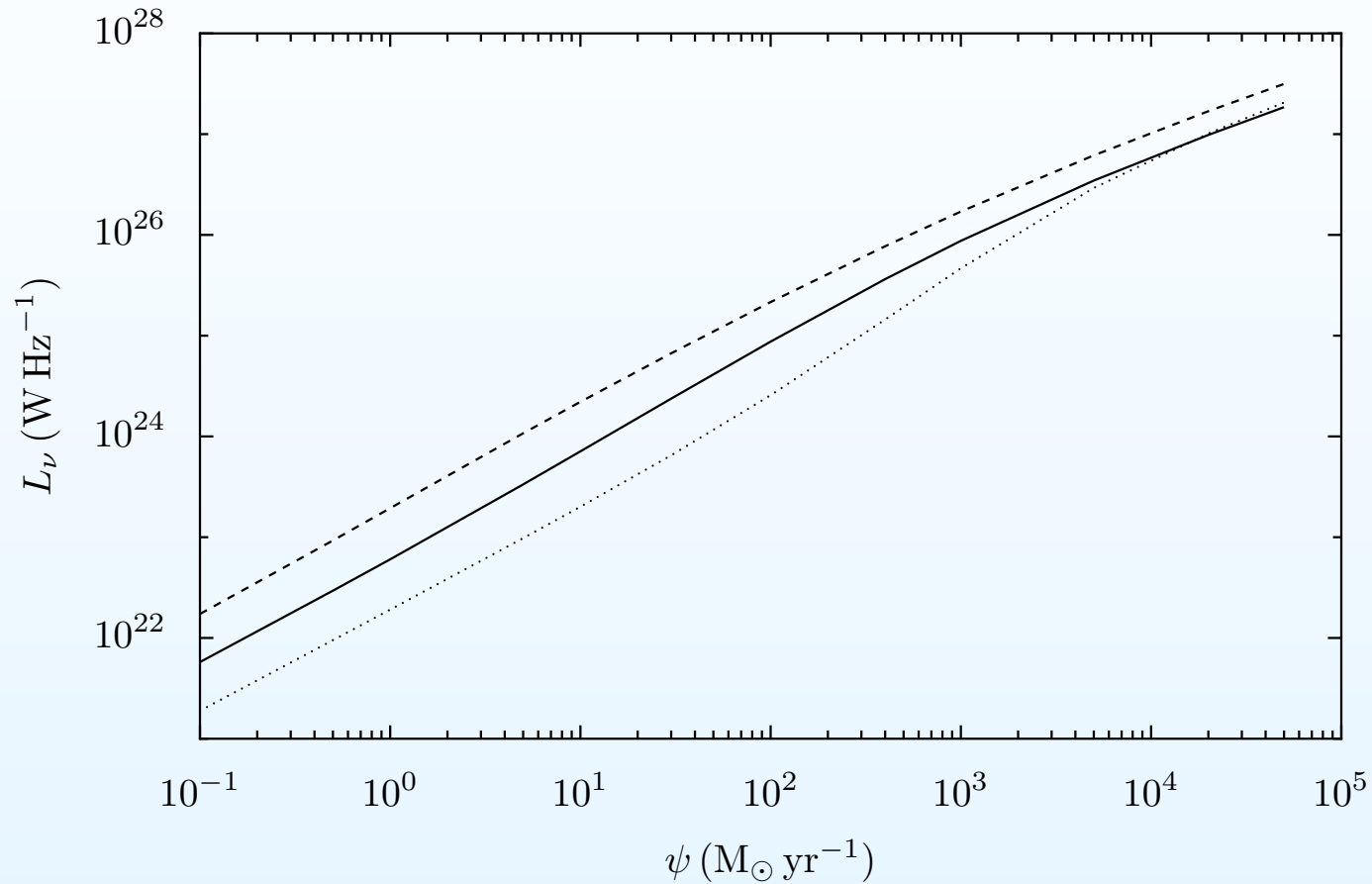
Heating radiation radiative transfer



Dust emission radiative transfer

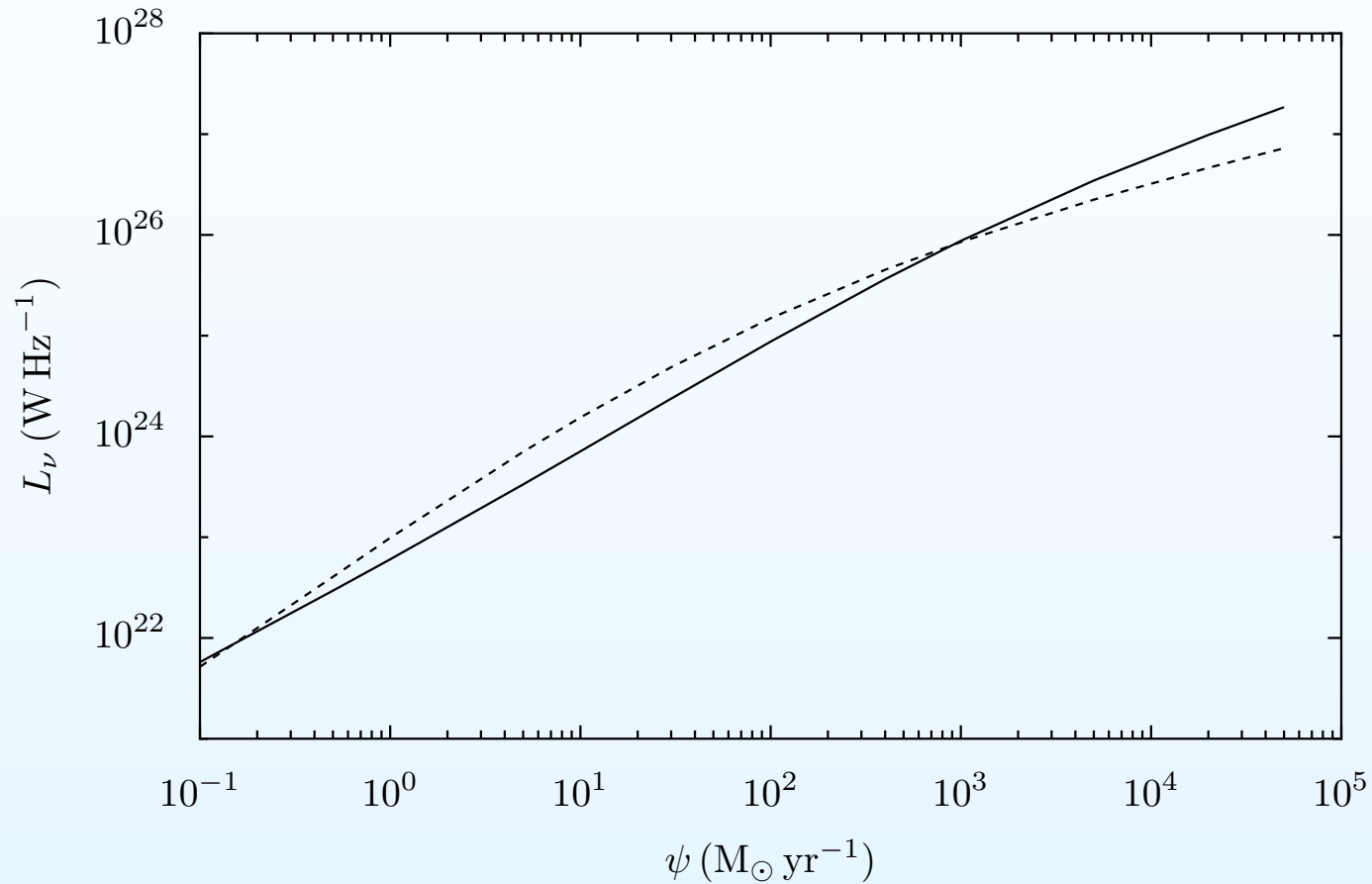
Some basic results

Mid-IR as a SFR tracer



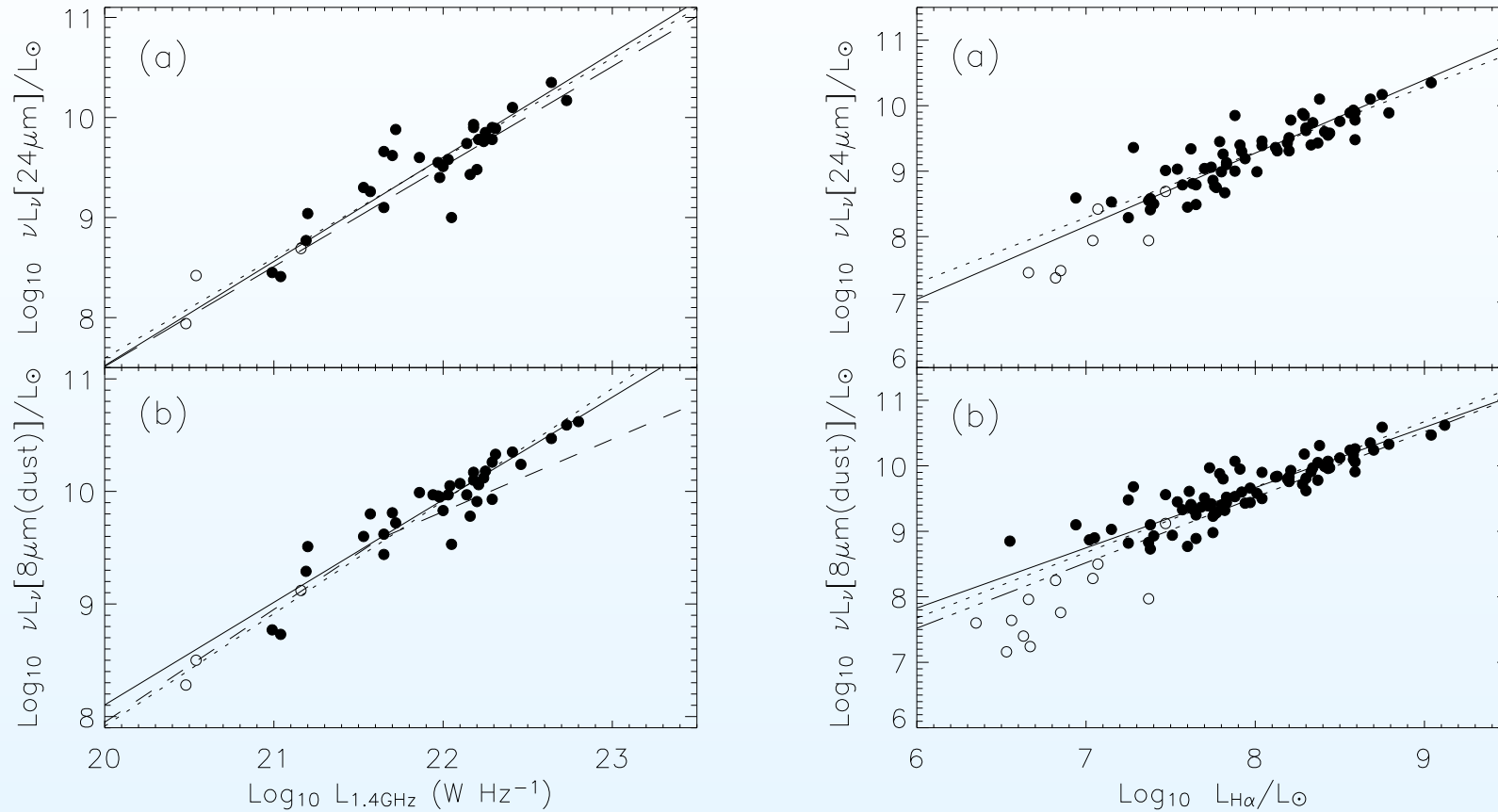
Peak specific luminosities of the 3.3 μm (dotted line), 7.7 μm (full line) and 11.3 μm (dashed line) emission features as functions of the star-formation rate (ψ). The starburst age was 10^8 yr, column density 10^{22} cm^{-2} and shell radius 100 pc.

Mid-IR as a SFR tracer



Peak specific luminosity of the $7.7 \mu\text{m}$ emission feature (full line) and $24 \mu\text{m}$ continuum (dashed line) as functions of the star-formation rate (ψ). The starburst age was 10^8 yr , column density 10^{22} cm^{-2} and shell radius 100 pc .

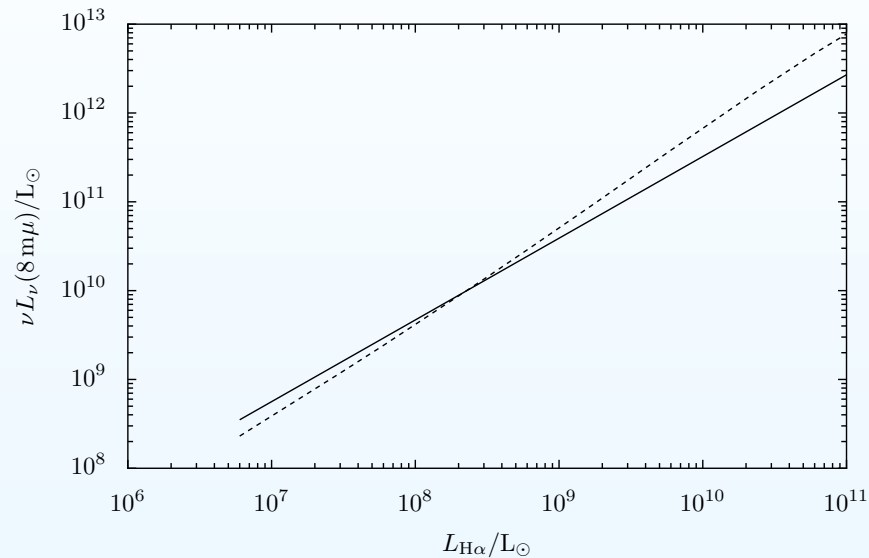
Observed mid-IR / SFR correlation



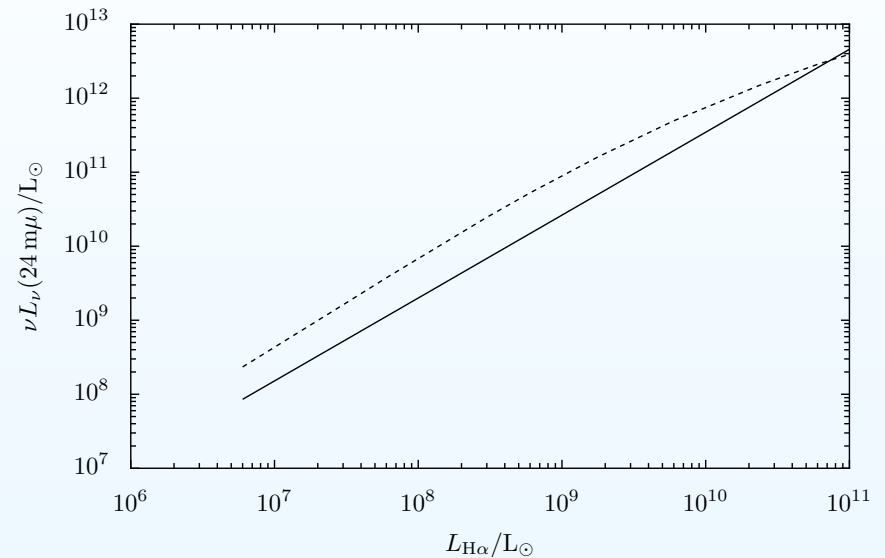
Correlations between mid-IR (features and continuum) and SFRs (estimated from radio continuum and $\text{H}\alpha$), [Wu et al.(2005)]. Based on the *Spitzer* first look survey.

Comparison of model vs observation

Shell radius 100 pc



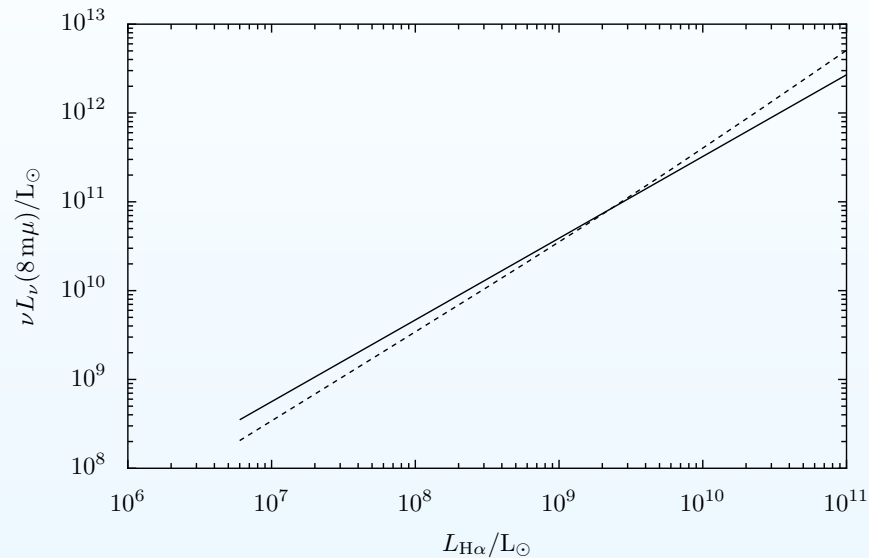
Model 8 μm dust luminosity (broken line) as function of H α luminosity compared to the best fitting line of [Wu et al.(2005)] (solid line).



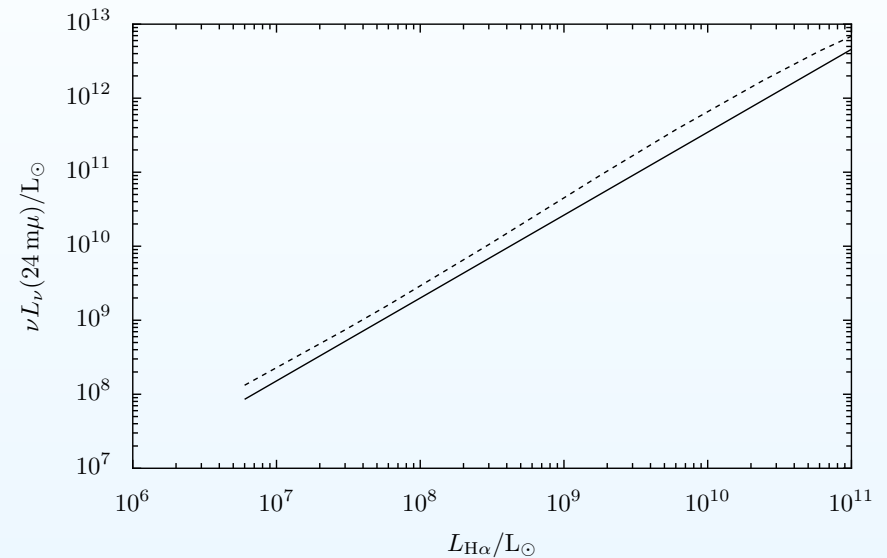
Model 24 μm dust luminosity (broken line) as function of H α luminosity compared to the best fitting line of [Wu et al.(2005)].

Comparison of model vs observation

Shell radius 500 pc



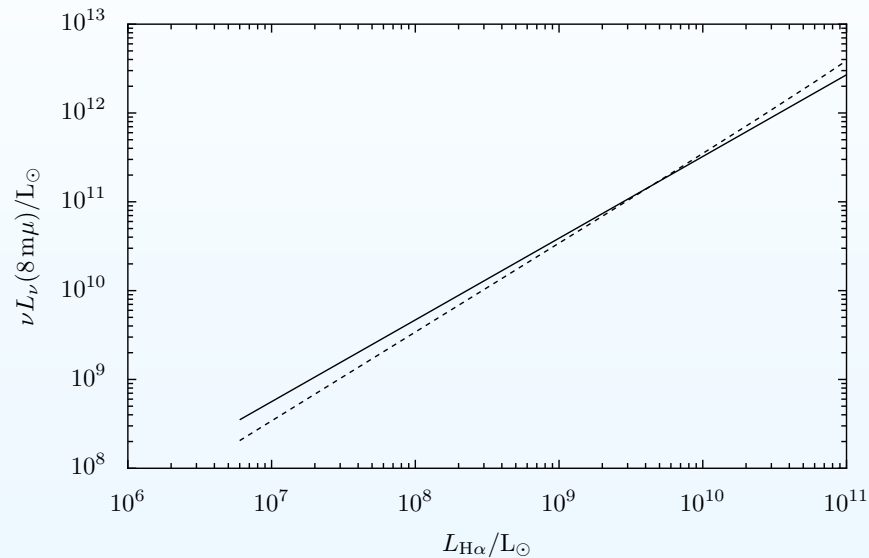
Model 8 μm dust luminosity (broken line) as function of H α luminosity compared to the best fitting line of [Wu et al.(2005)] (solid line).



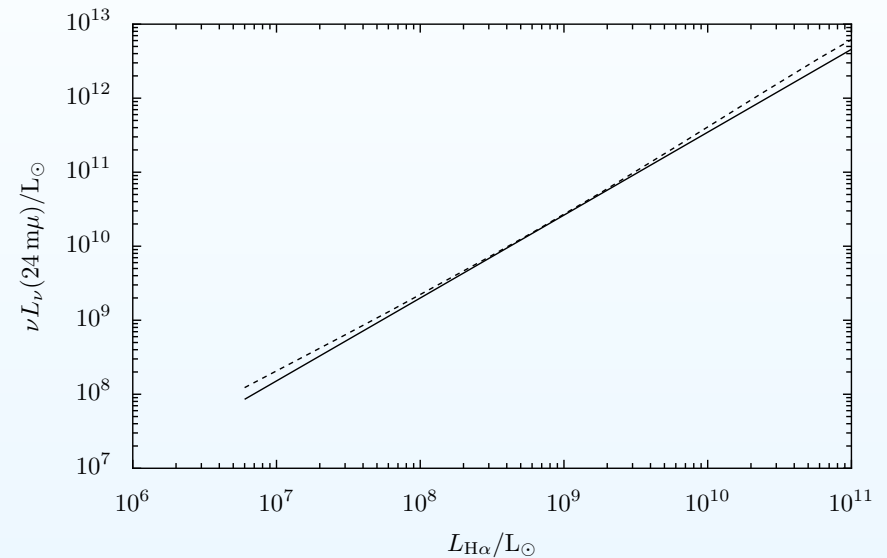
Model 24 μm dust luminosity (broken line) as function of H α luminosity compared to the best fitting line of [Wu et al.(2005)].

Comparison of model vs observation

Shell radius 2 kpc

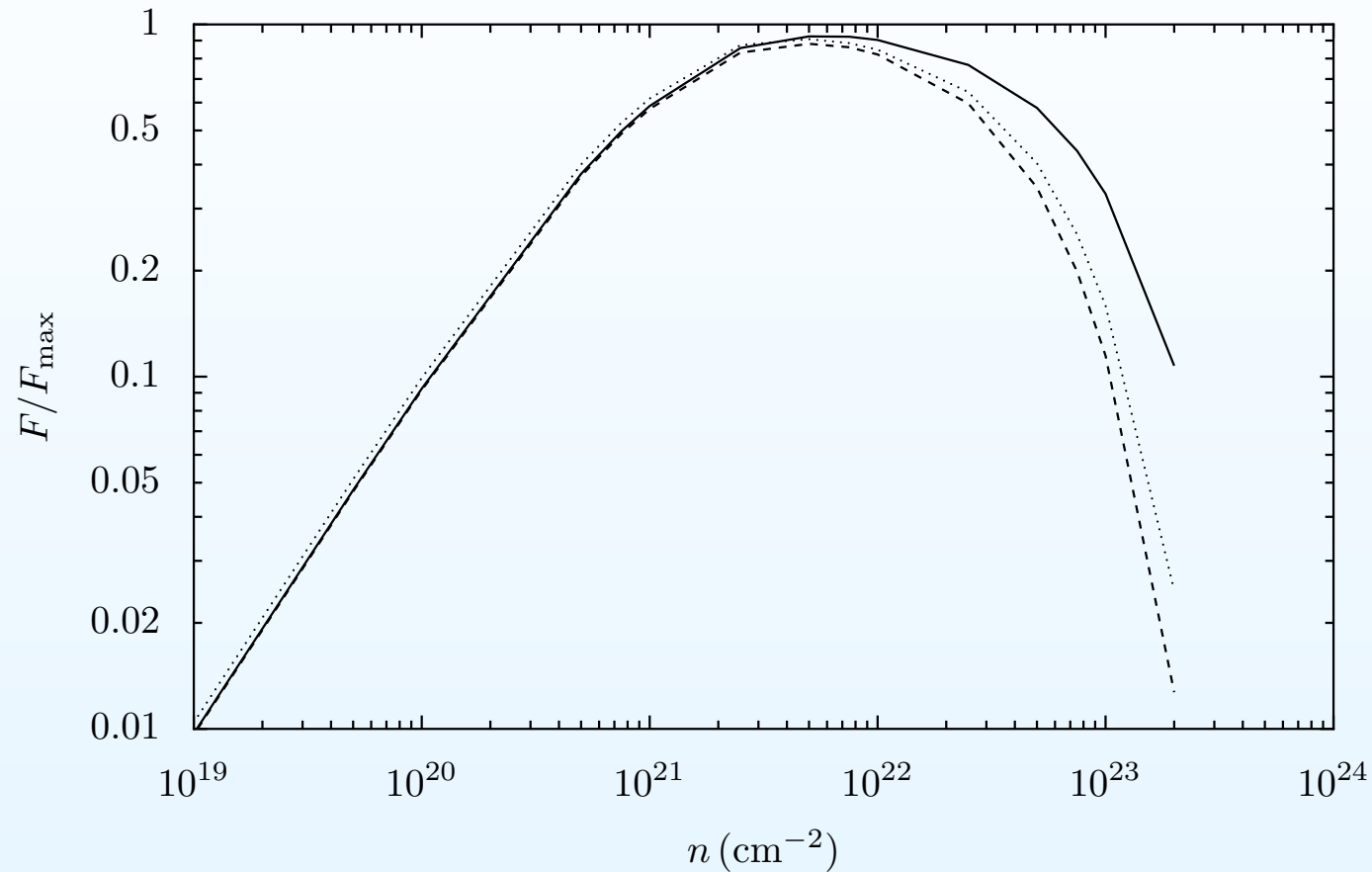


Model 8 μm dust luminosity (broken line) as function of H α luminosity compared to the best fitting line of [Wu et al.(2005)] (solid line).



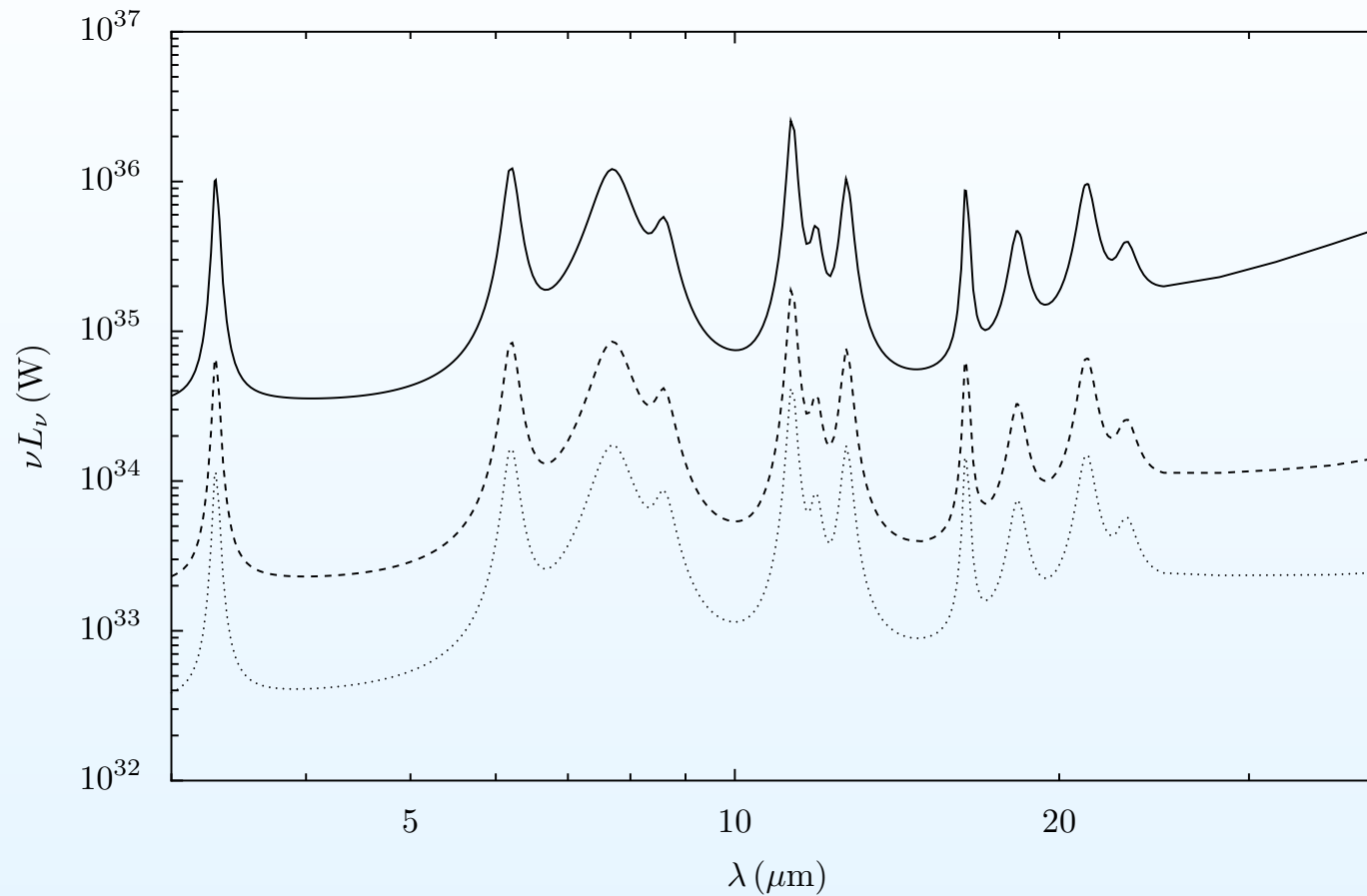
Model 24 μm dust luminosity (broken line) as function of H α luminosity compared to the best fitting line of [Wu et al.(2005)].

How important is the column density?



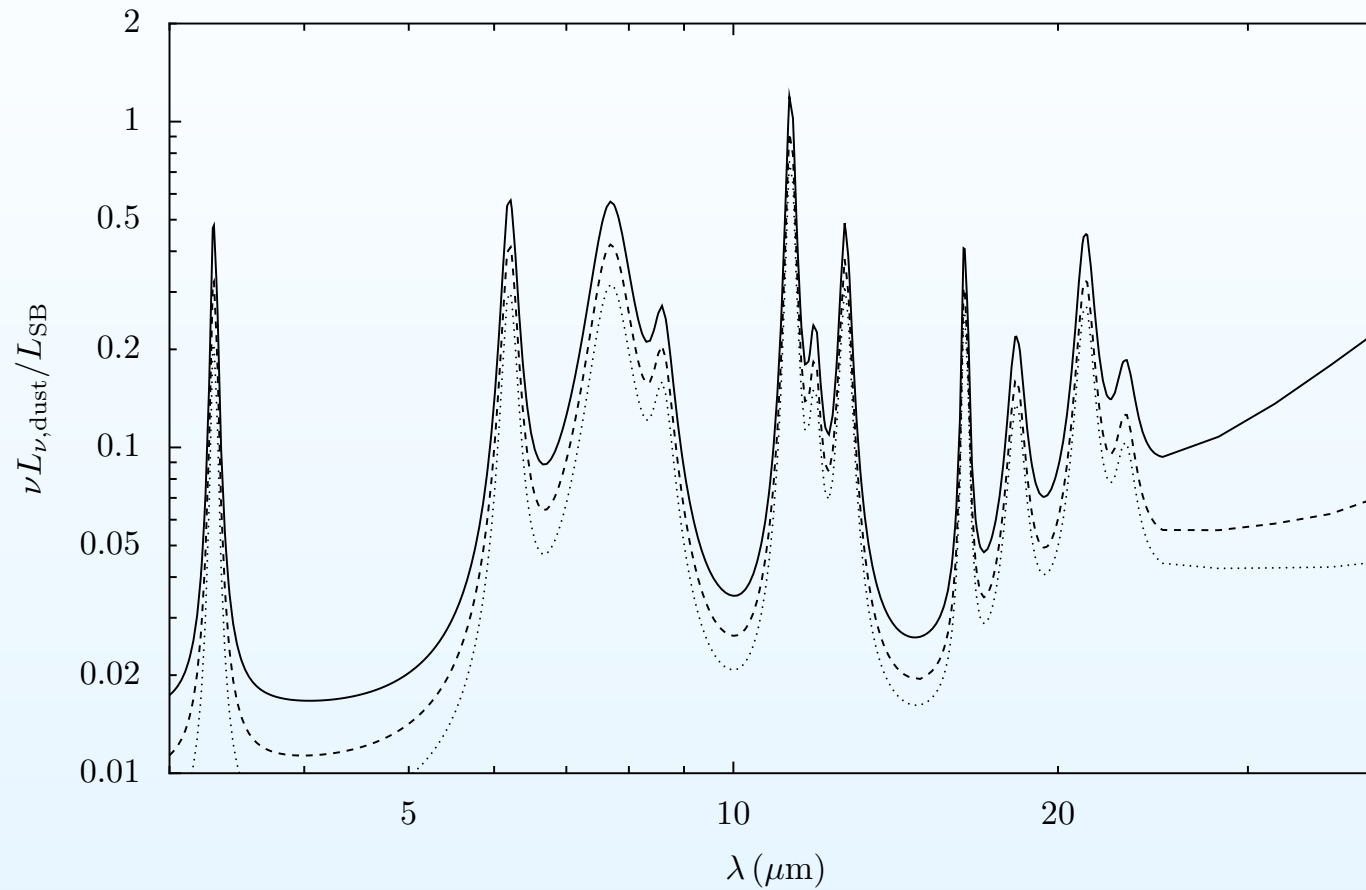
Normalised strengths of the 3.3 μm (dotted line), 7.7 μm (full line) and 11.3 μm (dashed line) emission features as functions of column density. Normalization is to the maximum possible if all of the exciting radiation is absorbed but no dust re-absorption occurs.

Evolution with starburst age



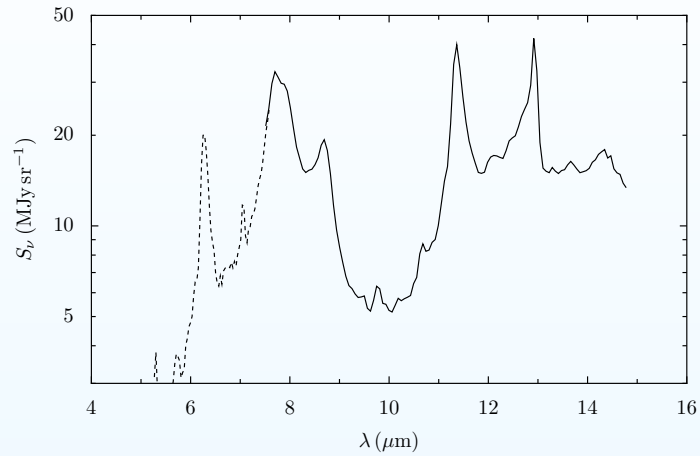
Mid-infrared luminosity spectra of a $10^7 M_{\odot}$ starburst at three times from the star-formation epoch: 5×10^6 yr, 30×10^6 yr and 100×10^6 yr

Evolution with starburst age

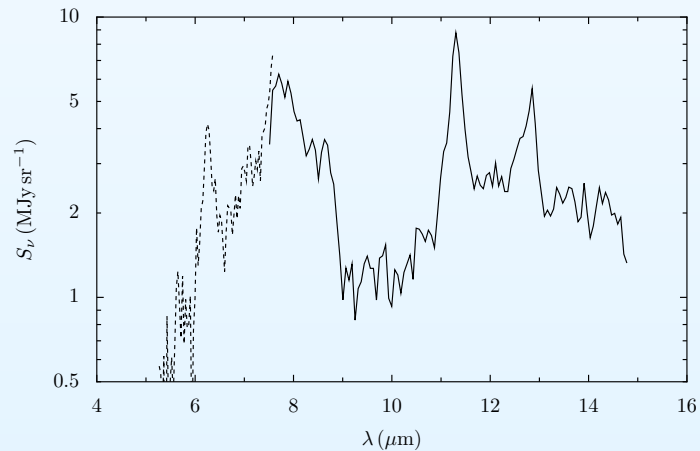


As before but normalised by the total starburst luminosity

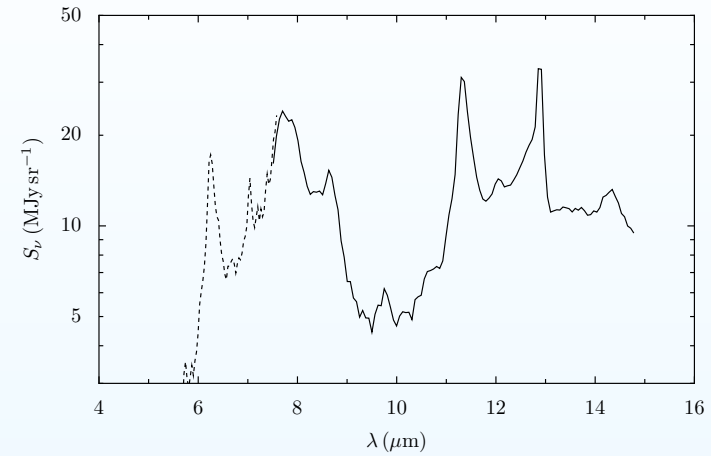
Sample Mid-IR spectra



NGC 2798



NGC 7793



NGC 3351

Spitzer Near Galaxies Legacy Survey: nuclear IRS spectra of (a random subsample of) spiral galaxies.

Sample Mid-IR spectra (trend with luminosity)

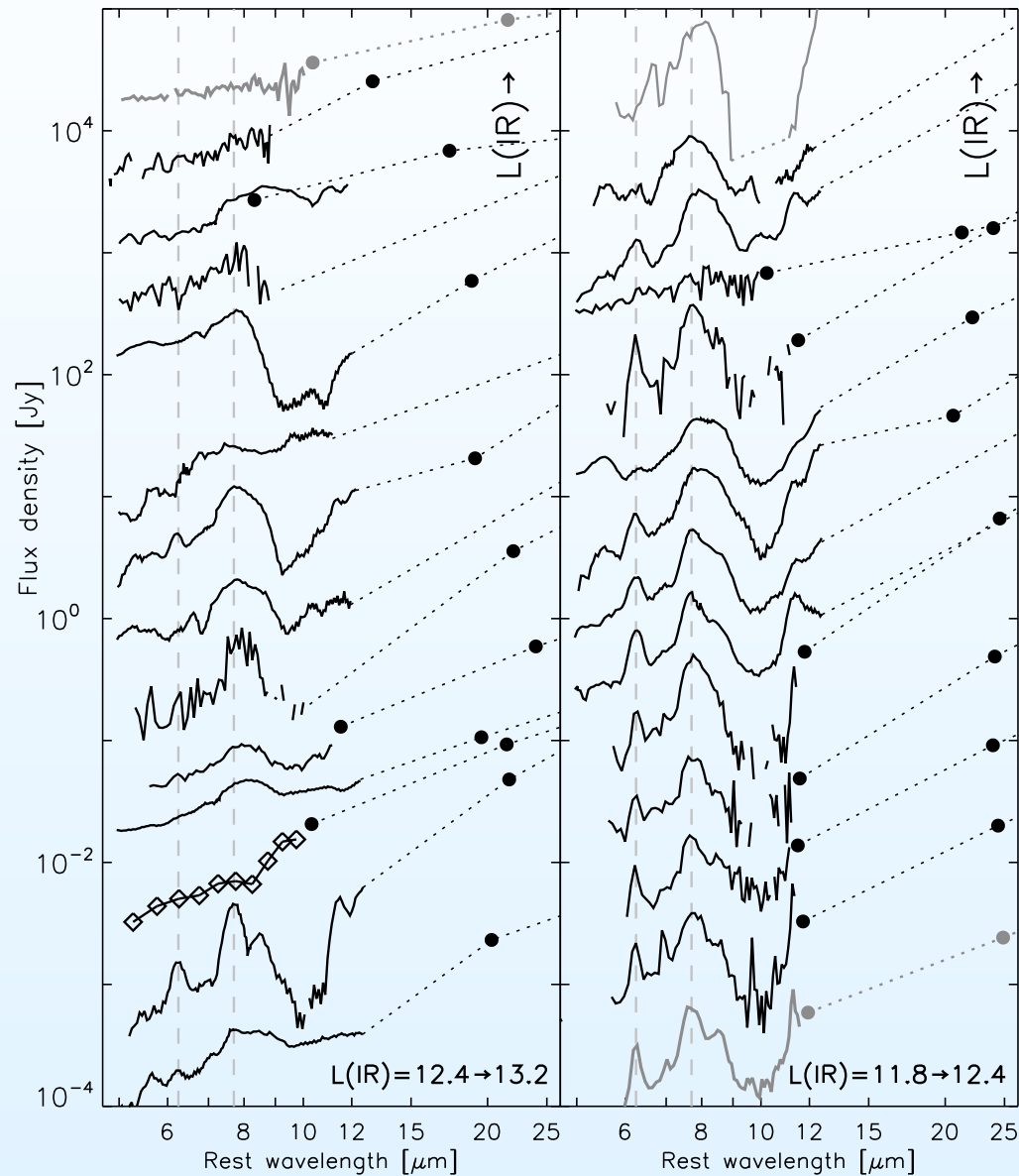


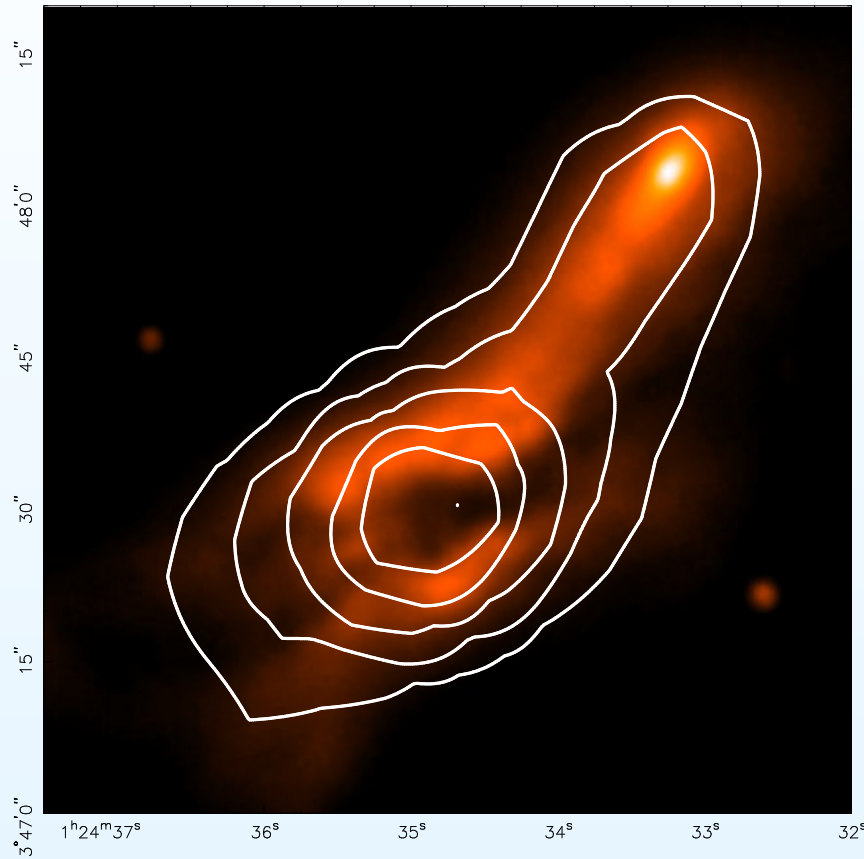
Figure by [Peeters(2004)]: Collection of *ISO* mid-infrared spectra shown sorted by luminosity.

Case study: NGC 520

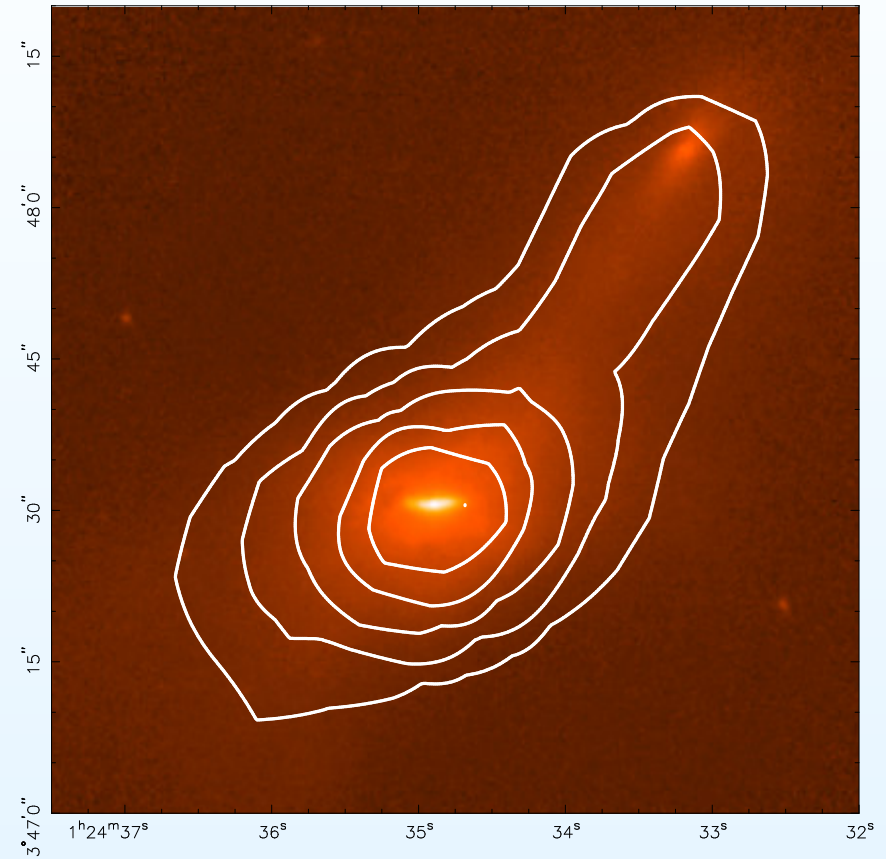
NGC 520



NGC 520: imaging



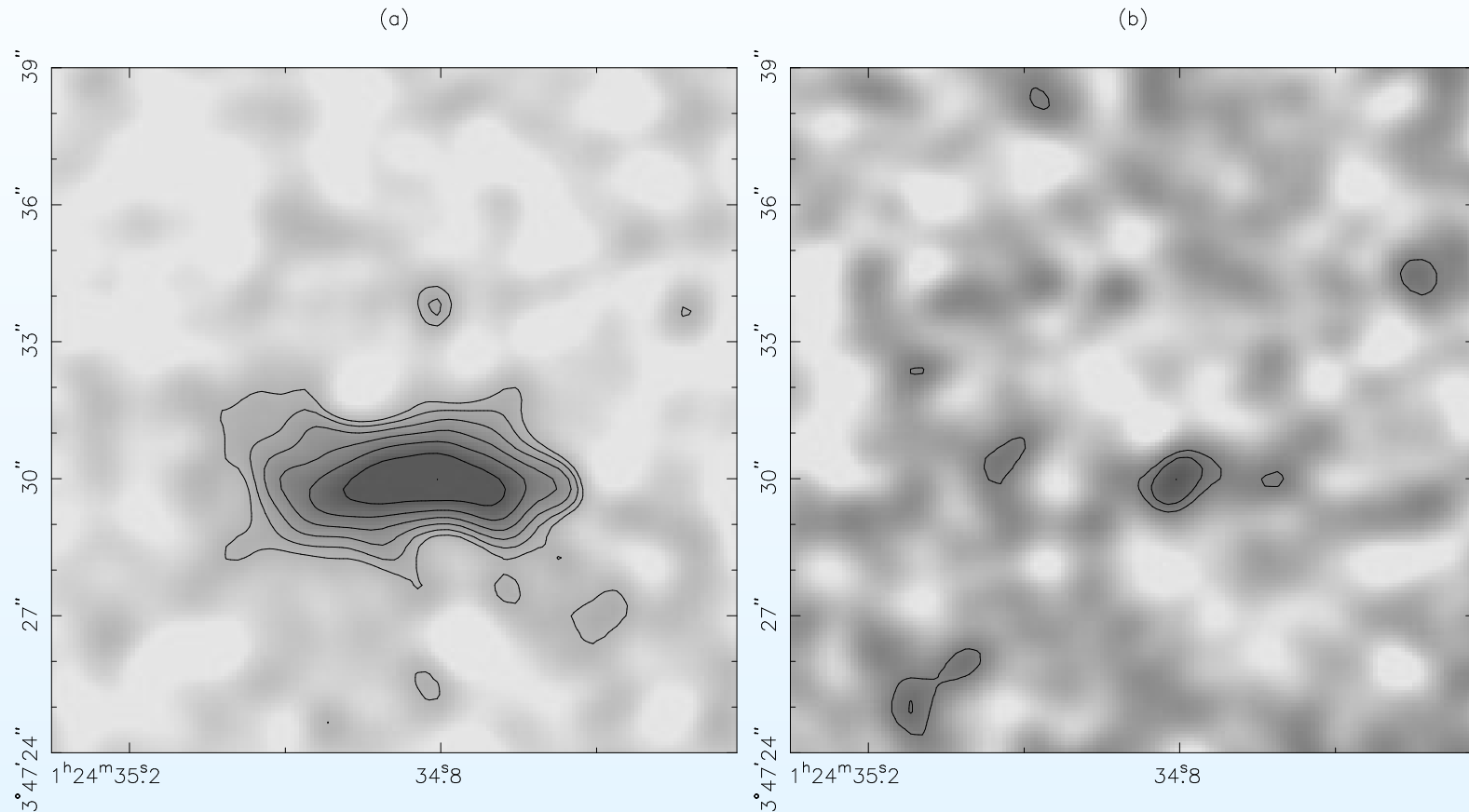
R-band image (from [Xu(2000)]) overlaid with mid-infrared contours (from *ISO*).



K-band image (from [Kotilainen(2001)]) overlaid with mid-infrared contours (from *ISO*).

MICHELLE imaging of NGC 520

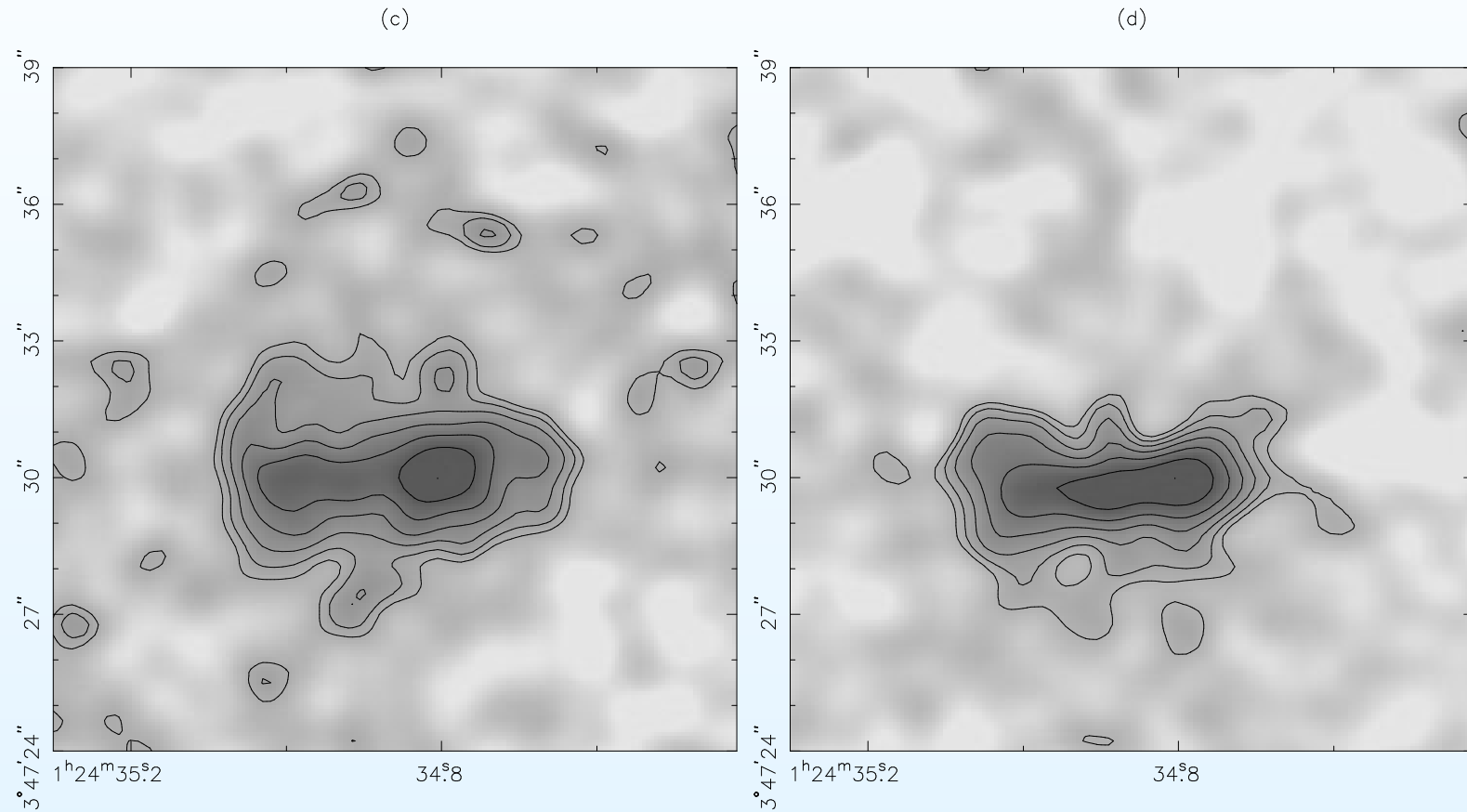
7.9 μm and 9.7 μm filters



(a) 7.9 μm filter ($S_{\text{peak}} = 109 \text{ mJy arcsec}^{-2}$); (b) 9.7 μm filter (no firm detection, $S_{\text{peak}} = 28 \text{ mJy arcsec}^{-2}$);

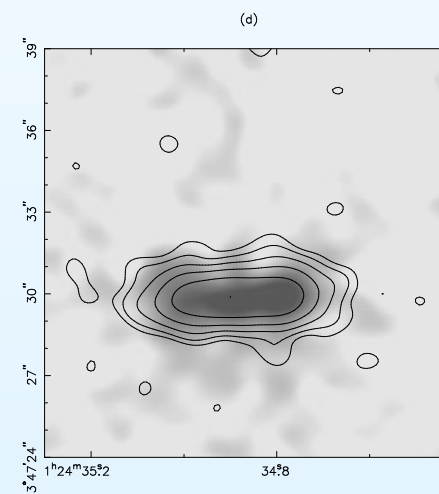
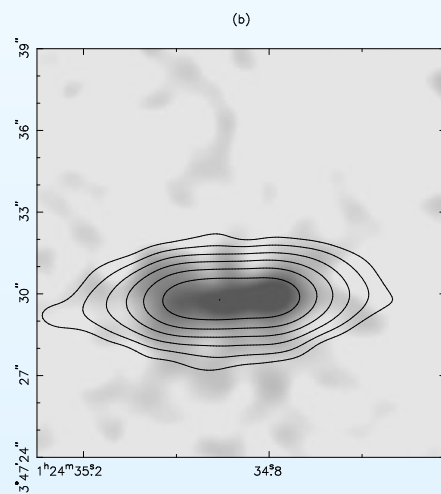
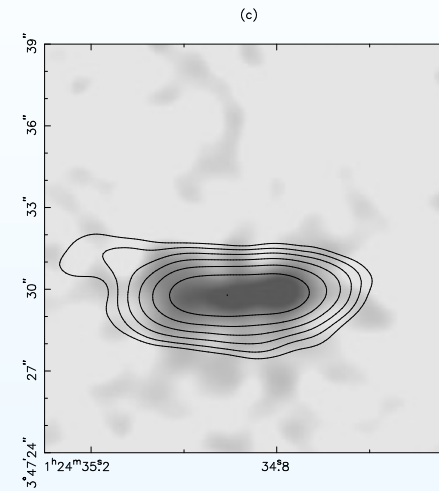
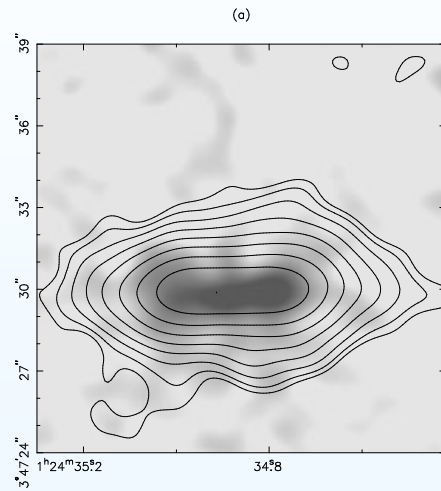
MICHELLE imaging of NGC 520

11.6 μm and 12.5 μm filters



(c) 11.6 μm filter ($S_{\text{peak}} = 44 \text{ mJy arcsec}^{-2}$); (d) 12.5 μm filter ($S_{\text{peak}} = 80 \text{ mJy arcsec}^{-2}$);

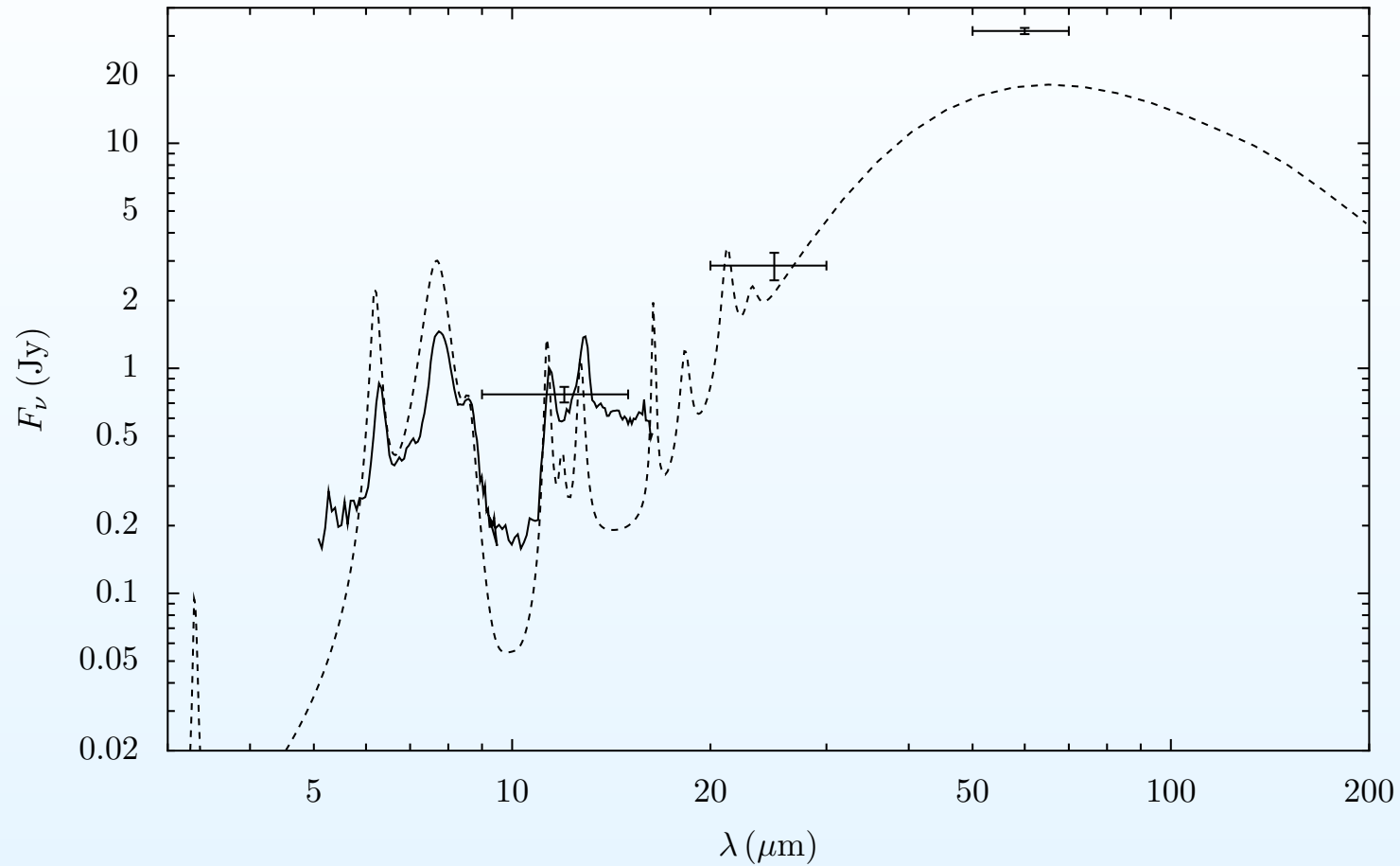
NGC 520 in the Radio



About NGC 520

- Mid-infrared imaging:
 - The majority of emission from a disk-like region around 400 pc in radius.
 - Very weak emission in the filter covering the silicate absorption band.
- Near-infrared H recomb-lines:
 - SFR rate about $7 M_{\odot} \text{ yr}^{-1}$.
 - Obscuring column density $6.2 \times 10^{22} \text{ cm}^{-2}$.
- Radio observations:
 - Also indicate a SFR of $7 M_{\odot} \text{ yr}^{-1}$, confined within the mid-ir/molecular disk region.

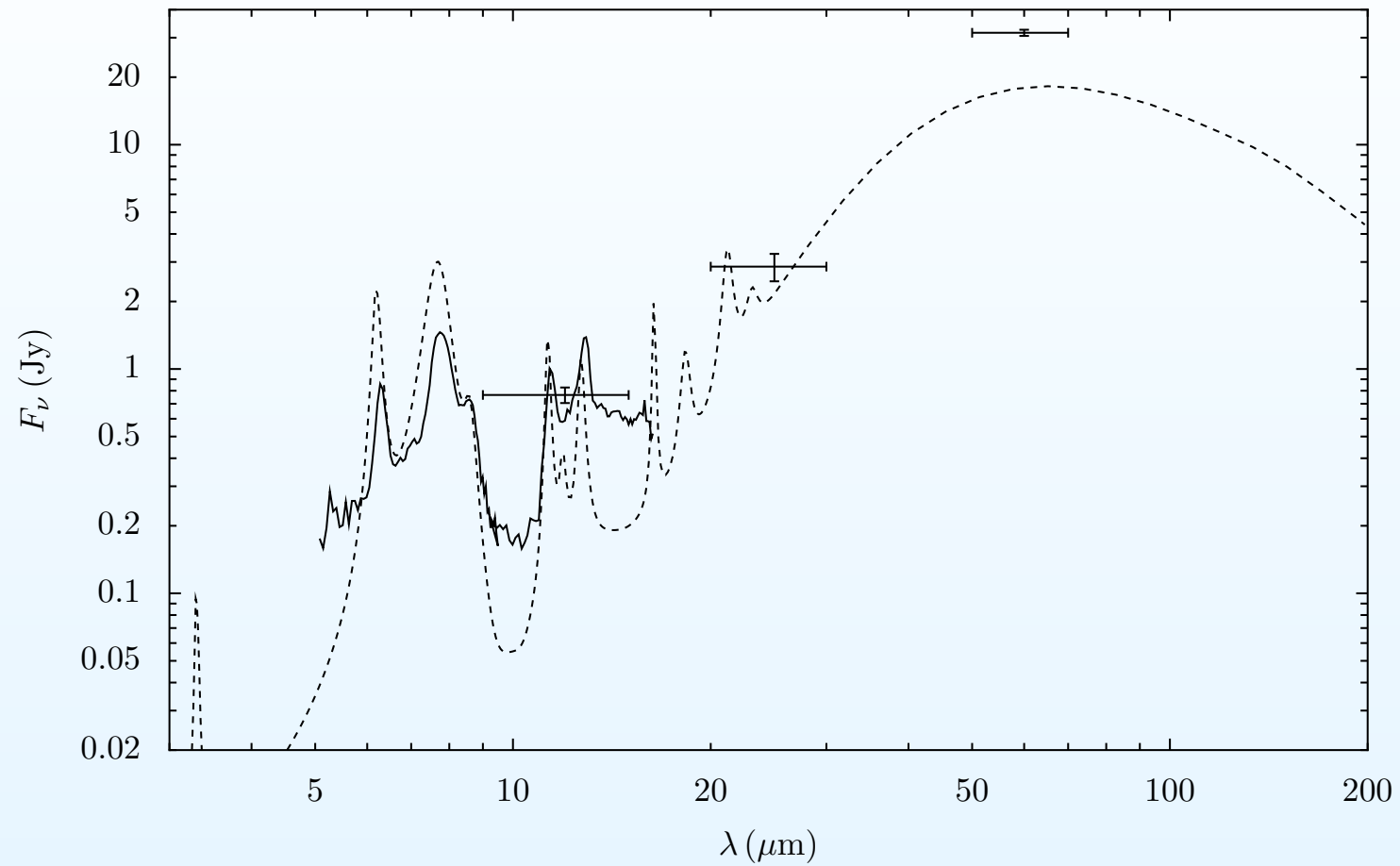
NGC 520 model



Standard dust model, $7 M_\odot \text{ yr}^{-1}$, shell radius 400 pc, column density $6.2 \times 10^{22} \text{ cm}^{-2}$.

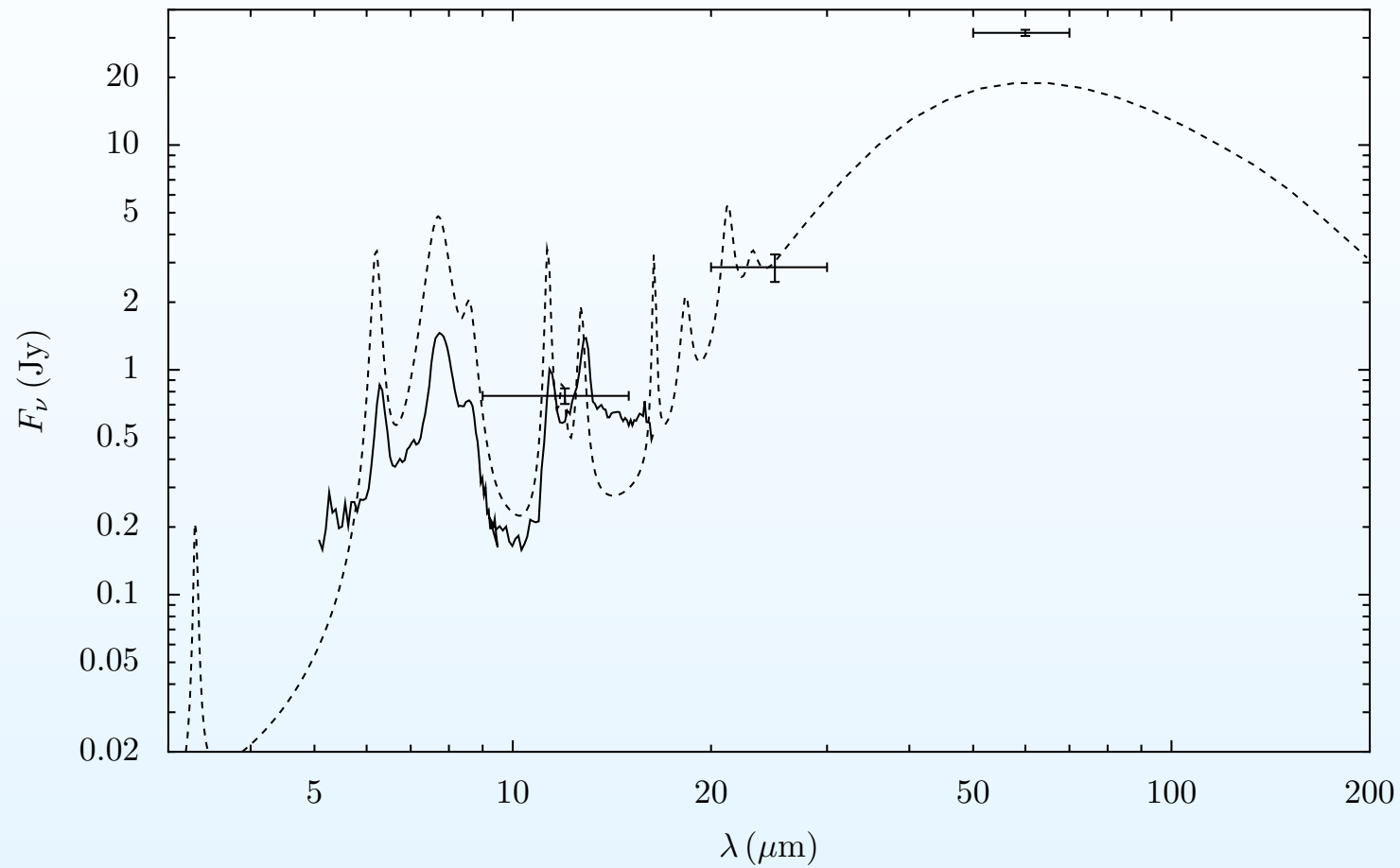
Full line: *ISO-CVF* spectroscopy

NGC 520 model: column density



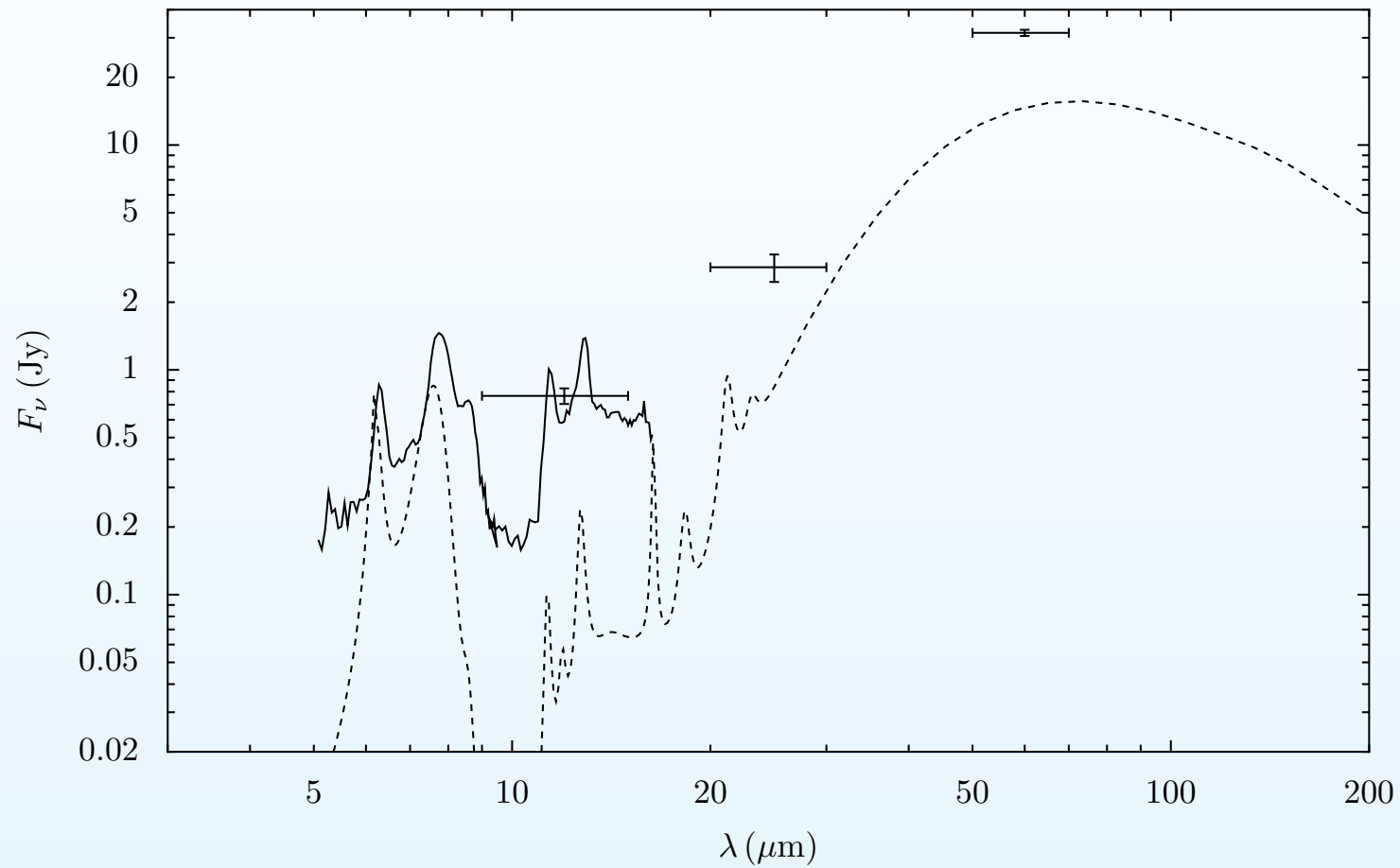
Column density: $6.2 \times 10^{22} \text{ cm}^{-2}$

NGC 520 model: column density



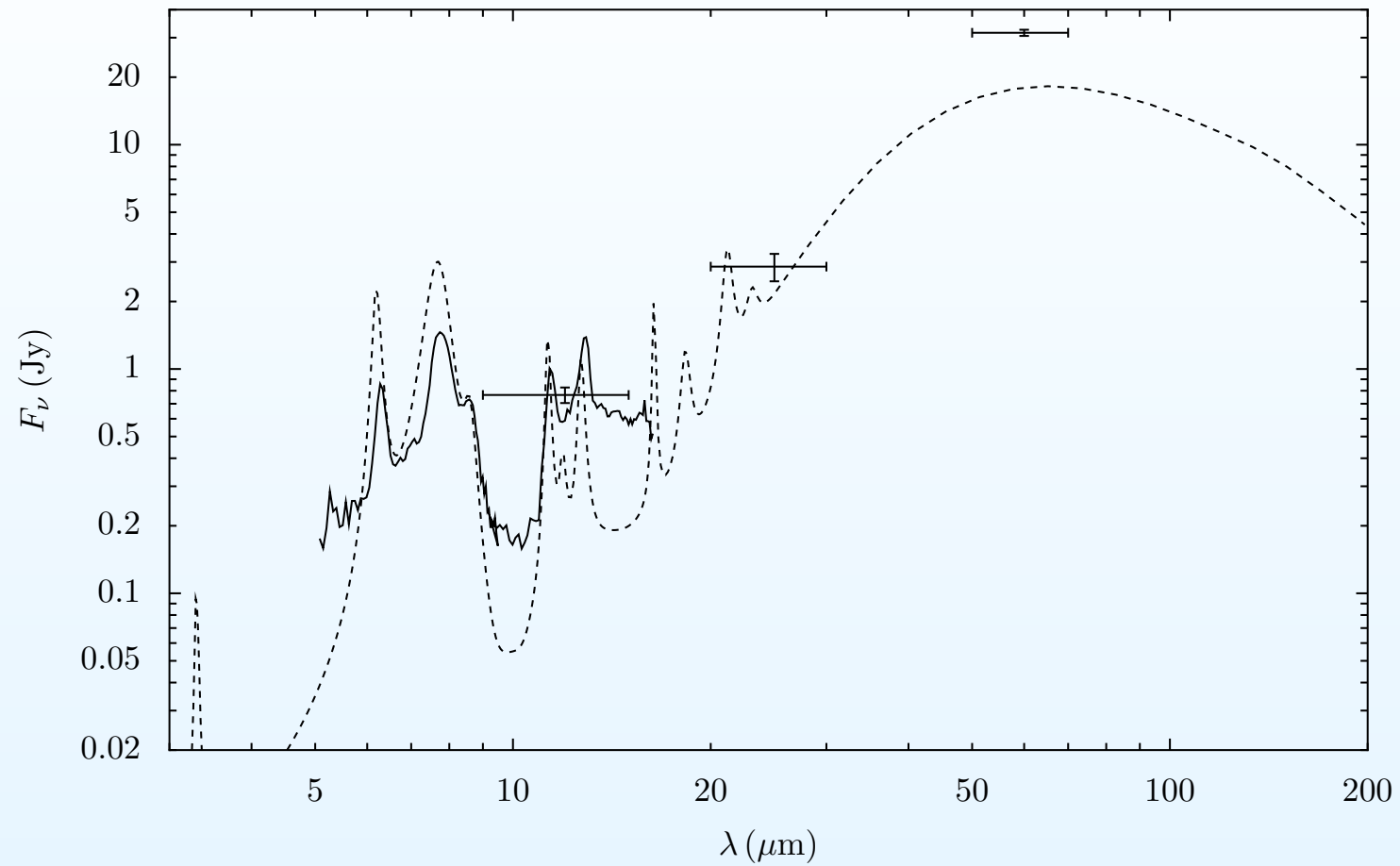
Column density: $2 \times 10^{22} \text{ cm}^{-2}$

NGC 520 model: column density



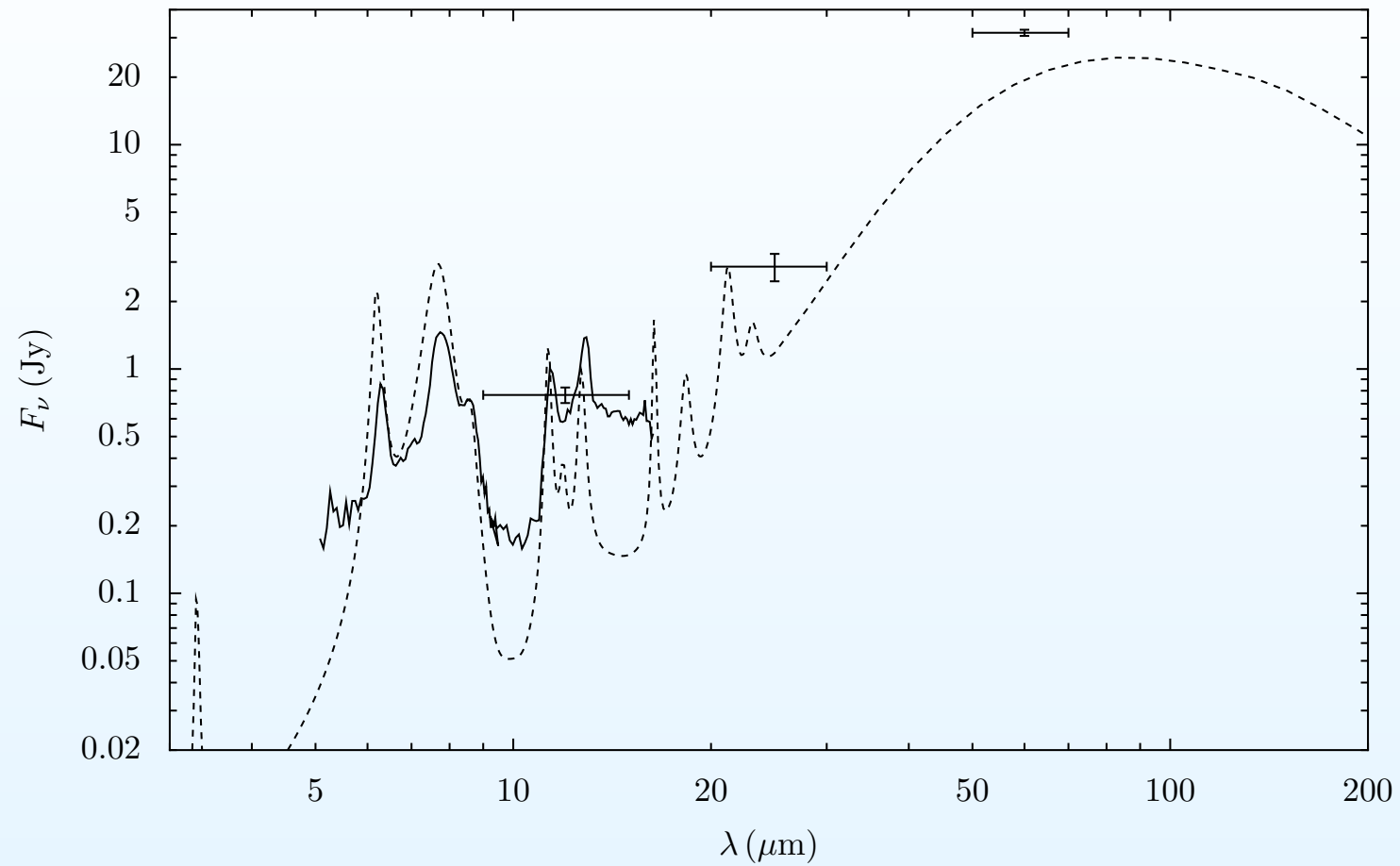
Column density: $18 \times 10^{22} \text{ cm}^{-2}$

NGC 520 model: shell radius



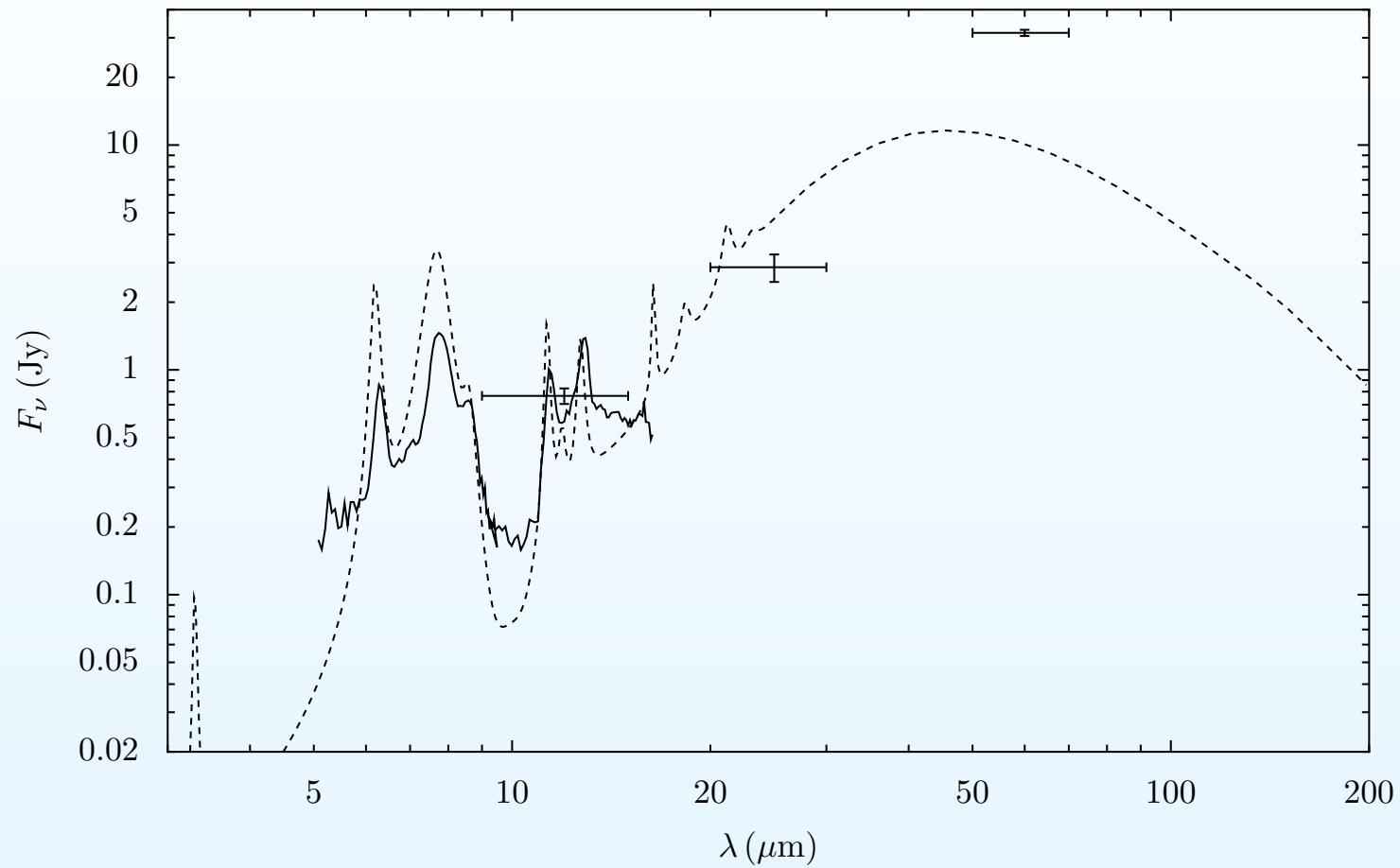
Shell radius 400 pc.

NGC 520 model: shell radius



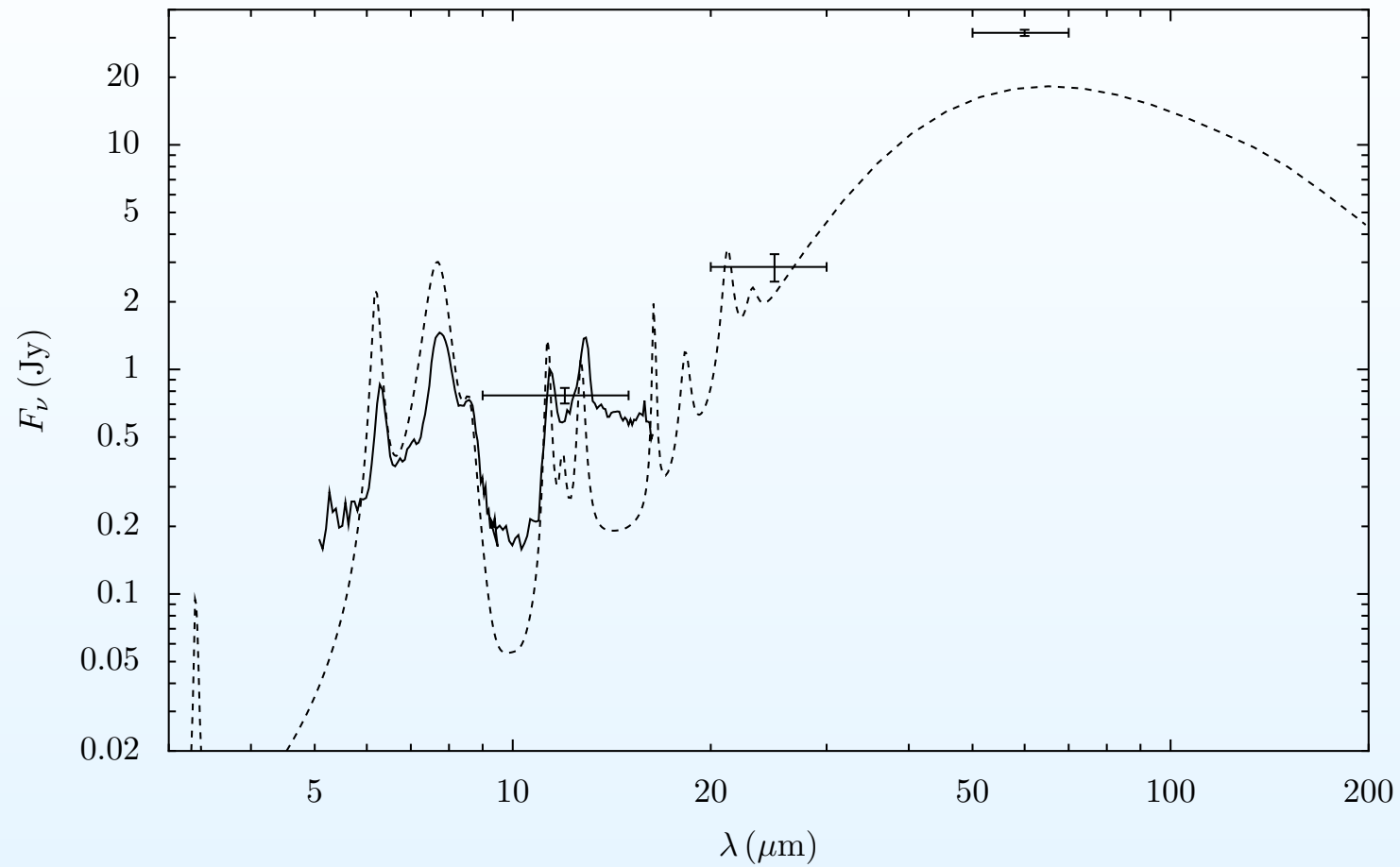
Shell radius 1 kpc.

NGC 520 model: shell radius



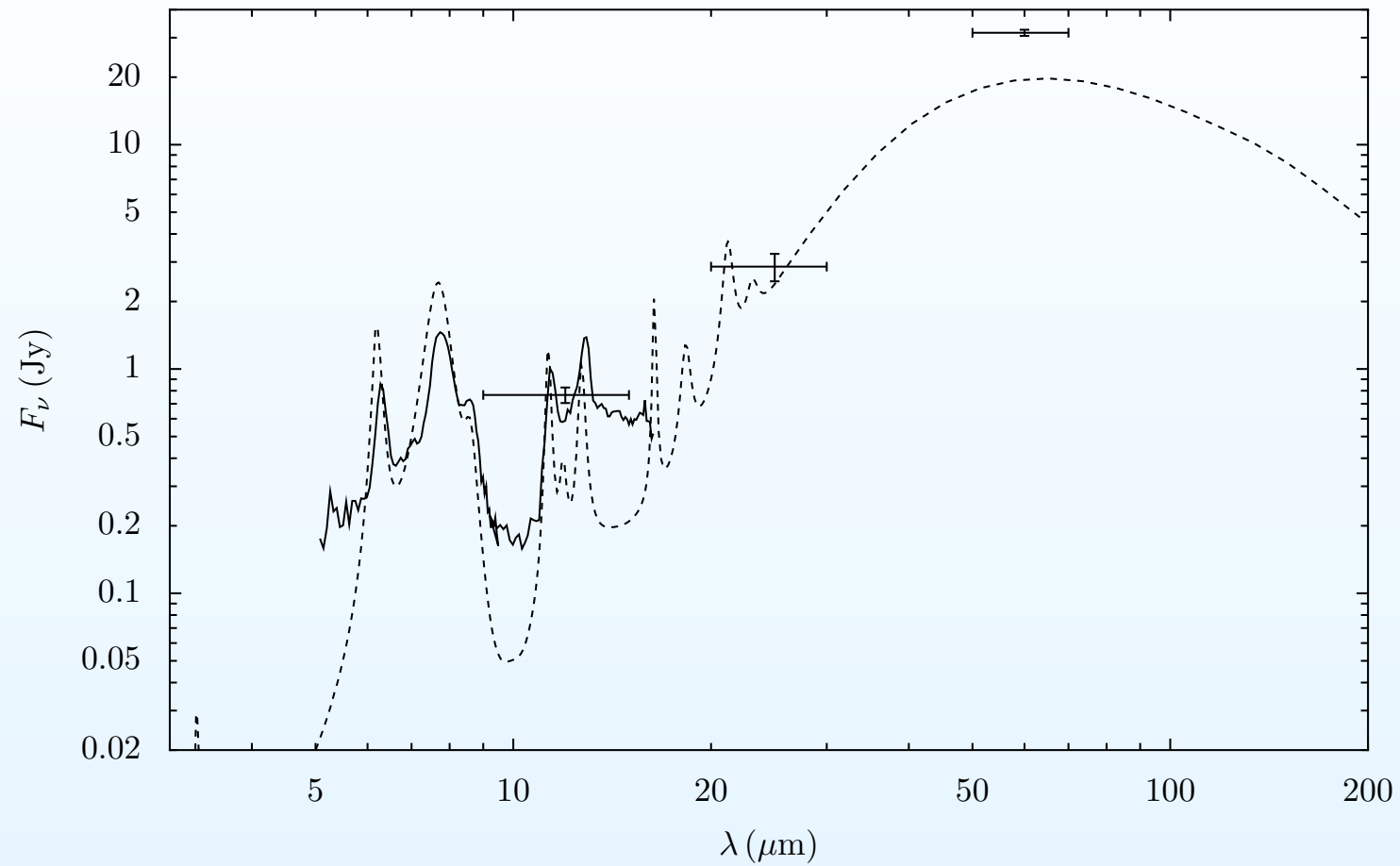
Shell radius 100 pc.

NGC 520 model: grain destruction



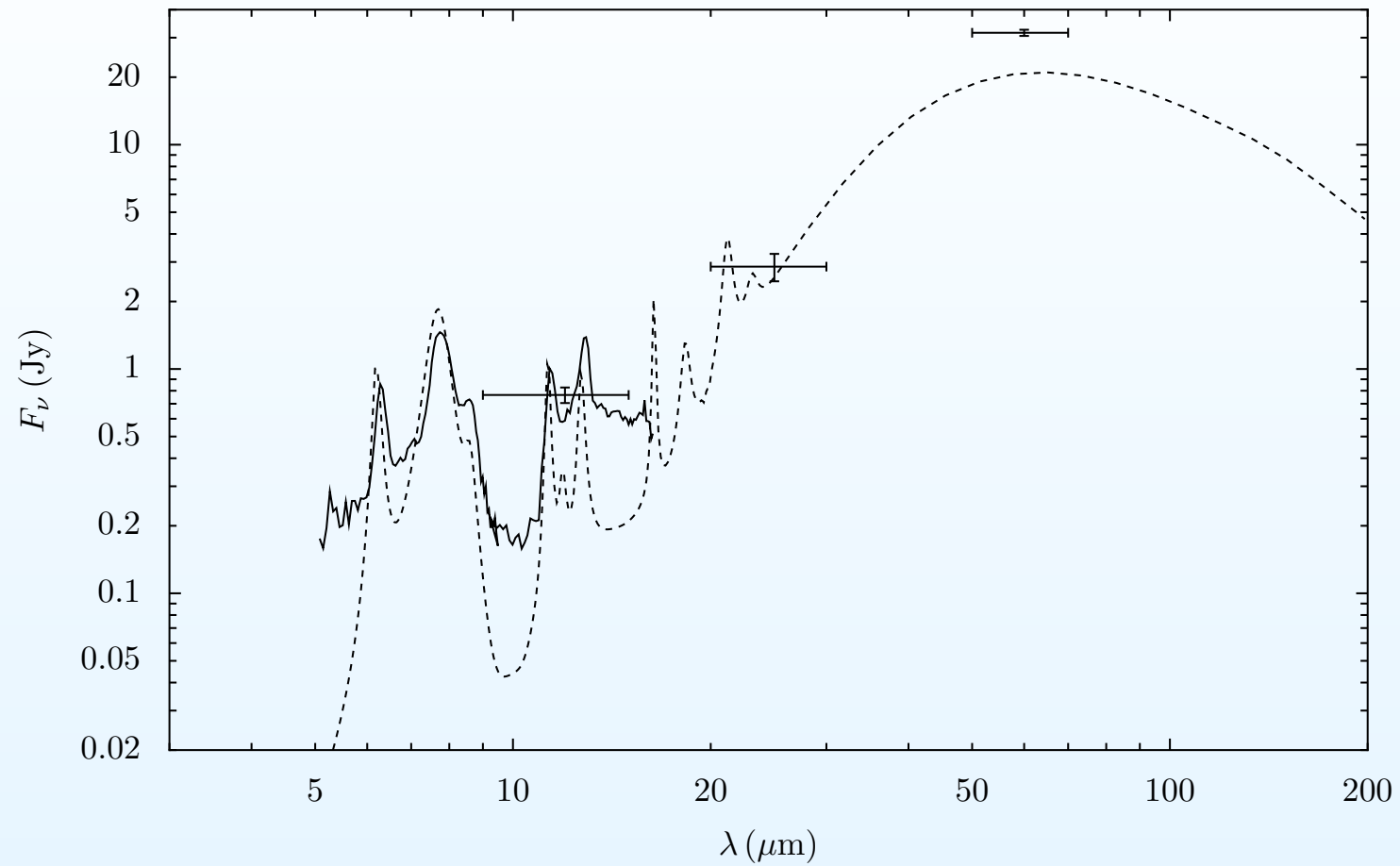
Smallest grain size 3.5 Å

NGC 520 model: grain destruction



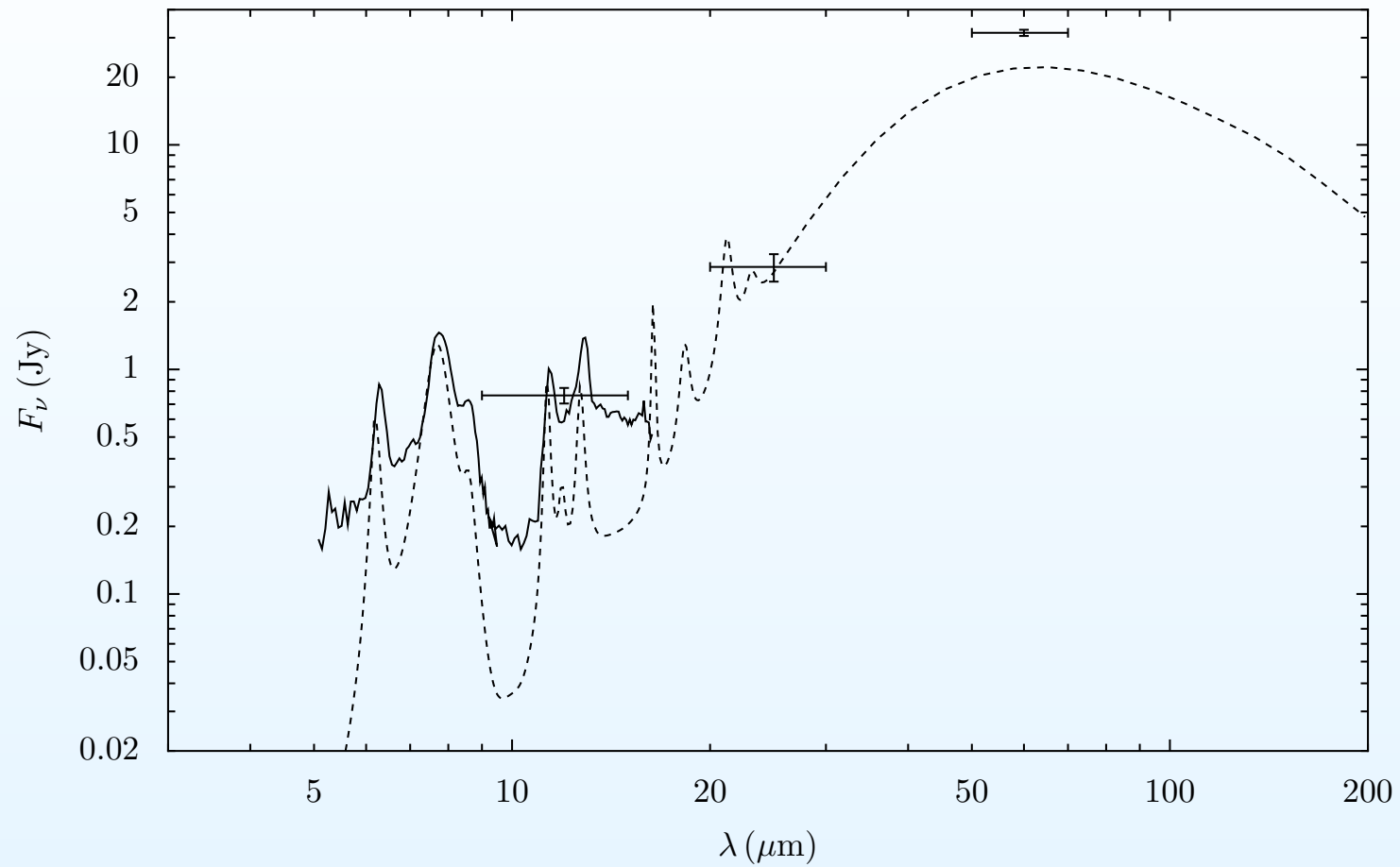
Smallest grain size 5 Å

NGC 520 model: grain destruction



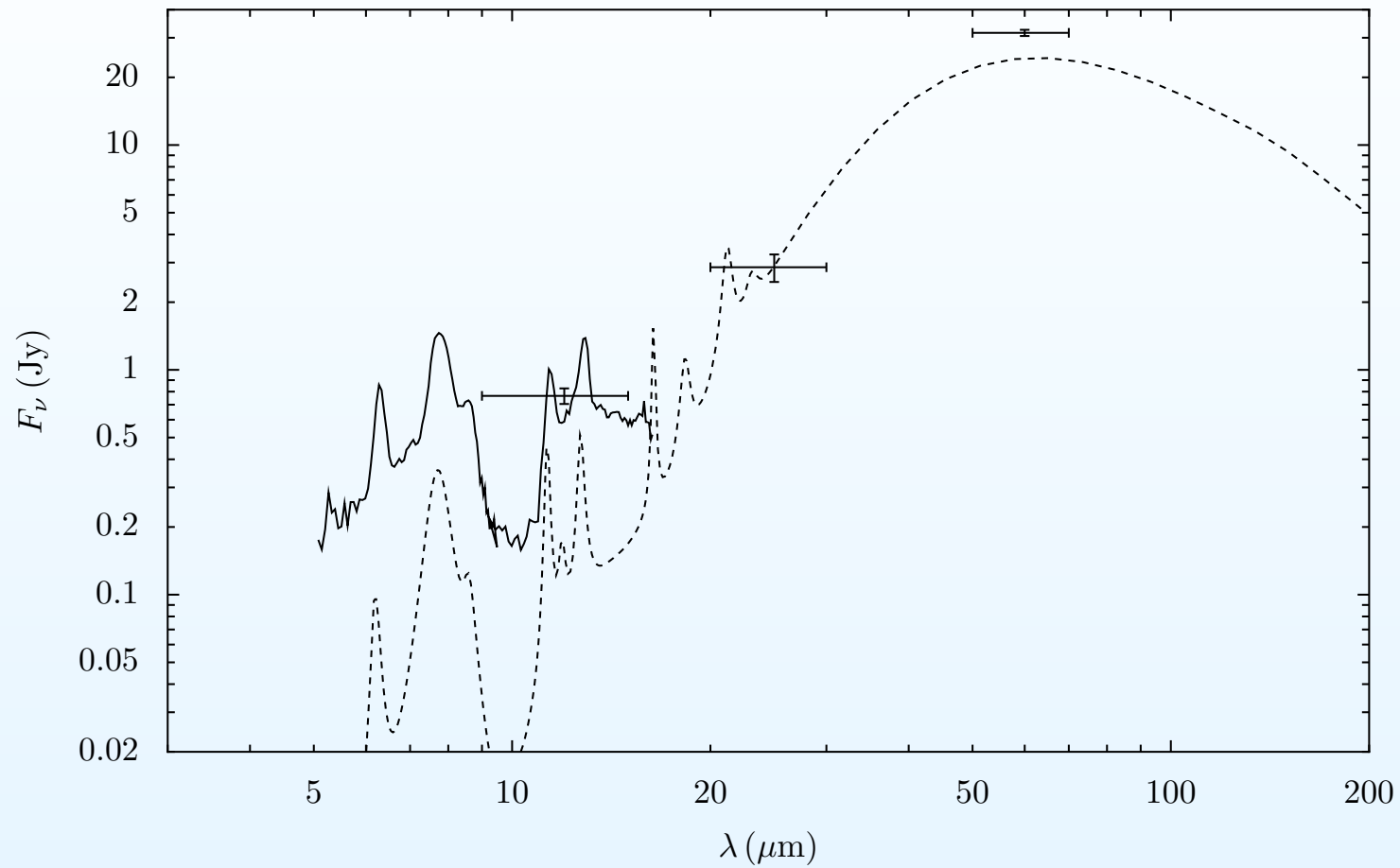
Smallest grain size 6 Å

NGC 520 model: grain destruction



Smallest grain size 7 Å

NGC 520 model: grain destruction

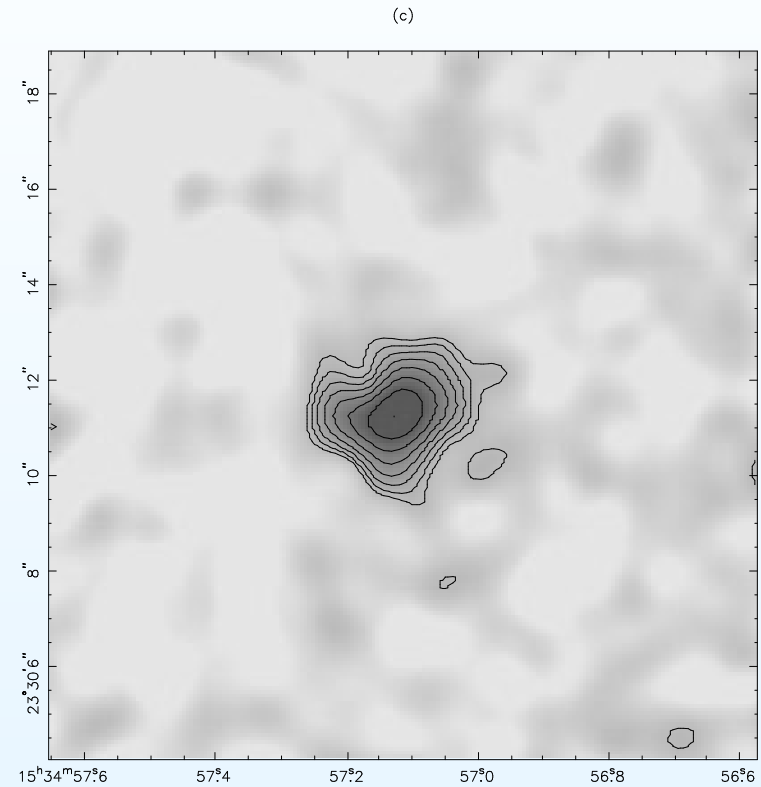


Smallest grain size 10 Å

Case study II: Arp 220



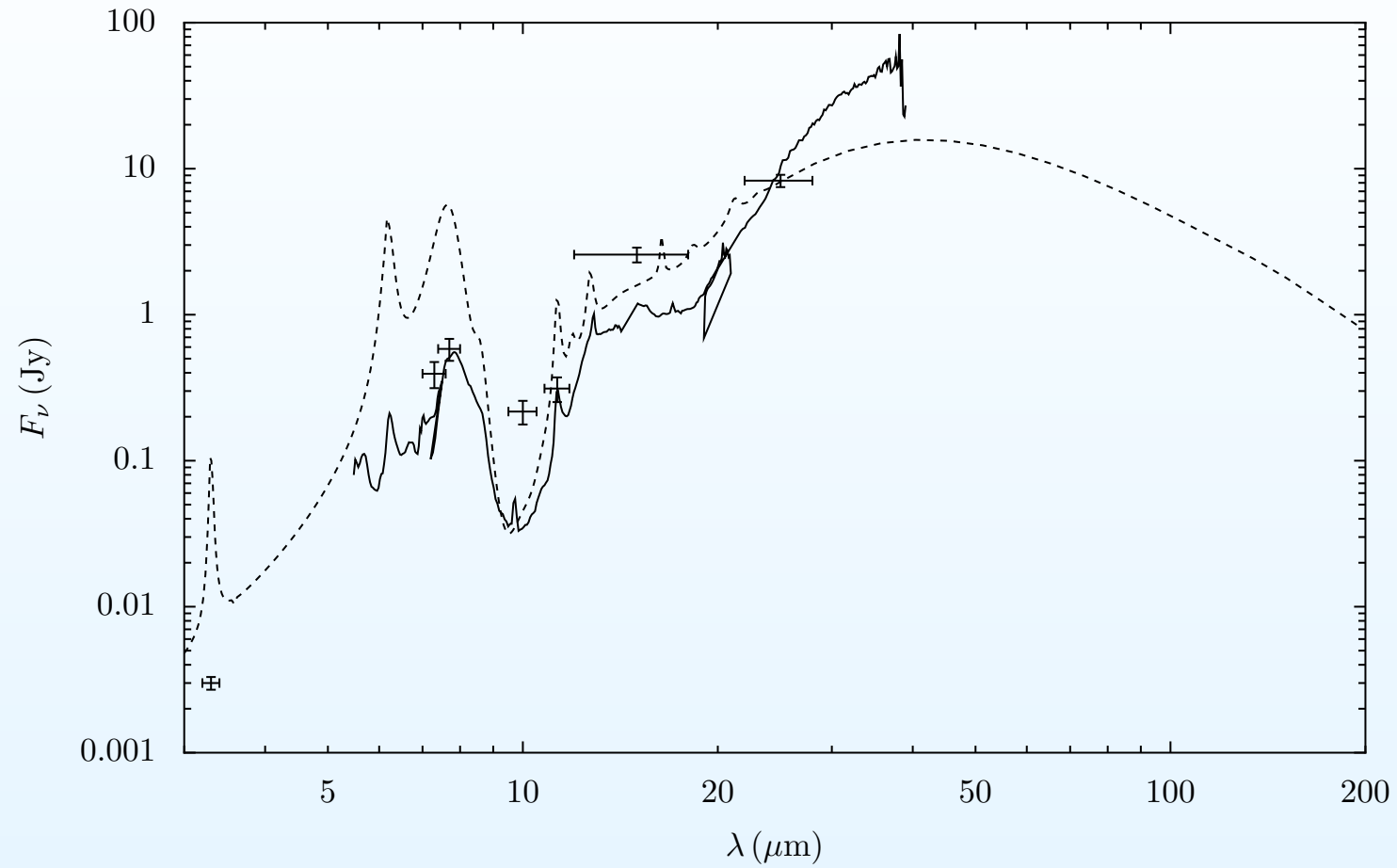
HST/NICMOS [Thomson et al]



UKIRT/MICHELLE

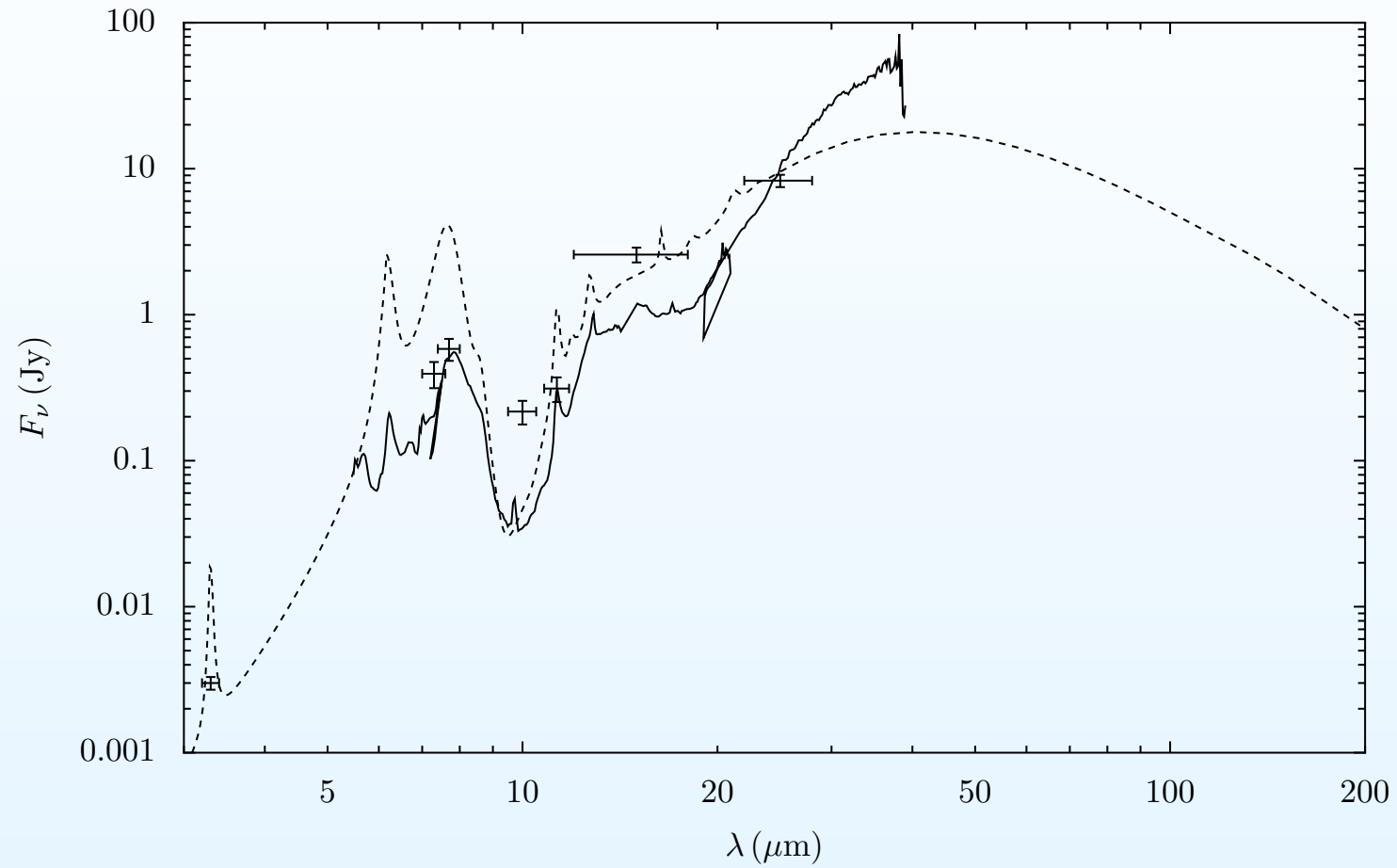
SFR: $120 M_{\odot} \text{ yr}^{-1}$; Mid-IR emission radius 150 pc; gas col. dens. $12 \times 10^{22} \text{ cm}^{-2}$.

Arp 220 model



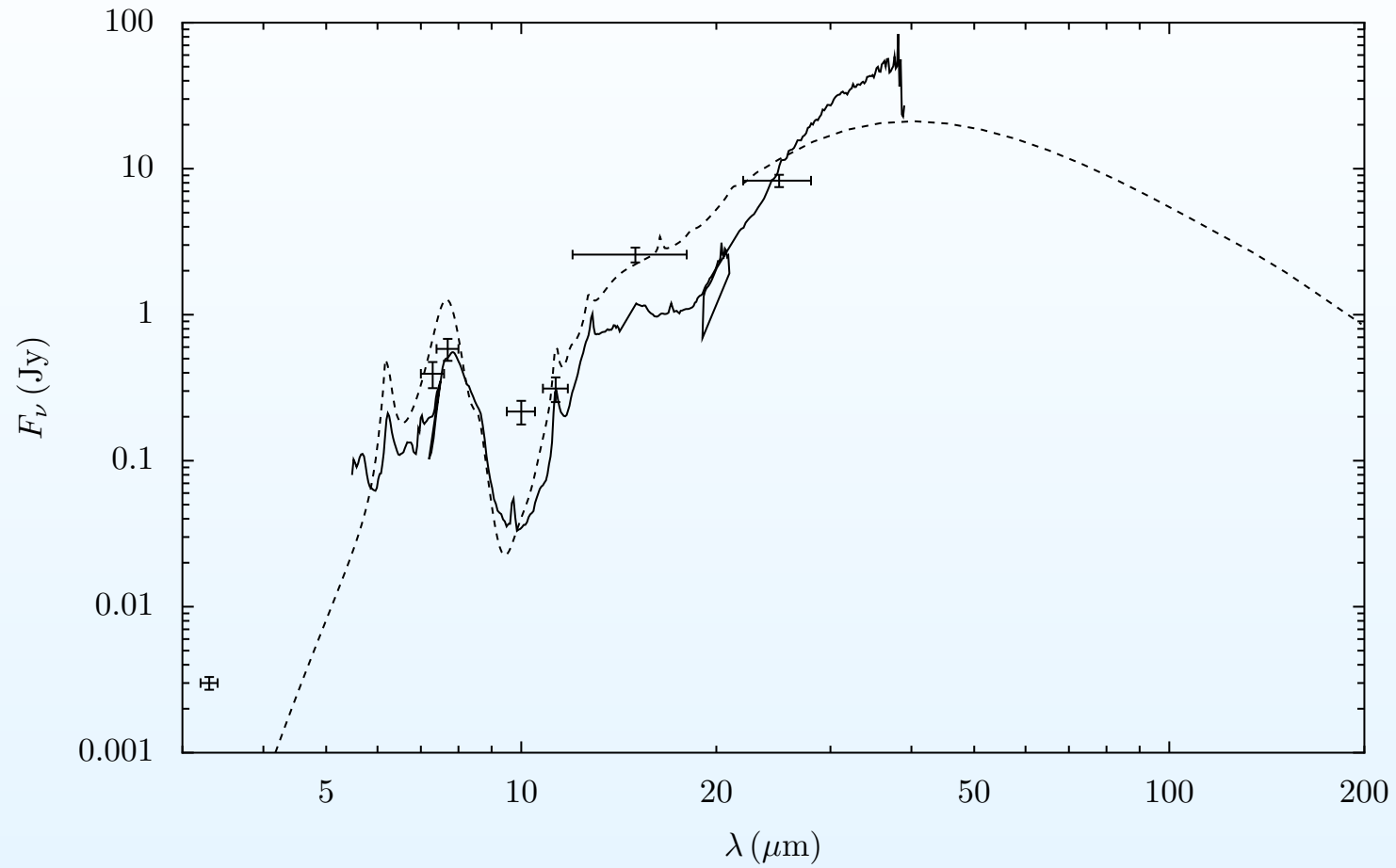
Smallest grain size 3.5 Å

Arp 220 model



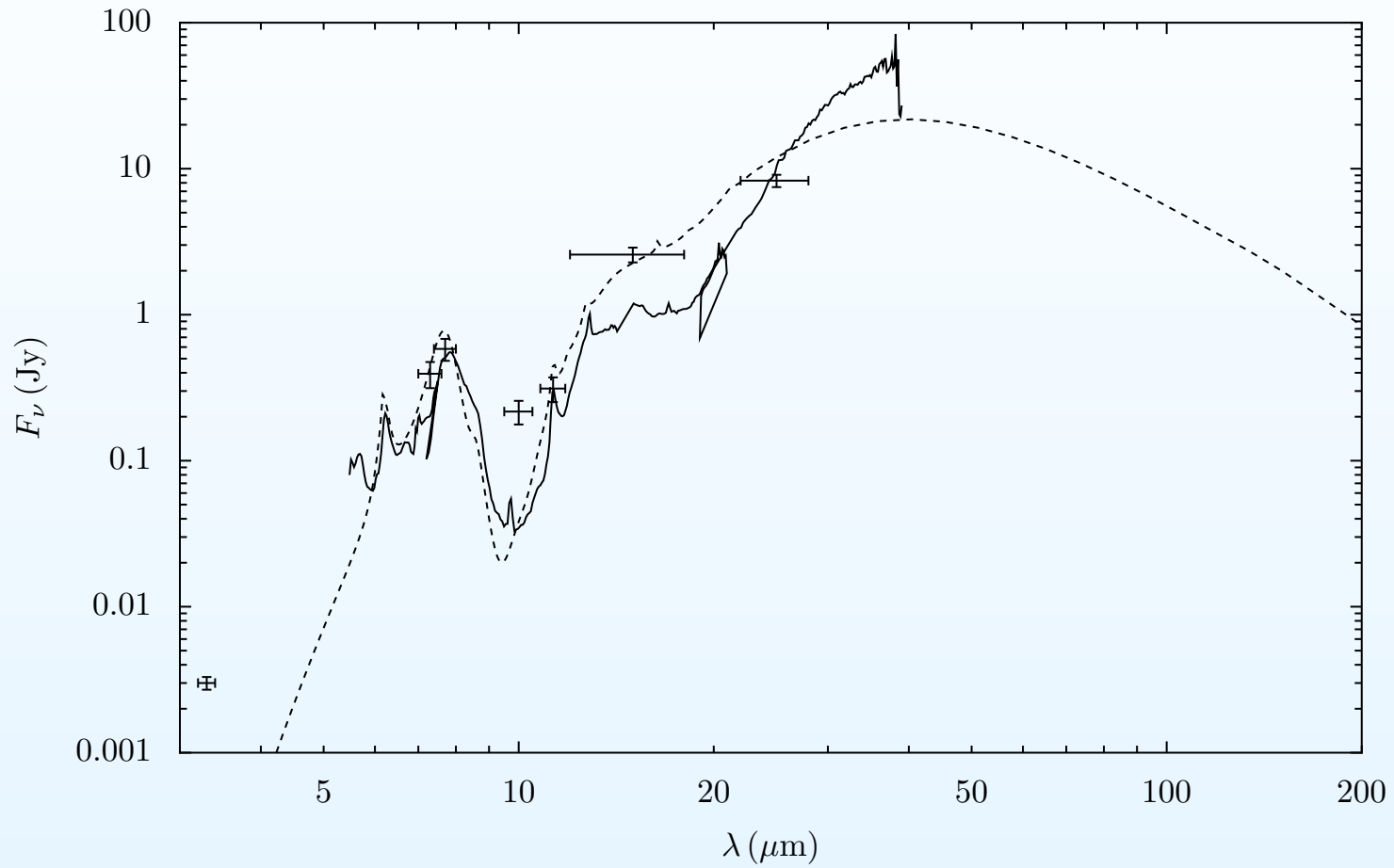
Smallest grain size 6 Å

Arp 220 model



Smallest grain size 20 Å

Arp 220 model



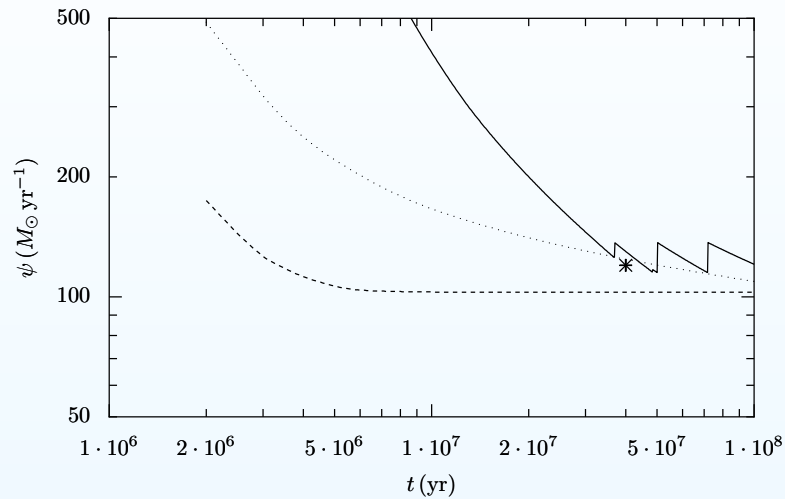
Smallest grain size 35 Å

Conclusions

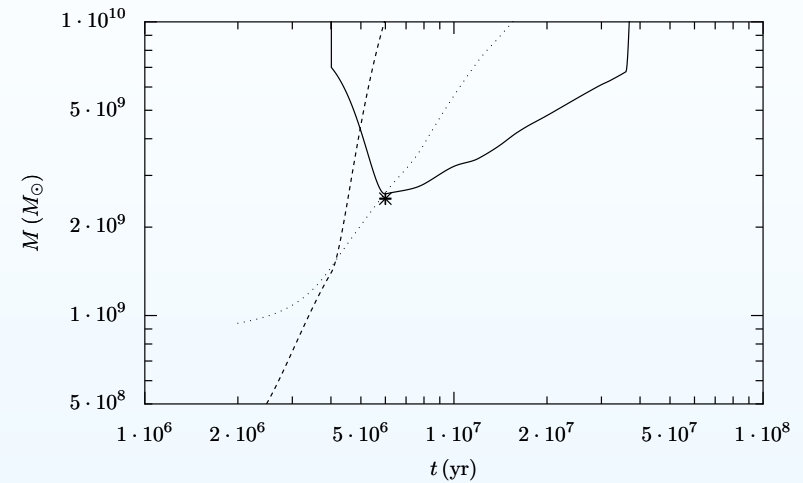
- A *physical* framework for modelling the mid-IR emission from galaxies.
 - Can directly relate the properties of the heating source (starburst), dust and geometry to observations.
- Validated on the observed correlations between mid-IR emission and star-formation rates.
 - Suggests dust absorbing from young stars is not directly associated with the parent molecular clouds.
- Applied to a moderate and an intense starburst (NGC 520 and Arp 220)
 - Properties of dust *must* be changing!
 - Destruction of small grains plausible.
- The 3.3 μm PAH feature often overlooked but very useful.

Supplementary

SF in Arp 220



Modelling H-recombination, bolometric luminosity and radio luminosity of Arp 220 as due to a continuous star burst



Modelling H-recombination, bolometric luminosity and radio luminosity of Arp 220 as due to an instantaneous star burst

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